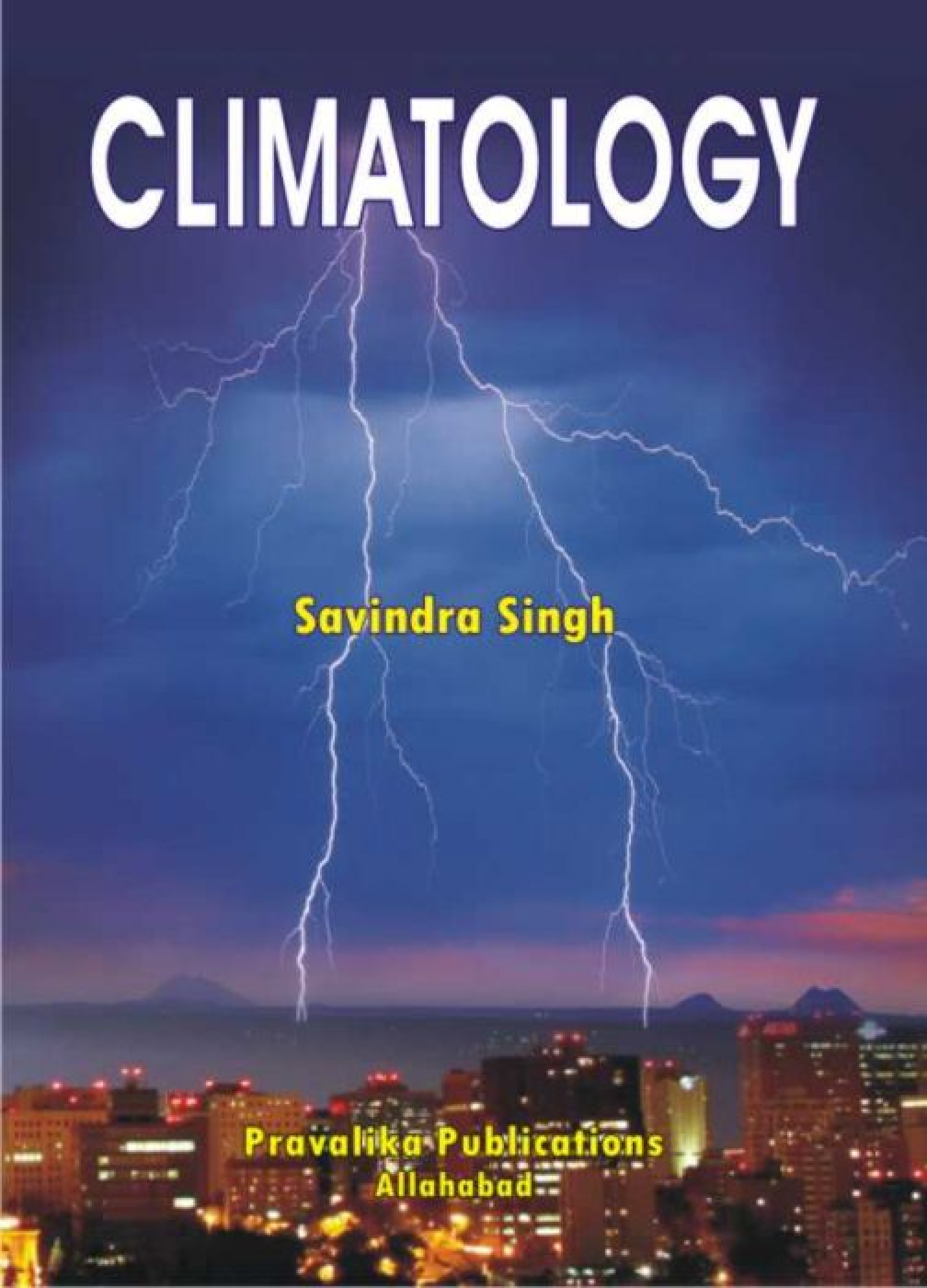
CLIMATOLOGY



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CLIMATOLOGY : BASIC CONCEPTS

1.1 CLIMATOLOGY : A PART OF PHYSICAL GEOGRAPHY

Physical geography is one of the two major branches of geography, namely physical geography and human geography. Physical geography was previously considered as the agglomeration of different branches of earth sciences or natural sciences such as the science of atmosphere (meteorology and climatology); the science of seas and oceans (oceanography); the science of solid earth (geology); the science of soils (pedology); the science of landforms (geomorphology); the science of plants and animals (life sciences—biogeography) etc. but presently physical geography is not only the agglomeration and unification of earth sciences as referred to above but it also studies the patterns of interactions between technologically advanced man and physical environment including land, air, water, plants and animals. As a distinct branch' of geography physical geography studies the spatial patterns and spatial relationships of environmental components of the globe in regional context, it also studies the causes of regional patterns of such spatial relationships, and simultaneously it incorporates the explanation of spatial and temporal changes of environmental components and causes thereof (Savindra Singh, 2003).

It may be mentioned that on an average physical geography includes the consideration of various aspects of four components of the earth e.g. (i) lithosphere (geomorphology), hydrosphere (oceanography), atmosphere (meteorology and climatology), and biosphere (biogeography—environmental geography). It is significant to note that the atmosphere is very important and critical component of the living earth system because it, together with the lithospheric and hydrospheric components, makes the earth a suitable habitat/place for numerous species of flora and fauna. Needless to say that climatology is the study of various elements and aspects of atmosphere.

1.2. CLIMATOLOGY : AN ATMOSPHERIC SCIENCE

The atmosphere is a complex thick gaseous envelope which surrounds the earth from all sides and is attached to the earth's surface by the gravitational force and it is a significant component of the biospheric ecosystem because the life on the earth is due to the existence of this atmosphere otherwise the earth would have become barren like moon. Besides providing all necessary gases for the existence and survival of life forms in the biosphere, it also filters the incoming solar electromagnetic radiation waves and thus prevents the ultraviolet radiation waves reaching the earth's surface and protects the earth from becoming too hot. Besides providing energy to earth's biospheric ecosystems, it also plays a key role in the distribution and redistribution of solar energy both horizontally and vertically on the earth's surface. It is thus obvious that the detailed study of different components of the atmosphere has gained currency. The comprehensive study of the atmosphere is called **atmospheric science** which has been conveniently divided into a few significant branches e.g. aerology, meteorology and climatology. It has now become imperative to distinguish between these three branches, though inseparable, of the atmospheric sciences.

(1) Aerology

Aerology, also called as aeronomy, is in fact a part of meteorology, as a dictionary meaning reveals that it is considered as a branch of meteorology which involves the study of the characteristics of the composition of the atmosphere based on the observations by means of baloons and aeroplanes whereas **aeronomy** involves the study of chemical and physical composition of the atmosphere. It may be pointed out that presently aerology/aeronomy is considered as a part of meteorology wherein we include the consideration of the chemistry of different layers of the atmosphere and physical reactions occurring in these vertical layers.

(2) Meteorology

As per dictionary meaning (Webster) meteorology is a science which deals with the atmosphere and its phenomena, including weather and climate i.e. the atmospheric conditions and weather of an area. 'Meteorology is the science that deals with motions and phenomena of the atmosphere, with a view to both forecasting weather and explaining the processes involved. It deals largely with the status of the atmosphere over a short period and uses the principles of physics to reach its goals' (J.E. Oliver and J.J. Hidore, 2003). In simple words it may be defined as that branch of atmospheric sciences which studies the characteristics and behaviour of the atmospheric conditions based on the study of individual phenomenon and motions of the atmosphere involving principles of physics.

(3) Climatology

Climate is defined as the study of aggregate weather (atmospheric) conditions of any region in long-term perspective. Thus, climatology includes the systematic and regional studies of the atmospheric conditions i.e. weather and climate. **Weather** refers to the sum total of the atmospheric conditions in terms of temperature, pressure, wind, moisture, cloudiness, precipitation and visibility of a particular place at any given time. Infact, weather denotes short-term variations of atmospheric conditions and it is highly variable.

Thus, **climatology** is the study of average atmospheric conditions of a place or region over long period of time. According to Trewartha 'climate represents a composite of day to day weather conditions and of atmospheric elements, within a specified area over a long period of time.' According to Critchfield 'climate is more than statistical average; it is the aggregate of the atmospheric conditions involving heat, moisture, and air movement. Extremes must always be considered in any climatic description in addition to means, trends, and probabilities.' According to Koeppen and De Long, 'climate is a summary, a composite of weather conditions over a long period of time, truly portrayed, it includes details of variations, extremes, frequencies, sequences of weather elements which occur from year to year, particularly in temperature and precipitation. Climate is (thus) aggregate of the weather'. G. F. Taylor has maintained that 'climate is the integration of weather, and weather is differentiation of climate. The distinction between weather and climate is, therefore, mainly one of time.'

Climatology is, thus, defined as 'that science which studies the nature of climate, the causes and interpretation of its spatial variations and its association with the elements of natural environment and human activities' (Critchfield). It is now apparent that climatology is that atmospheric science which includes the consideration of weather conditions (atmospheric conditions) of a place or an area of different spatial scales over long period of time, of frequent and infrequent weather phenomena as well as average weather conditions. Climatology becomes both meteorological (because it studies atmospheric conditions) and geographical (because it includes the consideration of weather conditions of a place having certain location on the earth's surfaces e.g. climate of a city like Allahabad, Delhi, London, New York, etc., of an area e.g. the Ganga plain, Malabar coast-India, England, Great Plains-USA, Red basin-China, of a continent etc.). Following E.T. Stringer it may be forwarded that 'climatology does not belong entirely within the fields of meteorology or geography. It is a science-really an applied science-whose methods are strictly meteorological but whose aims and results are geographical' (quoted in Climatology by Oliver and Hidore, 2003).

Since the emergence of man as an important factor and agent of climate after Industrial Revolution, which started in 1860 world over, the aims and scope of physical geography have undergone sea change. The technological man and his economic activities have changed and are changing the natural atmospheric conditions through weather modification schemes (like cloud seeding and induced artificial precipitation, hail storm suppression, dissemination and clearance of fogs etc.), urbanization, industrialization, land use changes (clearance of forest cover), building activities etc. Thus, it has become necessary to include human interferences in atmospheric conditions and processes in any meaningful definition of climatology. Simultaneously, the impacts of climate on human health and wealth should also be included in the definition of climatology.

Thus, climatology may be defined by the author *as that branch of atmospheric science which includes the study of long-term weather conditions of a place or an area of varying spatial scales over long period of time, of frequent and infrequent weather phenomena, systematic study of climate and its distribution on the earth's surface both horizontally and vertically, effects of human economic activities on different components of the atmosphere leading to weather and climatic changes and effects of weather and climate on man and his activities in particular and other flora and fauna in general.*

1.3. CLIMATOLOGY : TYPES AND SUBDIVISIONS

The science of climatology is divided into various branches on different bases depending on the nature of requirement and objectives of the study of climatic conditions of a definite location e.g. spatio-temporal variations of weather and climatic elements, range of spatial units of study i.e. scale consideration, climatic variations and differences etc. H.J. Critchfield identified three distinct branches of climatology e.g. 1. physical climatology, 2. regional climatology, and 3. applied climatology.

1. Physical Climatology

Physical climatology also known as **dynamic climatology** deals with the interpretation of factors responsible for the spatial and temporal variations of exchange of air circulation, heat and humidity. It studies various elements of weather, namely insolation, temperature, air pressure, wind, evaporation and humidity, precipitation, fogs, visibility etc. Different climates are formed due to combinations of these weather elements. The occurrences of different combinations of these weather elements are accomplished through different processes and mechanisms say dynamic processes. Thus, **dynamic climatology** studies these processes of exchange of heat, humidity and interactions between the atmosphere and the earth's surface. It is, thus, evident that physical climatology studies the factors and processes of regional variations of climatic conditions. Physical climatology is, infact, related to meteorology wherein atmospheric physics and chemistry and atmospheric dynamics provide basis for general principles of climatology. It may be concluded that physical and dynamic climatology studies the systematic description and analysis of energy balance of the atmosphere and the earth (i.e. global radiation balance or heat budget), atmospheric temperature, humidity and precipitation, atmospheric motions and air circulation, air masses and atmospheric extreme events (atmospheric disturbances, droughts, floods etc.).

2. Regional Climatology

Climatic conditions significantly vary from one region to the other region. In other words, there are spatial variations in the combinations of elements of weather and climate (insolation, temperature, air pressure, humidity etc.) and hence different climate types are originated. The regional climatology studies different types of climates determined by almost similar climatic conditions having a set of combination of elements of weather and climate in an areal (spatial) unit the size of which varies according to the spatial scales e.g. from a vegetable garden to crop fields, villages, cities, forest cover, desert, mountains, plains, countries and even the continents. It is, thus, apparent that the size of areal unit for the study of regional climatology varies from a micro area (e.g. crop field) to macro area (e.g. a continent). Thus, the primary goal of regional climatology is to study the differences in the climatic conditions of the areal units having different spatial scales. Based on spatial scale M.M. Yoshino identified the following four groups of climates to be included in regional climatology : 1. microclimate, 2. local climate, 3. mesoclimate, and 4. macroclimate.

(1) Microclimate : The climatic condition of the smallest areal unit having a horizontal extent from less than one meter to 100 meters and vertical extent from the ground surface to 100 meters (e.g. single crop field or a single household or the area around a single tree) is termed as microclimate. It may be mentioned that data of climatic variables (e.g. temperature, air pressure, humidity, evaporation, precipitation, air circulation etc.) are not available in published climatological data records and hence such data are always obtained through fieldwork (measurement of these data by suitable instruments) by the individual (investigator). It is evident that the microclimate is related to weather conditions at ground surface level and hence the findings of microclimatic study of different ground surface covers (ranging from bare surface to grass covers, crop covers, tree covers, human structure covers etc.) may reveal different microclimatic environments which may enable the investigators to present a generalized picture of variation of microclimatological processes operating over varying ground surfaces and their impacts on human being, and micro-organisms. This is the reason that a few climatologists consider microclimate as part of applied climatology.

(2) Local Climate : The local climate comprises a few microclimatic areas and hence its dimension in terms of areal coverage is larger than microclimate. The areal unit of local climate has the horizontal extent from 100 meters to 1000 meters and vertically, the area extends from ground surface upto 1000 meters. It may be mentioned that in the study of local climate of an area (having different characteristics, namely a forest cover, an orchard, a village, an urban area etc.) the horizontal differences in climatic conditions are given more importance than the vertical differences. Local climate varies even in forest covers depending upon the nature of forest canopy, density of trees, ground cover, vertical structure, seasonality etc.

(3) Mesoclimate : The mesoclimate incorporates several local climatic areas which has horizontal extent from 100 meters to 20 km and vertical extent from the ground surface to 6 km in the atmosphere. It may be mentioned that topographically the mesoclimatic area is homogeneous which is characterized by similar physical controls of climate e.g. the Ganga Delta, Konkan coastal plain, middle Ganga plain, Sundarban, Rewa plateau, Tarai region of Uttar Pradesh, Godavari Delta, Sardar Sarovar area etc. may be cited as examples of typical mesoclimatic areas. It may be pointed out that in the beginning spatial scales (i.e. scales of area) were used to determine the areas for mesoclimatic studies but recently the scales of atmospheric motions are given more importance and the study of mesoscale meteorological phenomena involving atmospheric motions like severe atmospheric storms (supercyclones, severe tornadoes and hurricanes), pattern of precipitation in a physical unit, heat wave areas, cold wave areas etc. has gained currency with the advancement in obtaining meteorological data through advanced satellite and radar techniques.

(4) Macroclimate : Macroclimate also known as **geoclimate** or **geographical climate** covers largest area of all the other three types of regional climate as refred to above. The horizontal distance is more than 20 km, it may be several hundred kilometers and vertical extent from ground surface may be more than 6 km. Thus, the macroclimatic area may cover even the whole continent or a large country like the USA, China, Russia, Brazil, India etc. It may be mentioned that during the climatic study of microclimatic area which comprises several mesoclimatic areas averages of atmospheric circulation patterns over longer period of time are considered to determine the general characteristics of the study area while smaller scale (in terms of time and space both) patterns of atmospheric motions (circulation) are filtered out (omitted) e.g. for the study of climate of India, circulation of heat waves (loo) will be ignored. Similarly, mesoscale motions such as mountain and valley winds, land and sea breezes, local cold or warm winds would not be considered in the study of general characteristics of macroclimatic area.

Based on the approach of analysis of macroclimates, climatology is divided into (i) **descriptive climatology**, and (ii) **synoptic climatology. Descriptive climatology** of macroclimatic area includes the study of the climatic characteristics of the ground surface, namely temperature, air pressure, humidity, precipitation etc. **Synopic climatology** includes the analysis of dominant patterns of atmospheric circulation.

'This approach (synoptic approach) obtains a synopsis, or condensed view, of the atmosphere at a given time and is referred to as the **synoptic climatology**' (Oliver and Hidore, 2003).

It may be mentioned that the descriptive approach of macroclimatic studies involves the classification of world climates into certain types on the basis of surface climatic characteristics and the principles of synoptic climatology e.g. equatorial climate, monsoon climate, Mediterranean climate etc.

3. Applied Climatology

Applied climatology studies the climatic controls of human activities and the application of climatic principles and knowledge to solve various problems faced by human society e.g. global warming and climate change. It may be mentioned that in the beginning the emergence of the concept of environmental determinism in the late 19th century gave rise to **climatic determinism** because climate being major environmental component of physical environment was demonstrated as the most dominant factor in guiding and controlling human activities. E. Huntington's 'Civilization and Climate' (1915) and 'Season of Birth' (1938) clearly demonstrate the strong control of climate on humans. Now the study of relationships between climate and human activities has become more logical and rational because this is based on careful analysis and interpretation of available data say it is based on quantitative methods.

Consequently, now the applied climatology studies the interactions between climate and biosphere i.e. how does climate influence and control plants, animals including man and in turn how does man modify climate by introducing advertent and inadvertent changes in the physical environment and by making certain weather modifications e.g. cloud seeding and induced precipitation. Further, applied climatology includes the study of variability of climate, climatic changes, air pollution, climate and comfort, climate and heath, climate and society, climate and recreation, climate and archietecture, extreme weather events (e.g. supercyclones, tornadoes and hurricanes, floods and droughts) and their impacts, climate and agriculture, climate and manufacturing industries, climate and urban planning, weather forecasting, climate and transport and communication, weather modification etc.

Human biometeorology, which studies the reactions of human bodies to changes in the atmospheric environment, has gained currency recently. It lays emphasis on to 'establish how much of the overall biological variability is the result of changes in weather, climate and season' (J.E. Hobbs, 1980).

The study of applied climatology is also divided into three categories based on influences of climatic environment on human health and behaviour on different spatial scales e.g. microclimate, ecoclimate, and geoclimate. According to **M. Bates (1966)** three levels of climatic environment affect human behaviour: (1) **microclimate,** which represents weather conditions surrounding an individual organism; (2) **ecological climate** or **ecoclimate**, which represents weather elements of the habitats of the organisms, in the case of man the habitat may be his house and working places like factory, office, mine, agricultural farms, pasture etc.; and (3) **geographical climate** or **geoclimate**, which represents weather conditions of larger areal unit and longer temporal span.

Satellite Climatology

The satellite climatology deals with climatic data obtained through satellites which view the wider areas from above and provide useful data of day to day weather conditions. The weather satellites provide images of the earth and cloud covers. It may be mentioned that it is the orbit and sensors of weather satellites which determine the types and nature of weather data. Generally, two types of orbits are used, namely (i) high-altitude geostationary orbit, and (ii) the low-level polar orbit while sensing instruments are classified into two major categories e.g. (i) imaging system, and (ii) sounding system. The satellite imageries obtained from both polar orbiting and geosynchronous (geostationary) platforms provide useful information about weather conditions mainly cloud cover. 'Satellite climatology is becoming increasingly important as digital archives are growing' (Oliver and Hidore, 2003). This aspect has been further elaborated in the 17th Chapter (weather forecasting) of this book.

1.4. AIMS AND SCOPE OF CLIMATOLOGY

The primary goal of climatology is to study the identification, demarcation and distribution of different types of climates, the mode of origin of different types of climate, causes and processes that lead to climatic variations both horizontally and vertically in the world, different elements of weather and climate, the varying combinations of which give birth to different climatic types, the interactions of weather and climate with human society and consequent impacts on human activities and human health covering both physiological and psychological aspects. It may be pointed out that the objectives of climatology should not be confined only to the study of description of elements of weather and climate like insolation (atmospheric energy balance), temperature, air pressure, atmospheric circulation, humidity and precipitation and characteristic features of different climate types but should also be widened so as to include its applied aspect (e.g. applied climatology) including the explanation of relationships between climate and human activities and processes and causes of such relationships at varying spatial scales e.g. micro, meso and macro levels. The climatologists' aims should also focus to identify relationships between climatic regions and biomes comprising plant and animal communities. Besides, the goal of climatology also includes the investigation of palaeoclimates and their reconstruction, causes and factors of climatic changes and effective devices of weather forecasting.

It is pertinent to point out that the contents (scope) of any discipline largely depend on its aims and objectives. The scope covering all the contents of climatology may be described through its major branches i.e. physical and dynamic climatology, regional climatology and applied climatology. As already stated '**physical climatology** deals largely with energy exchanges and physical processes. **Dynamic climatology** is more concerned with atmospheric motion and exchanges that lead to and result from that motion' (J.E. Oliver and J.J. Hidore, 2003). Thus, the main contents of physical and dynamic climatology comprise global radiation and energy (heat) balance, atmospheric temperature (distributional patterns-horizontal and vertical, and factors influencing temperature distribution), atmospheric moisture (hydrological cycle, absolute, specific and relative humidity, evaporation, condensation and precipitation), motions in the atmosphere (causes and distributional patterns of pressure belts, air circulation), global atmospheric circulation (horizontal circulation and planetary winds, meridional circulation, Walker circulation and southern oscillation), airmasses and fronts (regional patterns of airmasses, frontogenesis, cyclogenesis-convergent circulation, divergent circulation-anticyclones), atmospheric extreme events (atmospheric disturbances-tropical cyclones, hurricanes and tornadoes, floods and droughts) etc.

As stated above **regional climatology** aims at the study of different types of climates of the world and hence the subject matter of regional climatology comprises the classification of world climates of macro spatial scale, location and distribution and systematic description involving temperature, air pressure and winds, precipitation and effects of climate on natural vegetation. The approaches to the classification of world climates are (i) genetic approach, (ii) empirical approach, and (iii) objective approach and thus climatic classification falls under three broad categories, namely (1) **genetic classification,** (2) **empirical classification, and** (3) **numerical classification.** The schemes of classification of world climates by Koeppen, Thornthwaite and Trewartha fall under empirical system of climatic classification. Genetic system of climatic classification is based on either physical determinants or airmass dominance as stated by Oliver and Hidore (2003). Regional climatology at macro level also includes the study of reconstruction of palaeoclimates (past climates) and prediction (forecast) of future climates, climatic changes over geological time and causes of climate changes.

Applied climatology includes the consideration of the impacts of climate on human activities and human society and human responses to climates, namely physiological and psychological response. Significant relationships between climate and human activities and society include climate and health, climate and civilization, climate and architecture, climate and urban environment, climate and agriculture, climate and industry, climate and transportation and communication, climate and tourism and commerce etc. Effects of human activities on atmospheric environment resulting into changes in global radiation balance due to global warming caused by increase in the emission of greenhouse gases (mainly carbon dioxide and methane) at alarming rate and ozone depletion also become major contents of investigation in applied climatology. Presently, climatic changes and weather forecasting have more focussed contents of climatology.

1.5 CLIMATOLOGY : A HISTORICAL PERSPECTIVE

Like other branches of knowledge the discipline of climatology has also its roots in the philosophical ideas and postulates of ancient Greeks, Romans and Egyptians. Infact, Greece, Rome and Egypt, the centers of ancient cultures and civilization, have been cradles of philosophical and scientific ideas. The present status of climatology is the result of gradual but successive development of climatological knowledge and concepts developed in different periods by innumerable thinkers and scientists. Even the word 'climate' has its Greek origin as the word consists of two Greek words **klima,** meaning thereby slope or inclinitation of the axis of the earth, and **logos,** meaning thereby discourse or description. Klima 'specifies an earth region at a particular place on that slope-that is, the location of place in relation to parallels of latitude' (Oliver and Hidore, 2003). The historical evolution of the concepts and theories together with the development of the subject (contents) of climatology may be briefly outlined as follows :

Ancient period : A few concepts and ideas about the weather conditions were advanced by Greek and Roman thinkers. The Greeks tried to understand the nature of atmosphere and its influences on human health and culture. The first written documents on atmosphere appeared in 400 B.C. when Hippocrates produced 'Air, Water, and Places' wherein he described the influence of climate on health. The first compendium on meteorology, entitled **Meteorologica** was produced by Aristotle wherein he discussed different aspects of weather science i.e. meteorology. Theophrastus described different aspects of winds and presented critical explanation of Aristotle's ideas on weather science in his book **'De Ventis'** in 300 B.C. The ancient Greek thinkers divided the globe into three temperature zones on the basis of latitudes e.g. (i) tropical zone, (ii) temperate zone, and (iii) frigid zone.

Dark Age : The initiatives taken by ancient Greek and Roman thinkers in the field of atmospheric knowledge and weather conditions could not be carried forward for many hundred years, say for nearly 1400 years during which a lull prevailed in the development of geographical as well as climatological ideas and thoughts, though a few Arab thinkers broke the monotony of academic lull in the 9th and 10th centuries during which some sporadic ideas regarding atmosphere and weather were put forth.

Period of renewed interest : The long continued academic silence of about 1400 years was suddenly broken by the emergence of great desire of the Europeans to undertake voyages for different purposes. The period from 15th to 16th centuries is called **Great Age of Discovery and Exploration** because efforts were made to discover and explore new areas and their characteristic features including atmospheric and weather conditions. It may be mentioned that the explorers reported atmospheric and weather conditions of the areas they reached according to their own experiences and understandings. Such reports of weather and climate of different regions outside Europe 'were quite fanciful; they provided for the basis of misconceptions about parts of the world that prevailed for centuries.'

Period of scientific analysis : It may be pointed out that the knowledge about weather and climate upto 16th century was purely descriptive and non-coherent because this was based on qualitively observed data and description by the non-professional individuals. The science of climatology blossomed in the 17th century when a few instruments were invented to measure climatic variables. The proper recording of temperature started with the invention of thermometer by Galileo in 1593 and by Santorre in 1612. The measurement of atmospheric air pressure became possible with the invention of barometer by Torricelli in 1643. Thus, the availability of data on temperature and air pressure provided basis for formulation of a few laws about atmospheric conditions, namely Francis Bacon's treatise on wind in 1662; Boyle's laws about air pressure and atmospheric gases etc. Boyle presented a series of laws regarding relationships among air pressure, volume and density of gases taking temperature as constant. His gas laws are stated below :

(i) First law :

$$P_0V_0 = P_1V_1 = k_1$$

where

P_0 and P_1 are pressure at two times

V_0 and V_1 are volume of gas at two times

K is constant

The Boyle's first law of gases states that if pressure increases, the volume of gases decreases whereas decrease in pressure causes increase in gas volume.

(ii) The Boyle's second law of gases denotes relationship between air pressure (P) and density of gas (D).

$P/D = k$ (at constant temperature)

This means increase in air pressure results in increase in gas density and vice versa.

It is evident that Boyle postulated inverse relationship between air pressure and gas volume and direct relationship between air pressure and gas density.

With the availability of measuring (of atmospheric variables) instruments France started systematic and regular measurement and observations of weather phenomena in 1664 with its weather station located at Paris. Edmund Halley studied planetary winds and presented a map showing trade winds in 1668. Du Crest introduced centigrade scale for temperature in 1641. Hadley proposed the cell model of tropical circulation between the tropics of Cancer and Capricorn in 1735 which is widely known as **Hadley cell.**

Period of regional description : The period ranging from 18th to 19th centuries was characterized by the study of weather phenomena at regional and global levels and efforts were made to prepare maps of the countries, continents and the globe depicting climatic variables like, insolation, temperature, air pressure and winds, atmospheric disturbances, precipitation etc. on the basis of extensive data measured by improved and standardized weather instruments. Recording of climatic data mainly surface temperature and precipitation on regular basis in many of the European countries and the USA enabled the weather men to store mass dataset for hundreds of years. Luke Howard, for the first time, presented a well documented **classification of clouds** in 1803 into two categories viz. main cloud types and secondary cloud types. It may be mentioned that Howard used Latin words to name the clouds (like stratus, from Latin stratum, meaning thereby layer; cumulus, meaning pile-heap; cirrus, meaning hair). With the advancement in the knowledge about clouds at world level, his classification was revised by the International Meteorological Committee (IMC) in 1895 and in order to have uniformity world over the clouds were renamed. It may be mentioned that World Meteorological Organization (WMO), an UN organization, now publishes International Cloud Atlas.

Another important contribution regarding temperature distribution was made by Alexander Von Humboldt in 1817 when he prepared a **world map of mean annual temperature using isotherms.** Efforts were made to devise instruments to measure atmospheric humidity and ultimately August became successful in constructing **psychrometer** in 1825. H.W. Dove studied polar and equatorial air currents and postulated the **laws of atmospheric storms** while origin, development and movement of atmospheric storms were described by Espy in 1841. By now the scientists became able to prepare weather maps at different spatial scales. For example, **first weather map** of United States of America was prepared by William Redfield in 1831. Another breakthrough was made in inventing weather instruments by the scientists in 1837, when **pyrheliometer** to measure the total intensity of the sun's energy radiation i.e. insolation was made. The deflective force of the earth due to its rotational movement causing deflection in the direction of wind was identified and formulated by Gaspard de Coriolis, popularly known as **coriolis force,** in 1844. The identification of Coriolis force led to the postulation of two important laws viz.

(i) Ferrel's law related to deflection of wind direction, and

(ii) Law of pressure and wind direction by Buys Ballot, a Dutch meteorologist in 1857.

The data of precipitation of different meteorological centers world over enabled Berhaus to prepare **first world map of precipitation** in 1845. The construction of world map of mean annual temperature in 1817 was followed by the construction of **world map of mean monthly temperature** by Dove in 1848. Renou prepared the **first map of mean air pressure** of the western Europe in 1862. Soupan rejected the Greeks' division of the globe into tropical, temperate and frigid zones on the basis of latitudes and used isotherms to divide the globe into temperature zones. He used 20°C annual isotherm to determine outer limit of tropical zone. The boundary between temperate and frigid zones was determined by 10°C July isotherm for the nothern hemisphere and by 10°C January isotherm in the southern hemisphere. Finally, he presented a map showing temperature regions of the world in 1879. Lord Rayleigh (1842-1919) described the process of scattering of solar radiation and its effect, which is known as **Rayleigh scattering.** By the end of the 19th century scientists became interested in understanding the characteristics of upper air and the use of baloons started in 1892. It may be mentioned that by the turn of the 19th century ample data about weather elements became available and hence scientists started thinking about the classification of world climates and German meteorologist Koppen is given credit for using the term of **classification of climate** for the first time in 1900. A significant contribution in the form of publication of books on climatology and meteorology was made by J. Von Hann in 1897 when he published 'Handbook of Climatology'.

20th century : the period of modern climatology : The climatological study was enriched by more and more information about atmospheric conditions mainly upper air circulation and weather phenomena obtained through advanced techniques. This period was marked by (i) advancement in techniques to obtain detailed regular climatic data, (ii) concerted efforts for the classification of world climates, (iii) concerns about climatic changes, (iv) weather forecasts, (v) international cooperations to tackle the future problems of climatic changes at local, regional and global levels caused mainly by anthropogenic factors etc.

The existence of stratosphere and ozone layer was discovered in 1902 and 1913 respectively. Vigorous investigation of jet streams started during Second World War and four-stage **index** cycles of jet streams was propounded. V. Bjerknes and J. Bjerknes propounded **'polar front theory'** in 1918 to explain the origin and development of temperate cyclones. The last century was marked by systematic weather data collection using aircrafts, radars and weather satellites. The use of satellites in providing climatic data became so important that a new branch of climatology known as **satellite climatology** gained wide recognition. The use of aircrafts for collecting atmospheric data started in 1925, while radiosondes were first used in 1928. The first meteorological satellite, **TIROS 1**, was launched by the United States in 1960. The use of radar, mainly **doppler radar** has become more useful and popular in monitoring atmospheric conditions mainly upper air circulation patterns. The decade 1940s was characterized by the development of **synoptic climatology** which 'is the study of local and regional climates in terms of properties and motions of the overlying atmosphere. The term **synoptic** is used by meteorologists to denote instantaneous weather conditions shown on a synoptic weather chart' (Oliver and Hidore, 2003).

Basically, two types of weather satellites, namely geosynchronous (geostationary) satellites and polar orbiting satellites, with a variety of sensing instruments (sensors) were developed to collect weather data of various sorts. The visible and infrared radiations are sensed and related data are sent to earth's center by **NOAA-15** satellites. It may be mentioned that the satellites are attached with the instruments of imaging and sounding systems. The following sensors have been developed for different purposes: (1) Earth Radiation Budget **(ERB)** sensor to monitor energy budget of the earth and the atmosphere, (2) Total Ozone Mapping Spectometer **(TOMS)** for obtaining data of ozone, (3) Solar Backscatter Ultraviolet Energy **(SBUV)**sensor to monitor and evaluate the condition of atmospheric ozone, (4) Stratospheric and Mesospheric Sounder **(SAMS)** to record temperature, (5) **GOES** imager to record solar radiation and the solar energy reflected from the earth's surface etc.

It may be mentioned that weather conditions at local level are controlled by weather events which occur in other parts of the world. For example, weather conditions in India are affected by El Nino phenomenon occurring in the eastern Paciffic Ocean, off the Peruvian coast. 'In recent years, much research has been undertaken to understand which patterns and anomalies occur, and many of them are rooted in **teleconnections**— the influence on local climatic conditions by events happening in other world areas' (Oliver and Hidore, 2003). Such local conditions include **ENSO** (El Nino Southern Oscillation) events, **PDO** (Pacific Decadal Oscillation), **NAO** (North Atlantic Oscillation), **AO** (Arctic Oscillation) etc. These events were studied in the later half of the 20th century.

The 20th century climatology was also characterized by the formulation of several schemes of **classification of world climates** employing both empirical and genetic approaches. The German botanist and climatologist Wladimir Koppen presented his descriptive scheme of the classification of world climates first in 1900 based on vegetation zones. He revised his scheme in 1918 wherein he included two easily measurable weather elements, namely mean monthly and annual temperature and precipitation. He again modified his scheme in 1931 and 1936. Koppen's original scheme was modified in 1953 by Geigger-Pohi. C.W. Thornthwaite, an American climatologist, presented his first scheme of classification of climates of North America in 1931. Later he extended his scheme for the world climates in 1933. His 1931 classification was based on precipitation effectiveness and thermal effectiveness. He modified his scheme in 1948 and included four indices of moisture index, thermal efficiency or potential evapotranspiration index, aridity and humidity indices, and index of concentration of thermal efficiency of potential evapotranspiration. G.T. Trewartha, an American climatologist, presented a simple scheme of classification of world climates having a blending of both empirical and genetic approaches to climatic classification. **Airmass approach** was developed by J.J. Hidore in 1969 for the classification of world climates. The Hidore scheme of climatic classification based on the characteristics of airmasses is an example of genetic classification of world climates.

The 20th century climatology was also characterized by growing **concern about climatic changes** and international cooperations to tackle the problems. It may be mentioned that temporally climatic changes may be grouped into two categories, namely (1) climatic changes in the past (palaeoclimate), and (2) climatic changes in future (future climate). Various devices and methods were developed to reconstruct the palaeoclimates based on glaciation; ice sheets, cores and isotopes; ancient sediments, records of sea level changes, fossils of past flora and fauna, continental drift etc. The main concern is about the nature and magnitude of present and future climatic changes due to global warming consequent upon ozone depletion and increased emissions of greenhouse gases caused by human economic activities. It is commonly agreed by the scientific communities that if the current rate of concentration of greenhouse gases mainly carbon dioxide and methane is allowed to continue it will result in the increase of global mean temperature by 2°C above mean global temperature of pre-industrial period by 2030 A.D. This increase in mean global temperature will lead to drastic climatic changes affecting all the biota. The following is the sequence of steps taken to tackle the problems of possible climatic changes at international level.

1957-58 : Continuous measurements and recording of atmospheric carbon dioxide were initiated.

1979 (Feb. 12-33) : First World Climate Conference was held in Geneva and it was concluded that the emission of anthropogenic carbon dioxide leading to increase in the concentration of atmospheric carbon dioxide would have far reaching impact on climate.

1980 : Conference on Industries and Climate was held in Vienna (Austria) to discuss the impact of industrialization on climate change.

1985 : Vienna Convention (Austria) discussed measures for protection and maintenance of ozone layer.

1987 : Montreal Protocol was agreed upon for the reduction of production and consumption of ozone depleting substances (chlorofluorocarbons-CFCs) in order to check ozone depletion. The Montreal Protocol initiated by United Nations Environment Programme (UNEP) and agreed by 35 developed countries included the following provisions: (i) to freeze the production of CFCs at 1986 level by 1989 (but not translated into practice), (ii) to decrease the production of CFCs by 20 per cent by the end of 1993 (but not followed), (iii) to allow further 30% cut in the production by 1998 (seldom implemented).

1988 : Toronto Summit (June 27-30), Conference on Changing Atmosphere: Implication for Global Security; for reduction in the emission of carbon dioxide by 20 per cent by 2005 AD, was held in Toronto city of Canada. The summit also called for establishment of **world atmosphere fund** but the developed industrialized countries backed out from the agreement.

1988 : Constitution of **Intergovernmental Panel on Climate Change** (IPCC) by **UNEP** and **WMO** (World Meteorological Organization) for the study of climate changes and presentation of four-yearly report on effects of greenhouse gases on the earth.

1990 : Fourth Plenary Session of IPCC was held in Sundsvall, Sweden, between August 27-30 to adopt first assessment report. The report cautioned the scientific community about increase in mean global temperature by 1°C above 1990 level by 2005 A.D. and by 3°C by the end of 21st century if the present scenario of emission of greenhouse gases continued.

1990 : Second World Climate Summit (Conference) was held in 1990 in Geneva to search effective measures to check the emission of greenhouse gases. An Intergovernmental Committee was constituted and 137 countries agreed to negotiate a **world climate treaty.**

1991 : First meeting of **Intergovernmental Negotiating Committee (INC-1)** was held in Washington from February 4 to 14, 1991 and approved special efforts to encourage participation of developing countries in the meetings and conferences related to climate changes.

1992 : Fifth **INC (5)** meeting was held between February 18-20 in New York for stabilization of greenhouse gas emission.

1992 : Un **Framwork Convention on Climate Change** (FCCC) was adopted on May 9 in NewYork.

1992 : The United Nations Conference on Environment and Development (**UNCED**) better known as **First Earth Summit** or **Rio Summit** was held in June 1992 in Rio De Janeiro city of Brazil which was attended by 154 countries. The **Climate Change Convention** (Framework Convention and Climate Change) was signed.

1994 : The signed Climate Change Convention during 'first earth summit' was given practical shape which aimed at the reduction in carbon emission and to stabilize the emission at 1990 level by 2000AD but it could not be implemented in letter and spirit by the allotted time frame.

1995 : The first **Conference of Parties** (CoP) better known as **Berlin Summit** was held in June 1995 in Berlin city of Germany but nothing concrete could be achieved except for the launching of **Ad Hoc Groups on Berlin Mandate** (AGBM).

1996 : The second summit of Framework Convention of Climate Change (FCCC) was held in Vienna city of Austria in July 1996 but this summit also proved unsuccessful as no agreement on the amount of carbon emission could be struck.

1997 : United Nations **Second Earth Summit** was organized in New York from June 23 to 27, 1997 to evaluate the implementation of Agenda 21 of the first earth summit held in 1992.

1997 : The third summit of FCCC on climate change was held from December 1 to 10, 1997 in Kyoto city of Japan and **Kyoto Protocol** on climate change was agreed which envisaged 5.2 per cent cut in carbon emission by developed countries. The Kyoto Protocol was opened for signature in New York on March 16, 1998.

2000 : The conference on climate change (FCCC) held in Hague in 2000 drew a blank as no agreement could be reached in curtailing the emission of greenhouse gases.

It is evident from the above mentioned sequence of events that the present scientific community is more concerned about climate changes caused by anthropogenic factors. The climate change will be a major agenda in the present century.

A number of books on different aspects of weather and climate appeared in the 20th century. A few important contributions came from E. Huntington and S.S. Visher (1922, 'climate changes'), N. Shaw (1930, 'mannual of meteorology'), N. Shaw (1940, 'the drama of weather'), C.E.P. Brooks (1949, 'climate through ages', historical climatology), V. Conard and L.W. Pollok (1950, 'methods in climatology'), M.G. Grant (1944, 'cloud and weather atlas'), B. Hauritz and J.M. Austin (1944, 'climatology'), R. Zon (1941, climate and man), T.F. Malone (1951, 'compendium of climatology'), D. Brunt (1952, 'physical and dynamic climatology'), V. Conard (1952, 'fundamentals of physical climatology'), G. Sutton (1953, 'micro-climatology'), H. Shapley (1953, 'climatic change—evidences, causes and effects'), A.A. Miller (1953, 'meteorology'), H. Riehl (1954, 'tropical meteorology'), T.A. Blair (1954, 'weather elements'), S. Petterson (1958, 'introduction to meteorology'), S. Petterson (1956, 'weather analysis and forecasting'), H. Landsberg (1958, 'physical climatology'), C.F. Koppen and G.C. de Long (1958, 'weather and climate'), J. Gentilli (1958, 'geography of climate'), H.R. Byers (1959, 'general meteorology'), Wilet and Sanders (1959, 'descriptive meteorology'), F.K. Hare (1961, 'the restless atmosphere'), G.T. Trewartha (1961, 'an introduction to climate'), B.J. Mason (1962, 'clouds, rain and rainmaking'), G. Sutton (1962, 'the change of atmosphere'), P. Pedlaborde (1963, 'the monsoon'), E. R. Ritter (1963, 'jet streams meteorology'), W. D. Sellers (1965, 'physical climatology'), J.F. Griffiths (1966, 'applied climatology'), R.C. Sutcliffe (1966, 'weather and climate'), A. A. Miller, (1966, 'meteorology'), C.S. Ramage (1971, 'monsoon meteorology'), B.J. Mason (1971, 'the physics of clouds'), H.H. Lamb (1972, 'climate : present, past and future'), D. Riley and L. Spolton (1974, 'world weather and climate'), E. C. Barret (1974, 'climatology from satellites', an example of **satellite climatology**), F.W. Cole (1975, 'introduction to meteorology'), H.J. Critchfield (1975, 'general climatology'), W.G. Woodcock (1976, 'weather and climate'), R.G. Bary and R.J. Chorley (1976, 'atmosphere, weather and climate'), S. Nieuwolt (1977, 'tropical climatology'), H. Riehl (1978, 'introduction to the atmosphere'), J.E. Hobbs (1980, '**applied climatology**'), J.J. Hidore (1985, 'weather and climate'), J.E. Oliver (1981, 'climatology : selected applications', an example of **applied climatology**), J. E. Oliver and R.W. Fairbridge (1987, 'encyclopedia of climatology'), R. Goody (1995, 'principles of atmospheric physics and chemistry'), J.J. Hidore (1996, 'global environmental change'), J.M. Moran and M.D. Morgan (1997, 'meteorology : the atmosphere and the science of weather'), M.D. Morgan and J.M. Moran (1997, 'weather and people'), R.A. Warrick et. al (1993, 'climate and sea level change'), R.P. Wayne (1999, 'chemistry of atmosphere'), G.P.Brasseur et.al (1999, 'atmospheric chemistry and global change'), E. Aguado and J.F. Burt (2001, 'understanding weather and climate)', C.D. Ahrens (2001, 'essentials of mateorology'), F.K. Lutgens and E.J. Tajbuck (2001, 'the atmosphere'), J.E. Oliver and J.J. Hidore (2003, 'climatology-an atmospheric science') etc.

1.6 ELEMENTS OF WEATHER AND CLIMATE

Weather refers to the sum total of the atmospheric conditions in terms of temperature, pressure, wind, moisture, cloudiness, precipitation and visibility of a particular place at any given time. In fact, weather denotes short-term variations of atmospheric conditions and it is highly variable. On the other hand, climate is defined as aggregate weather conditions of any region in long-term perspective. According to Trewartha 'climate represents a composite of day to day weather conditions, and of the atmospheric elements, within a specified area over a long period of time.' According to Critchfield 'climate is more than a statistical average; it is the aggregate of atmospheric conditions involving heat, moisture, and air movement. Extremes must always be considered in any climatic description in addition to means, trends, and probabilities.' According to Koeppen and De Long 'climate is a summary, a composite of weather conditions over a long period of time; truly portrayed, it includes details of variations-extremes, frequencies, sequences-of the weather elements which occur from year to year, particularly in temperature and precipitation. Climate is the aggregate of the weather.' G.F. Taylor has maintained that 'climate is the integration of weather, and weather is the differentiation of climate. The distinction between weather and climate is, therefore, mainly one of time'. R. G. Bary and R.J. Chorley have aptly remarked (2002) that 'climate introduces the longer time scales operating in the atmosphere. It is sometimes loosely regarded as 'average weather', but it is more meaningful to define climate as the long-term state of the atmosphere encompassing the aggregate effects of weather phenomena-the extremes as well as the mean values'. Temperature, air pressure, wind, humidity, precipitation, cloudiness etc. are the elements of weather and climate, the combination of which introduces spatial and temporal variations in weather and climatic conditions both horizontally and vertically.

1.7. CONTROLS OF WEATHER AND CLIMATE

There are frequent changes in weather conditions. These changes from one day to the other or from one place to the other are due to variations in the quantity, intensity and distribution of the elements of weather and climate. Similarly, there is variation in climatic conditions from one area to the other area. The factors controlling the variations of the elements of weather and climate from one place to the other place and from one season to the other season are called controls of weather and climate. These factors include latitudes, altitudes, unequal distribution of land and water, ocean currents, air pressure and wind, mountain barrier, nature of ground surface, different types of atmospheric storms etc. Man has now emerged a potent controlling factor of weather and climate. His economic activities like industrialization, urbanization, land use changes mainly deforestation, building and construction activities are responsible for global warming due to increase in the concentration of atmospheric carbon dioxide due to emission of greenhouse gases at alarming increasing rate and ozone depletion resulting into changes in global radiation balance leading to climate change. The international communities are scared of catastrophic adverse effects of future climatic change on different spheres of man and nature e.g. deglaciation and sea level changes, submergence of island nations and major coastal lowlands, atmospheric dynamics including evaporation and precipitation, global radiation balance, photosynthesis and ecological productivity, plant and animal community, human health and wealth and many more.

1.7 IMPORTANT DEFINITIONS

Aerology : aerology (also aeronomy) is a branch of meteorology which involves the study of chemical and physical composition of the atmosphere.

Dynamic climatology : dynamic climatology is concerned with the study of atmospheric motions and 'exchanges that lead to and result from that motion.'

Ecological climate : ecological (also ecoclimate) represents weather elements of the habitats of organisms including man.

Geoclimate : geoclimate represents weather elements and conditions of very large area such as small country.

Human biometeorology : human biometeorology is the study of the reactions of human bodies to changes in the atmospheric environment.

Physical climatology : physical climatology is the study of the energy exchanges and physical processes of the atmosphere.

Satellite climatology : satellite climatology deals with climatic data obtained through satellites which view the wider areas from above.

Teleconnections : teleconnections are concerned with the understanding of the influences of local climatic conditions by events happening in other areas of the world such as influences of ENSO events on Indian monsoon.

2

ORIGIN, COMPOSITION AND STRUCTURE OF ATMOSPHERE

2.1 MEANING AND SIGNIFICANCE

The atmosphere, a multilayered gaseous envelope surrounding the planet earth, is a significant component of natural/physical environment and the biospheric ecosystem because it provides all the gases necessary for the sustenance of all life-forms in the biosphere. The atmosphere is attached with the earth by its gravitational force. Besides providing all necessary gases for the sustenance of all the biota in the biosphere, it also filters the incoming solar radiation and thus prevents the ultraviolet solar radiation waves reaching the earth's surface and protects the earth from becoming too hot. The height of the atmosphere is estimated to range between 16 to 29 thousand kilometers from the sea level. The atmospheric processes, both physical and chemical, and the elements of weather and climate (temperature, air pressure and wind, humidity, cloudiness and precipitation, storms etc.) have affected and controlled the origin, evolution, and development of plants and animals in the biosphere. There is mutual interaction between the components of the atmosphere and the biotic components of the biosphere (plants and animals). Though there are secular changes in weather and climate at local, regional and global levels due to natural factors but since the emergence of man as the most advanced 'technological man,' the atmospheric processes are under tremendous changes because man has become able and competent to change and modify the basic composition and structure of atmospheric components through his intentional and unintentional, direct and indirect actions. It may be mentioned that the original natural atmosphere was in equilibrium condition regarding its composition in terms of gaseous composition. Any change in the natural gaseous composition of the atmosphere, i.e. proportion of different gases, by anthropogenic factors disturb the atmospheric equilibrium causing various environmental problems, like atmospheric pollution, global warming and climate changes, which may, in turn, disturb the ecological balance and ecosystem stability. It is, therefore, not only desirable but necessary to understand different characteristics and processes of the atmosphere.

2.2 ATMOSPHERE : AS A PART OF BIOSPHERIC ECOSYSTEM

The atmosphere is a significant component of the biospheric ecosystem because it provides all the gases necessary for the sustenance of all life-forms in the biosphere. It also filters the incoming solar radiation and thus prevents the ultraviolet solar radiation waves to reach the earth's surface and hence protects the earth's surface from becoming too hot. Thus it is imperative to study the composition and structure of the atmosphere and the elements of weather and climate.

The atmosphere is a gaseous envelope which surrounds the earth from all sides and is attached to the earth's surface by gravitational force. The height of the atmosphere is estimated between 16 to 29 thousand kilometers from the sea level. It is estimated that 97% of the effective atmosphere is upto the height of 29 km. The atmosphere is composed of (i) gases, (ii) vapour and (iii) particulates. Nitrogen (78%) and oxygen (21%) are the major gases which constitute 99% of the total gaseous composition of the atmosphere. The remaining 1 per cent is represented by carbon dioxide (0.03%), hydrogen, neon, helium, argon, xenon, ozone etc. The vapour content in the atmosphere ranges between zero to 5 per cent by volume. The atmospheric vapour is received through the evaporation of moisture and water from the water bodies, vegetation and soil covers of the lithosphere and seas and oceans. Vapour in the atmosphere decreases from the equator towards the poles and this trend of distributional pattern of atmospheric vapour affects vegetation though temperature is also significant factor which controls vegetation. The moisture content in the atmosphere is responsible for the creation of several forms of condensation and precipitation (clouds, fogs, frost, rainfall, dew, ice, hailstorm, snowfall etc.). Vapour is transparent for incoming short wave solar radiation so that solar rays reach the ground surface without much obstacles but vapour is less transparent for outgoing terrestrial longwave radiation and therefore it helps in heating the earth's surface and the lower portion of the atmosphere. The soild particles present in the atmosphere include dust particles, salt particles etc. These particulates help in the scattering of solar radiation which results in the appearance of blue colour of the sky, charming colour during sun-rise and sun-set. Salt particles become hygroscopic nuclei and thus help in the formation of drops, clouds and various forms of condensation and precipitation.

There are definite layers having varying characteristics of temperatures and combinations of gases in the atmosphere e.g. (from the lower atmosphere to the upper atmosphere (i) troposphere, (ii) stratosphere, (iii) mesosphere, (iv) ionosphere and (v) exosphere. (i) The lowermost layer of the atmosphere is known as **troposphere** and is the most important layer because almost all of the weather events (e.g. fog. clould, dew, frost, hailstorm, storms, cloud-thunder, lightning etc.) occur in this layer. Thus the troposphere is of utmost significance for all life-forms including man because these are concentrated in the lowermost portion of the atmosphere. Temperature decreases with increasing height at the average rate of 6.5°C per 1000 m (one kilometer) which is called as normal lapse rate. The height of troposphere changes from equator towards the poles (decreases) and from one season of a year to the other season (increases during summer while it decreases during winter). The average height of the troposphere is about 16 km over the equator and 6 km over the poles. The upper limit of the troposphere is called as **tropopause**.

(ii) **Stratosphere**-There is contrasting opinion about the height of the stratosphere. The average height over the middle latitudes has been determined to be 25-30 km, whereas it is estimated to be 80 km by others. On an average, the upper limit of the stratosphere is taken to be 50 km. A few scientists (e.g. H.J. Critchfield) are of the view that there is no change in temperature with increasing height in the stratosphere while others (e.g. A.N. Strahler) held that there is gradual rise in temperature and there is 0°C or 32°F temperature at the height of 50 km, the upper limit of the stratosphere which is known as **stratopause.** The lower layer of stratosphere is very important for all life forms in the biosphere because there is concentration of ozone between the height of 15-35 km, (though ozone has been discovered upto the height of 80 km). Ozone acts as a protective cover for the biological communities in the biosphere because it absorbs almost all of the ultra-violet rays of solar radiation and thus protects the earth's surface from becoming too hot. Recently, the researches have shown that there is gradual depletion of ozone gas in the atmosphere mostly due to human activities. The depletion of ozone, its impact on biological communities and measures to replenish ozone will be discussed in detail in the 16th Chapter (section 16.3).

(iii) **Mesosphere** extends between 50 km and 80 km, and temperature again decreases with increasing height. At the upper limit of mesosphere (80 km) temperature becomes - 80°C. This limit is called as **mesopause**. (iv) **Thermosphere**-The part of the atmosphere beyond mesopause is known as thermosphere wherein temperature increases rapidly with increasing height. Thermosphere is further divided into two layers e.g. (A) **ionosphere** extends from 80 km to 640 km. There are a number of ionic layers known as (with increasing height) D-layer, E-layer, F1-layer, F2-layer etc. These layers reflect the signals received from the ground back to the earth's surface and therefore these are very significant for radio-communication (e.g. radio, television etc.). (B) **Exosphere** represents the uppermost layer of the atmosphere. We know very little about the atmosphere extending beyond 640 km height from the earth's surface.

The sun is a great engine that drives winds on the earth's surface, ocean currents, exogenetic or denudational processes and sustains life in the biosphere. Though the earth receives a very small amount of total energy emitted from the sun's surface (1/2 billionth of the sun's total energy output) yet this meagre amount of solar energy is sufficient enough to sustain life in the biosphere. The solar energy or 'the radiant energy received from the sun transmitted in a from analogous to short waves (1/250 to 1/6700 mm in length) and travelling at the rate of 1,86,000 miles a second, is called solar radiation or insolation' (G.T. Trewartha). The energy from the sun is emitted in the form of electromagnetic radiation which consists of four groups of wave lengths e.g. (1) **ultraviolet rays** represent the waves of shortest wavelengths e.g. gamma rays, x-rays, (ii) **visible rays** consist of violet, blue, green, yellow, orange and red rays which carry 41% of the total energy of the solar spectrum. The wavelengths of these rays range between 0.4 and 0.7 micron, (iii) **infrared rays** are of the wavelengths between 0.7 and 300 microns and these carry 50% of the total energy of the solar spectrum, and (iv) **long waves** include micro-waves, radar and radio waves, the wavelengths of which range between 0.03 cm and 100 m.

On an average, there is supposed to exist heat balance at the outer earth's surface and in the atmosphere. The earth receives most of its energy from the sun through shortwave solar radiation. The solar energy radiated towards earth's atmosphere is taken as 100 per cent or 100 units. Out of the incoming shortwave solar radiation (100%) 35% is sent back to the space (27% reflected from the clouds + 2% reflected from the ground + 6% scattered by the atmosphere and sent back to space = 35%), 51% is absorbed by the earth's surface (17% received as diffuse day light + 34% received as direct radiation = 51%) and 14% is absorbed by the atmosphere. The earth after receiving energy from the sun also radiates energy out of its surface into the atmosphere through longwaves. Thus 23% energy (out of 51% which the earth has received from the sun) is lost through direct long wave outgoing terrestrial radiation, 9% is spent in convection and turbulence and 19% is spent through evaporation. Thus, 51% of energy which was received at the earth's surface is sent back either to the atmosphere or in the space through terrestrial radiation, conduction and convection. The atmosphere receives 14% of incoming solar radiation and 34% from the earth's surface through various processes. Thus the total energy received by the atmosphere from the sun and the earth becomes 48% which is sent back to the space. The heat budgets of the earth and the atmosphere are not so simple as described above, rather these are very much complicated.

Solar energy is very important for autotrophic plants or primary producers in the biosphere because green plants prepare their food through the process of photosynthesis with the help of solar light. The biosphere also receives, though very insignificant amount (only 0.02% of total energy budget of the biosphere), energy from within the earth. This energy is known as **geothermal energy**.

The earth receives heat energy directly from the sun but the atmosphere receives most of its heat energy from the earth's radiation. The heating and cooling of the atmosphere take place through conduction, convection and radiation mechanisms. It is significant to point out that the atmosphere is more or less transparent to incoming shortwave solar radiation and thus behaves like window glass panes which allow the sunlight to come inside the room but stops the light to escape from the room. Similarly, the atmosphere allows the sunlight to reach the earth's surface but prevents the outflow of longwave outgoing terrestrial radiation from the lower atmosphere. This effect of the atmosphere is called as **green house effect** which helps in maintaining the temperature of the earth's surface.

The spatial distribution of temperature is very significant because different types of climates, vegetation zones, animals and human life etc., basically depend on the distribution of temperature, whether horizontal or vertical. The spatial distribution of temperature is controlled by a variety of factors e.g. latitudes or distance from the equator, height from seal level, distance from the sea coast, nature of land and water, properties of ground surface, nature of slope, prevailing wind, ocean currents etc. **Vertical distribution** of temperature denotes that temperature decreases with increasing height at the average rate of 6.5°C per 1000 metres (one kilometre). This is known as **normal lapse rate**. This rate is effective only in the troposphere, the lowermost layer of the atmosphere. This trend of vertical distribution of temperature largely controls the nature of flora and fauna along the mountains. Some times temperature increases with increasing height instead of normal trend of decrease of temperature with increasing height. This situation is called as **inversion of temperature**. Inversion of temperature has great climatic significance because it causes (i) fogs (which are beneficial to few crops like coffee and tea plantation but are dangerous to various types of transports), (ii) frost (which destroys those plants which have fibrous roots), and (iii) stability in the atmosphere which prevents the upward and downward circulation of air and thus lessens the possibility of rainfall.

The horizontal distribution of temperature denotes that temperature decreases from the equator towards the poles. The globe is divided into three thermal zones on the basis of variations of temperatures from the equator towards the poles e.g. (i) **tropical or torrid zone** extends between the tropics of Cancer (23.5° N) and Capricorn (23° 30' S). Sun's rays are more or less vertical over the equator throughout the year. Temperature is high throughout the year and there is no winter season around the equator but summer and winter seasons are well marked near the tropics of Cancer and Capricorn. (ii) **Temperate zone** extends between 23.5° and 66.5° in both the hemispheres. There is longer length of day and night but it no longer exceeds 24 hours. Summer and winter seasons are well marked and there is much contrast of temperatures between summer and winter seasons. (iii) **Frigid zone** extends between 66.5° and the poles in both the hemispheres. Temperature is constantly low throughout the year because of slanting sun's rays which become more or less horizontal near the poles. The length of day and night increases enormously towards the poles where the length of day and night becomes of 6 months duration.

The horizontal and vertical distribution of **air pressure** is of paramount significance for biological communities in the biosphere. The air pressure is a force per unit area which represents the total weight of atmosphere per unit area at sea level. It is presented in inches, centimetres or millibars (which represent the height of mercury in the tube of a barometer). There is inverse relationship between temperature and pressure e.g. if temperature increases, pressure decreases and if temperature decreases, pressure increases. The difference of pressure between two places is known as **pressure gradient** which causes air circulation. On an average there are certain pressure belts on the globe though their continuity is broken because of heterogeneous character of distribution of land (29% of the total surface area of the globe) and sea (71%). These pressure belts are of thermal and dynamic origin. (i) **Equatorial low pressure belt** extends between 5° to 10° N and S latitudes. This belt is induced due to high temperature throughout the year. (ii) **Subtropical**

high pressure belt is developed between 30^0-35^0 latitudes in both the hemispheres. Inspite of high temperature in this zone there is high pressure because of the fact that this belt is dynamically induced as the wind descends in this zone from above. This zone is also the zone of anticyclones. (iii) **Mid-latitude sub-polar low pressure belt** extending between 60^0-65^0 latitudes in both the hemispheres is also dynamically induced. This belt of low pressure, inspite of low temperature in this zone, is caused due to the rotation of the earth on its axis. (iv) **Polar high pressure belt** is found around the poles and this belt is thermally induced because there is constantly low temperature (below freezing point) in the polar areas

Planetary winds are more or less uniform throughout the year. There are three well defined belts of permanent winds e.g. (i) **Trade wind belt** extends between 30^0 N and 30^0 S latitudes wherein north-east trade winds blow from north-east to south-west and south-east trade winds blow from south-east to north-west direction. Besides trade winds, there are equatorial westerlies between 5^0 N and 5^0 S latitudes which are associated with atmospheric storms and disturbances. This belt is also called as the belt of **doldrum**. The meeting zone of the trade winds and equatorial westerlies is called as **intertropical convergence** (ITC). There is seasonal shift in the ITC which causes **monsoon** climate according to Flohn. (ii) **Belt of westerlies** extends between 30^0 and 60^0S latitudes in both the hemispheres. The south-west westerlies (in the northern hemisphere) are also associated with temperate cyclones which largely affect the climate of the coastal areas of north-west Europe and north-west America. The westerlies gain highest velocity in the southern hemisphere because of the dominance of oceans. The velocity of westerlies increases as one goes further southward. Due to increasing velocity the westerlies are called as **roaring forties** at 40^0 S latitude, **furious fifties** at 50^0 latitude and **shreiking sixties** at 60^0 S latitude. (iii) **Polar wind belt** extends between 60^0 and poles in both the hemispheres. There is seasonal shifting of pressure and wind belts with the northward and southward migration of the sun. This seasonal shifting of wind and pressure belts is responsible for the development of a few typical climatic types e.g. Monsoon climate, Mediterranean climate, etc. Besides permanent or planetary winds, there are some seasonal (e.g. monsoon), local (e.g. Chinook and Foehn warm wind, Sirocco-warm and dry wind, Harmattan-warm and dry wind, Mistral-cold polar wind, Bora-very cold and dry wind, Blizzard-cold polar wind, Loo-hot and dry wind in north India), land and sea breezes, mountain and valley breezes which provide different but special types of habitats which create typical ecosystems.

Different types of humidity are very important for various life-forms of plants and animals. The combination of temperature and relative humidity (which is a ratio between the moisture retaining capacity of a given air with definite volume and temperature and absolute moisture of that air, this is represented through fraction, ratio or percentage, e.g. $^1/_2$ 1 : 2 or 50%) affects plants, animals and human beings. Equatorial region is characterized by high temperature and high relative humidity and therefore it is not ideal for human health, both mental and physical. The combination of high temperature with low relative humidity of the hot deserts is also not favourable for human population. The combination of moderate temperature and moderate relative humidity of temperate areas is most ideal for human population

Various forms of condensation and precipitation are very crucial factors for the sustenance of biological communities in the biosphere. Fogs are formed when the condensation takes place around dust particles, smokes etc. and the droplets are suspended in the air. Fogs decrease the visibility which causes great problems to transport systems on the ground, in the water and in the air. On the basis of visibility fogs are divided into four types e.g. (i) light fogs (visibility upto 1100 m), (ii) moderate fogs (visibility between 1100 m-550 m), (iii) dense fogs (visibility 550 m-330m), and (iv) very dense fogs (visibility less than 330 m). Fogs are also classified into (i) Intra-airmassfogs and (ii) Frontal fogs. When fogs are associated with sulphur emitted from the factories, they become poisonous and deadly to organisms in general and human beings in particular. Such deadly poisonous fog was formed on October 26, 1948 in the Donora

Valley of Pennsylvania, U.S.A. which claimed 20 human lives and 43 per cent inhabitants of the valley became seriously sick of respiratory diseases and cough. Similar poisonous fogs were formed in 1930 in Meuse valley (Belgium) claiming 63 human lives and in 1952 in Londnon city where 4000 people lost their lives.

Clouds are aggregates of water and ice drops but are found at higher heights than fogs. Clouds have great impact on the weather and climate of any region because the nature of precipitation depends on clouds. Clouds are classified in 3 major types and 10 sub-types e.g. (i) **high clouds** are found between the height of 6000 m- 12000 m from the sea level. They are further sub-divided into 3 sub-types viz. (i) Cirrus Clouds are found at the highest elevation in the atmosphere. These are associated with clear weather. (ii) Cirro-stratus clouds are generally of white colour and are spread in the sky as a thin milky sheet. (iii) Cirro-cumulus clouds. (2) **clouds of medium height** (between 2500 m - 6000 m). These are sub-divided into two sub-types viz. (i) altostratus clouds. (ii) alto- cumulus clouds. (3) **low clouds** (upto 2500 m). These are sub-divided into 5 sub-types e.g. (i) strato-cumulus clouds, (ii) stratus clouds, (iii) nimbo-stratus clouds, (iv) cumulus clouds and (v) cumulo-nimbus clouds. Nimbo-stratus and cumulo-nimbus clouds are most significant from the stand point of precipitation

Rainfall is very important for all life forms in the biosphere. For condensation it is necessary that the saturation level of the air is achieved and this can be possible when the relative humidity of a given air at definite temperature with certain volume becomes 100 per cent. In other words, the moisture retaining capacity of that air becomes equal to the absolute humidity of that air. It is also known that moisture retaining capacity increases with increase in temperature and decreases with decrease in temperature. It is thus imperative for any air to ascend to yield precipitation, because when the air rises upward, temperature decreases, moisture retaining capacity also decreases, with the result relative humidity increases. The air continues to ascend till the condensation level is reached i.e. relative humidity becomes 100% and such air is known as saturated air. When the condensation level is reached below freezing point, precipitation occurs in solid form like snow fall, hailstorm etc., but when condensation occurs above freezing point, precipitation takes place in liquid form like dew, fog, rainfall etc.

Rainfall is of 3 types which are based on the mode of lifting of air upward e.g. (1) **Convectional rainfall** is caused when the air ascends due to heating of ground surface. Equatorial region receives most of its rainfall through convectional rainfall. (2) **Orographic rainfall** occurs along the hill ranges because the air is forced to ascend due to obstruction caused by the hill ranges. This situation occurs only when the hill ranges are transverse to the direction of the air. The onward side (the side of the hill which faces the air) receives more rainfall than the leeward side (opposite side of the hill through which the air descends). The leeward side of the hill is known as **rainshadow region**. Most of the world rains is received through orographic rainfall. The characteristics of ecosystems on onward or windward and leeward sides of the hill ranges are quite different because of pronounced differences in the amount of rainfall in two areas. (3) **Cyclonic rainfall** occurs when one air mass forces the other air mass to ascend and cool aloft. Temperate cyclone yields sufficient precipitation in the temperate areas.

The spatial and temporal distribution of rainfall over the globe is very significant because it determines the nature and type of vegetation which in turn determines the nature of organisms. Patterson has divided the globe into 15 precipitation zones on the basis of seasonality of precipitation e.g. (1) the zone having rainfall throughout the year, the zone of maximum rainfall, between 7^0 N and 7^0 S latitudes, (2,3) the zone having summer rainfall but dry winter - 7^0 to 16^0 in both the hemispheres, (4, 5) the zone of light summer rainfall - 16^0 - 20^0 in both the hemispheres, (6,7) the zone of all dry seasons, the zone of minimum rainfall 20^0-30^0 in both the hemispheres, (8, 9) the zone of light winter rainfall - 30^0 - 35^0 in both the hemispheres, (10, 11) the zone of dry summer and sufficient rain fall during winter-35^0-45^0 in both the hemispheres, (12, 13) the zone of precipitation in all seasons but maximum during summer, 40^0 - 70^0

in both the hemispheres, and (14, 15) the zone of scant precipitation in all seasons but maximum precipitation in the form of snowfall, 70^0 - 90^0 in both the hemispheres.

Thunderstorms, cyclones and anticyclones are other important weather phenomena which affect biological lives to greater extent in the biosphere. **Thunderstorms** are associated with strong convectional activity and are characterised by high velocity winds, thunder of cloud, lightning and heavy downpour often called as cloudhburst rainfall. The equatorial zone is most affected by thunderstorms where 75 to 150 days of a year are dominated by thunderstorms. The days of thunderstorms decrease from equator to the poles. The temperate cyclones in the middle latitudes (45^0 - 60^0) are also associated with thunderstorms. The copious rainfall with high intensity causes floods in the rivers and severe soil erosion. The strong squalls associated with thunderstorms inflict great damage to standing vegetation, human constructions and human lives. **Tornadoes** are special types of atmospheric disturbances and are very much active in the southern U.S.A. They cause great damage to human lives and property through their chirning wind of the greatest velocity of all the storms and copious rainfall.

The hurricanes and **typhoons** are most powerful destructive tropical cyclonic storms. The hurricanes affect the southern and south-eastern U.S.A. whereas the typhoons affect the coastal areas of the south and south-eastern and eastern Asia. The tropical cyclones inflict tremendous damages on inhabited islands and coastal areas. The eastern coasts of China and India are very often damaged by typhoons and cyclones. The mid-latitudes (45^0 - 60^0) are greatly affected by temperate cyclones which are originated because of the convergence of two contrasted air masses viz. cold north-eastern polar air masses and relatively warm south-westerly air masses. Different sections of temperate cyclones (warm front, warm sector, cold front and cold sector) are associated with varying weather conditions. For example, with the arrival of warm front temperature rises, wind pressure continues to fall, the sky becomes overcast with cumulo-nimbus clouds and precipitation starts. After the warm front passes away the warm sector comes in and there is sudden change in weather conditions as sky becomes clear because clouds disappear, wind direction becomes southerly, air temperature rises rapidly, air pressure decreases, precipitation stops but there may be light drizzle, on an average the weather becomes clear and pleasant. With the arrival of cold front there is again change in weather as the sky becomes overcast with cumulo-nimbus clouds, heavy precipitation occurs, the rainfall is though of short period but is in the form of heavy downpour, characterized by thunderstorm, there is cloud thunder and lightning. With the arrival of cold sector there is again sudden change in weather conditions as sky becomes clear of clouds, there is sudden fall in temperature and rise in pressure.

2.3 ORIGIN AND EVOLUTION OF ATMOSPHERE

The origin and evolution of the earth's atmosphere is associated with the origin of the earth but at much later date. It is believed that our planet earth was originated some 4.5 and 5 billion years ago by the accretion of small particles, named as planetisimals by T.C. Chamberlin. The earth's atmosphere originated and developed through several processes of **gassing** (addition of gases) and **degassing** (removal of gases). It has also been proved that the early atmosphere was **anoxygenic** (without oxygen). The non-existent gases in the first evolution stage of the atmosphere include argon, carbon dioxide, oxygen, helium, nitrogen etc. These gases were added to the atmosphere from time to time through several complex physical and chemical processes.

(1) According to **planetesimal hypothesis** of the origin of the earth as postulated by T.C. Chamberlin and H.R. Moulton in 1905, in the initial stage of the origin of the earth there was no atmosphere on it but as the earth grew in size it captured 'atmospheric materials and elements' by gravitational force which was continuously increasing due to everincreasing size of the earth. The earth's atmosphere was formed from two basic sources - external and internal sources. The **external source**-when the earth grew in size, it became successful in capturing free atmospheric molecules. The supply of atmospheric molecules

was more in the beginning but it decreased with the passage of time as most of the molecules were already captured by the earth. The **internal sources** provided carbon dioxide, water vapour and nitrogen gases. Another source of 'atmospheric materials' was **occuled gases** carried by the planetesimals captured by the nucleus of the earth. These occuled gas particles came out of the interior of the earth through volcanic and fissure eruptions and became part and parcel of the present day atmosphere. Oxygen was, thus, provided by volcanic eruption but their explanation of the origin of atmospheric oxygen is not acceptable to many scientists.

(2) According to the theory of **hot origin of the earth** in the beginning, the earth was a hot gaseous mass and the gases associated with the hot earth were also hot and hence they easily escaped from the earth and were lost in the atmosphere. Thereafter cooling and solidification of hot magma and the formation of the first primitive solid crust released a number of gases, namely water vapour, carbon dioxide, hydrogen, carbon monoxide etc. through the process of **degassing**. Thus, the first, though incomplete, atmosphere was formed by such released gases from the earth. The water vapour released from the earth's cooling provided the base for the formation of clouds. Thus, clouds so formed, started to yield precipitation but the rain drops could not reach the earth's surface because they were evaporated due to very hot conditions around the earth. Thus, precipitation, evaporation and again precipitation gave birth to 'evaporation - precipitation cycle' which resulted into further cooling of the earth and formation of water bodies on newly formed earth's crust. It may be mentioned that these initial water bodies provided suitable habitats for the origin and evolution of chemosynthetic and photosynthetic water living bacteria which later on became helpful in producing earth's atmospheric oxygen.

(3) It is believed without doubt that there was no free oxygen in the original earth's atmosphere. The molecular oxygen was probably formed only after the development of photosynthesising organisms due to splitting of water molecules by plant cells. The origin of atmospheric oxygen is supposed to have taken place through two processes e.g. **photochemical dissociation** and **photosynthesis**. Photochemical dissociation involves dissociation of water molecules into hydrogen and oxygen by solar ultraviolet radiation in high atmosphere. It is believed that the hydrogen, so dissociated, being lighter escaped the earth's gravity while oxygen being relatively heavier remained in the primitive atmosphere. The scientists believe that since this process occurs in high atmosphere and hence it might not have contributed much molecular oxygen (O_2) to the present atmosphere. Molecular oxygen was probably formed through the process of **photosynthesis** which involves the production of carbohydrates and oxygen by combining carbon dioxide, water and sunlight. It may be mentioned that water is split by plant cells and is reconstituted in about 2 million years and thus oxygen so produced circulates in the atmosphere through various components and is again recycled after about 2000 years. The oxygen continued to concentrate in the atmosphere from the time of its formation and presently it constitutes about 21 per cent (20. 9%) of total gaseous composition of the atmosphere. It may be argued that if the atmospheric oxygen was formed through the process of photosynthesis by green plants and these plants need oxygen, the question arises as to how plants survived before the formation of oxygen. Biological evidences revealed that before the evolution of photosynthetic green plants there existed chemosynthetic bacteria which prepared their food through chemical process (chemosynthesis). Presently, oxygen is produced through the process of photosynthesis by the autotrophic green plants of terrestrial ecosystems and phytoplanktons of marine ecosystems and to a lesser extent by the reduction of various mineral oxides.

2.4 COMPOSITION OF ATMOSPHERE

The earth's atmosphere is a multilayered gaseous envelope which surrounds the earth from all sides and is attached to the earth's surface by its (earth's) gravitational force. The air is a mechanical mixture of several gases. Basically, the atmosphere is composed of three major constituents, namely (1) gases, (2) water vapour, and (3) aerosols.

(1) Gases

The gaseous composition of the atmosphere consists of two categories of gases e.g. (i) **constant** or **permanent gases**, and (ii) **variable gases.** It may be mentioned that the study of atmospheric gases started in the 18th century when carbon dioxide was discovered and studied in 1752 followed by the discovery of gaseous nitrogen (N_2) by Rutherford in 1772 and was named as mephitic air. The oxygen was discovered and studied first by **Joseph Priestly** and the last gas to be discovered in 1874 was argon. The nitrogen and molecular oxygen constitute 78.1 and 20.9 per cent of gaseous composition of the present day atmosphere respectively, while argon represents 0.9 per cent. Thus, it is obvious that gaseous nitrogen, molecular oxygen and argon constitute about 99.9 per cent of the gaseous composition of the atmosphere. Table 2.1 represents the concentration of different gases in the atmosphere in parts per million (ppm), parts per billion (ppb) and percent by volume. The following gas laws have been formulated from time to time :

Table 2.1 : Gaseous Composition of dry Atmosphere below 80 km

Gas	Parts per Million (ppm)	Parts per Billion (ppb)	Percentage of volume
Nitrogen (N_2)	780,840.0	780.84	78.1
Oxygen (O_2)	209,460.0	209.46	20.9
Argon (A_r)	9,340.0	9.34	0.93
Carbon dioxide (CO_2)	350.0	0.35	0.03
Neon (Ne)	18.0	0.018	0.0018
Helium (He)	5.2	—	—
Methane (Me)	1.4	—	—
Krypton (Kr)	1.0	—	—
Nitrous oxide	0.5	—	—
Hydrogen (H_2)	0.5	—	—
Xenon (X_2)	0.09	—	—
Ozone (O_3)	0.07	—	—

Source : US Department of Commerce, NOAA, 1976 quoted in Climatology by Oliver and Hidore, 2003.

(a) **Boyle's gas law** (pertaining to relationships among air pressure, volume of gas and density of gas), (b) **Lussac's law** showing relationship among pressure, volume of gas and temperature, (c) **Charle's law** (showing relationship between pressure and temperature with constant gas volume), (d) **combined gas law** (to derive any one variable with two known variables) etc.

(i) The major **constant gases** are nitrogen, oxygen and argon which constitute 78, 20.9 and 0.9 per cent by volume of the gaseous composition of the atmosphere. It may be mentioned that proportion of constant or permanent gases remains constant in the lower atmosphere (upto 80 km from sea level). **Nitrogen** accounts for the largest percentage of atmospheric gases but it is not as much active as other constant gases. Nitrogen is very important for all life-forms in the biosphere because it is an essential part of amino acids which make up proteins. Nitrogen generally exists in seven forms in the atmosphere e.g. molecular nitrogen (N_2), Oxides of nitrogen (e.g. N_2O = nitrous oxides, NO = nitric oxide, and NO_2= nitrogen peroxide) and hydrogen - nitrogen compounds (e.g. NH = amino, NH_3= ammonia, and HNO_2= nitrous acids). Though nitrogen constitutes the largest proportion of atmospheric gases by volume, but living organisms cannot use nitrogen directly rather they obtain nitrogen in the form of ammonium salts and nitrate through their roots from the soils while animals get nitrogen from the plants and their products by eating them. The **nitrogen cycle** involves (i) transfer of atmospheric nitrogen into soils (known as nitrogen fixation), (ii) mineralization, nitrification and transfer of nitrogen from soils to plants and animals, and (iii) denitrification and return of nitrogen to the atmosphere.

Oxygen is chemically very active because it combines with majority of elements in the biosphere. It generally forms about 70 per cent atoms in living matter and plays a very important role in the formation of carbohydrates, fats and proteins. The molecular oxygen (O_2) mostly occurs upto the height of 60 km in the lower atmosphere while dissociated oxygen (0) is present above the molecular oxygen layer. Oxygen is produced through the process of photosynthesis by autotrophic green plants of terrestrial ecosystems and by phytoplanktons of marine ecosystems and to a lesser extent by the reduction of various mineral oxides. The oxygen is consumed in respiration by animals including man and in industrial combustion (burning of fossil fuels) and burning of wood. The proportion of molecular oxygen in the atmosphere is likely to decrease due to anthropogenic factors and gradual increase in the consumption of oxygen effected by increased burning of fossil fuels and wood and deforestation resulting into increase in the atmospheric carbon dioxide due to less consumption of CO_2 and decrease in the production of O_2 may cause imbalance in the gaseous composition of the atmosphere.

(ii) **Variable** or **minor gases** include water vapour, carbon dioxide, ozone, hydrogen, helium, neon, xenon, krypton, methane etc. Water vapour is very important because it is responsible for all sorts of precipitation whether in liquid or solid form. Ozone (O_3) is life saving gas because it filters the incoming shortwave solar radiation and absorbs ultraviolet rays and thus protects the earth from becoming too hot. **Ozone** defined as 'a three-atom isotope of oxygen (O_3)' or 'merely a triatomic form of oxygen (O_3), is a faintly blue irritating gas with a characteristic pungent odour'. Ozone is 'a strong oxidizing agent which can at high concentration decompose with an explosion'. It may be pointed out that ozone is present almost at all altitudes in the atmosphere but the bulk of its concentration is present in a layer from 10 km to 50 km up in the atmosphere and within this zone the highest concentration of ozone is between the altitudes of 12 km and 35 km in the stratosphere. Ozone gas is unstable because it is created as well as destroyed or disintegrated. The oxygen molecules are broken up or separated in the atmospheric layer between the altitudes of 80 to 100 km by ultraviolet solar radiation or by an electric discharge in oxygen or air during a thunderstorm in the troposphere in the following manner :

$$O_2 \rightarrow O + O$$

(Oxygen breaks up in two separate oxygen molecules)

These separated oxygen atoms (O) are then combined with oxygen molecules (O_2) and thus ozone (O_3) is formed.

$$O_2 + O + M \rightarrow O_3 + M$$

or

$$O_2 + O \rightarrow O_3 \text{ (Ozone)}$$

where M denotes energy and momentum balance produced by the collision of oxygen molecules (O_2) with another individual atom or molecule. It is important to note that most of the atmospheric ozone is formed in the atmosphere over tropical areas from where some ozone is transported by atmospheric circulation to the polar areas up in the atmosphere. Ozone (O_3) is also transformed back into oxygen by further collision of ozone with monoatomic oxygen (individual molecule of oxygen, O) in the following manner :

$$\text{Ozone } (O_3) + O \rightarrow \text{Oxygen } (O_2) + \text{Oxygen } (O)$$

The presence of ozone layer in the atmosphere is very crucial and significant for plants and animals in general and human being in particular because it provides a protective cover, known as earth's umbrella, to all organisms (including plants, animals, micro-organisms and man) in the biospheric ecosystem against their exposure to ultraviolet solar radiation. In fact, the ozone layer filters the solar radiation by absorbing ultraviolet rays and allowing only those radiation waves to reach the earth's surface which are essential for the maintenance of life on the planet earth.Any change in the equilibrium level of ozone in the atmosphere will adversely affect the life in the biosphere. There has been much hue and cry about the depletion of ozone since 1987. The ozone depletion refers to breaking of O_3 into $O_2 + O$. The main culprits of ozone depletion are halogenated gases (e.g. chlorofluorocarbons), halons and nitrogen oxides.

Carbon dioxide (an example of variable gas) represents 0.03 per cent of the total atmospheric gases. The gaseous carbon (CO_2) plays two significant roles e.g. (i) carbon dioxide helps in the process of **photosynthesis** wherin carbon, hydrogen, and oxygen are combined by the autotrophic green plants of terrestrial and marine ecosystems with the help of sunlight and thus the organic compounds are formed; (ii) carbon dioxide is transparent to incoming shortwave solar radiation but is opaque for outgoing longwave terrestrial radiation. Thus, carbon dioxide increases **greenhouse effect** and keeps the earth surface warm by re-radiating the terrestrial radiation back to the earth's surface. It is evident that carbon dioxide is most significant **greenhouse gas.** It may be mentioned that the concentration of atmospheric carbon dioxide is gradually increasing due to anthropogenic activities, namely burning of fossil fuels and wood and deforestation leading to probable climate change through global warming. It is estimated that at the beginning of industrial revolution (1860 A.D.) the concentration of atmospheric carbon dioxide was 290 ppm but it is supposed to have crossed the 350 ppm level.

(2) Aerosols

Suspended particulate matter (SPM) in the atmosphere including solid particles of varying sizes and liquid droplets are collectively called aerosols which include dust particles from volcanic eruptions, exposed (ploughed) soil cover, deserts, rocks, etc.. salt particles from seas and oceans; meteoric particles, organic matter (bacteria, seeds, spores, pollen etc.); smoke and soot. The aerosols are also variable elements of the atmosphere. The concentration of particulate matter decreases with increasing altitude of the atmosphere. The overall amount of particulate matter in the atmosphere varies from as little as 100 parts per cubic centimeter to several million parts per cubic centimeter' (Oliver and Hidore, 2003). Aerosols are concentrated mostly in the lower atmosphere while upper atmosphere receives particulate matter from disintegration of meteors resulting into meteoric dust, violent volcanic eruptions, nuclear explosions, strong duststorms travelling over warm deserts and ploughed fields.

Most of the solid particles are kept in suspension in the atmosphere. These particulates help in selective scattering of shortwave electromagnetic solar radiation which adds varied charming colour of red and orange at sunrise and sunset. Similarly, selective scattering of the electromangnetic shortwave solar radiation causes blue appearance of the sky. Some of the aerosols, mainly water droplets, absorb certain amount of solar radiation while some amount of radiant solar energy is reflected back to the space. Solid particulate matter mainly salt particles become hygroscopic nuclei and thus help in the formation of water drops, fogs, clouds and varied forms of condensation and precipitation. The smoke over the cities, when combined with sulphur dioxide, makes poisonous **urban smogs.** It is evident that the presence of particulate matter in the atmosphere causes variations in weather conditions.

(3) Water Vapour

Water vapour, though considered in the category of atmospheric gases, needs separate consideration because it is a very important constituent of the atmosphere and is responsible for different types of condensation and precipitation. In fact, water vapour is a gaseous form of water. The process of evaporation is responsible for the transformation of water into vapour. There is much spatial and temporal variation in vapour content in the atmosphere. The content of water vapour ranges horizontally from 0.02 per cent by volume in the cold dry air over polar areas to 5 per cent by volume over moist tropical areas. The content of vapour in the surface air in the moist tropical areas, at 50° and 70° latitudes is 2.6%, 0.9% and 0.2% (by volume) respectively. The content of water vapour also decreases with increasing altitude in the atmosphere. Water vapour is also considered as a primary greenhouse gas because it absorbs some portion (though very little) of incoming shortwave solar radiation and major portion of outgoing longwave terrestrial radiation and thus helps in keeping the earth's surface warm.

More than 90 per cent of the total atmospheric vapour is found upto the height of 5 km. If there is condensation of all the atmospheric vapour at a time, there would result a one-inch thick layer of water around the earth. Even this meagre amount of water vapour in the atmosphere is responsible for various types of weather phenomena. The moisture content in the atmosphere creates several forms of condensation and precipitation e.g. clouds, fogs, dew, rainfall, frost, hailstorm, ice, snowfall etc. Vapour is almost transparent for incoming shortwave solar radiation so that the electromagnetic radiation waves reach the earth's surface without much obstacles but vapour is less transparent for outgoing shortwave terrestrial radiation and therefore it helps in heating the earth's surface and lower portion of the atmosphere because it absorbs terrestrial radiation.

2.5 STRUCTURE OF ATMOSPHERE

The modern knowledge about the atmosphere is based on the information and data received through radar-wind-sounding (**rawisonde**) baloons, rockets, radars, satellite sounding systems, radio-waves etc. The effective height of the atmosphere is estimated between 16 and 29 thousand kilometers from sea level but the height of the atmosphere upto 800 km is most significant. About 50 per cent of the atmosphere in terms of concentration of major gases, mass, pressure and weather phenomena lies below the altitude of 5.6 km and 97 per cent of the total atmosphere is confined to the height of only 29 km. The earth's atmosphere consists of a few zones or layers like spherical shells. The layered structure of the atmosphere has been classified on two major considerations e.g. (i) thermal characteristics, and (ii) chemical composition.

(A) Thermal Characteristics

On the basis of the characteristics of temperature and air pressure the layering system of the atmosphere has been classified differently by the scientists. For example, S. Petterson divided the atmosphere into five vertical zones surrounding the earth e.g. (i) troposphere, (2) stratosphere, (3) ozonosphere, (4) ionosphere, and (5) exosphere. It may be mentioned that majority of scientists have included ozonosphere into stratosphere and ionosphere into exosphere. It may be remembered that much talked of ozone is very frequently termed as stratospheric ozone. On the basis of thermal consideration R.G. Barry and R.J. Chorley have identified three relatively warm layers, namely (i) near the earth's surface, (ii) between the altitude of 50-60 km, and (ii) the altitude of about 120 km, and two relatively cold layers *e.g.* (i) between the altitude of 10 and 30 km, and (ii) between the height of 80 km-100 km (Barry and Chorley, 1998). Generally, the atmosphere is supposed to have been formed of four vertical layers viz (i) troposphere, (2) stratosphere, (3) mesosphere, and (4) thermosphere. (fig. 2.1).

Troposphere

The lowermost layer of the atmosphere is known as troposphere which was named by Teisserence de Bort wherein the 'tropos' is a Greek word meaning there by 'mixing' or 'turbulence'. This is why sometime this zone is also called as '**turbulent zone**' because of the dominance of turbulent activities. This layer is also known as **convective layer** because of turbulence and eddies. Climatically, troposphere is most important because all the weather phenomena (e.g. evaporation, condensation and precipitation in different forms like fog, cloud, dew, frost, rainfall, snowfall, cloud thunder, lightning, atmospheric storms, etc.) occur in this layer; this layer contains about 75 per cent of gaseous mass of the atmosphere, most of water vapour, aerosols and pollutants. The troposphere is also important from the standpoint of biota because all the life-forms including man in the biospheric ecosystem owe their existence to the weather phenomena of troposphere.

Generally, the troposphere is divided into two or three zones. In a two-zone system, the lower troposphere is called **friction layer** which ranges in height from 1 km to 3 km from the surface of the earth. This lowermost layer is called friction layer because the surface topography causes maximum friction to the wind velocity and direction. This layer is also characterized by inversion of temperature (warm air lying over relatively cool air). This layer is affected by frequent daily changes in surface condition. The upper layer of the troposphere is not much affected by friction between the air and topographic surface and frequent daily changes but is more affected by secondary atmospheric circulation i.e. cyclonic storms.

The most characteristic feature of the troposphere is regular decrease in air temperature with increasing altitude with an average rate of 6.5°C per kilometer. This rate of decrease of temperature, called as **normal lapse rate**, is effected by decrease of density of atmospheric gases, air pressure and particulate matter. It may be mentioned that the lower atmosphere is heated not by absorption of incoming shortwave solar radiation but by transfer of heat from the earth's surface. The lower troposhere is also characterised by **inversion of temperature** wherein temperature increases with increasing height, in other words warm air overlies relatively cool air due to local conditions. There is **seasonal variation** in the height of troposphere. In other words, the height of troposphere changes (decreases) from equator towards the poles and from one season of a year to other season (height increases during summer and decreases during winter). The average height of the troposphere is about 16 km over the equator and 6 km over the poles.

The boundary of the upper limit of the troposphere is called **tropopause** (first used by Napier Shaw) which is zonal rather than linear in character. In other words, the tropopause is a boundary zone consisting of a series of layers. The tropopause having an average thickness of 1.5 km has a few significant characteristic features e.g. (i) the decrease of temperature stops at this point and hence it represents a **cold point**; (ii) the turbulent mixing stops at tropopause; (iii) it represents the upper limit of concentration of most of atmospheric water vapour etc. There is also spatial and temporal variation in the height of tropopause.

The height of tropopause is 17 km over the equator and 9 to 10 km over the poles. There is also seasonal variation in the height of tropopause. Its height is 17 km during January and July over the equator and the temperature at this height is –70°C. The height of tropopause during July and January over 45°N latitude is 15 km (temperature –60°C) and 12.5 km (temperature - 58°C) respectively. The height decreases further poleward as it is 10 km during July (temperature-45°C) and 9 km during January (temperature-58°C) over the north pole. It is apparent that temperature at the top of tropopause is lowest over the equator (-70°C) and is relatively high over the poles. Since temperature decreases upward at the rate of 6.5°C per 1000 m and hence it is natural that temperature at the height of 17 km over the equator becomes much lower than at the height of 9-10 km over the poles. The word troposphere literally means '**zone or region of mixing**' whereas the word tropopause means '**where the mixing stops**'. The air pressure at tropopause is only 100 millibars and about 250 millibars over the equator and the poles respectively. It may be mentioned that the uniformity and continuity of tropopause is disturbed (rather broken) in the zones of jet streams and tropical cycles.

Stratosphere

The layer just above the tropause is called stratosphere which was first discovered and studied by Teisserence de Bort in the year 1902. There is contrasting opinion about the height, thickness and thermal condition of this layer. Previously it was considered isothermal in character i.e. temperature remains uniform throughout this layer but this connotation has been refuted. The average height over the middle latitudes has been determined to be 25-30 km whereas it is estimated to be 80 km by others. On an average, the upper limit of the stratosphere is taken to be 50 km. There are also contrasting opinions about change or no change of temperature with increasing height in this layer. A few scientists believe that the stratosphere is isothermal i.e. there is no change in temperature with increasing height in this layer while others hold that temperature gradually rises upward as it becomes as high as 0 °C(32°F) at the height of 50 km, the upper limit of the stratosphere which is known as **stratopause.** The increase of

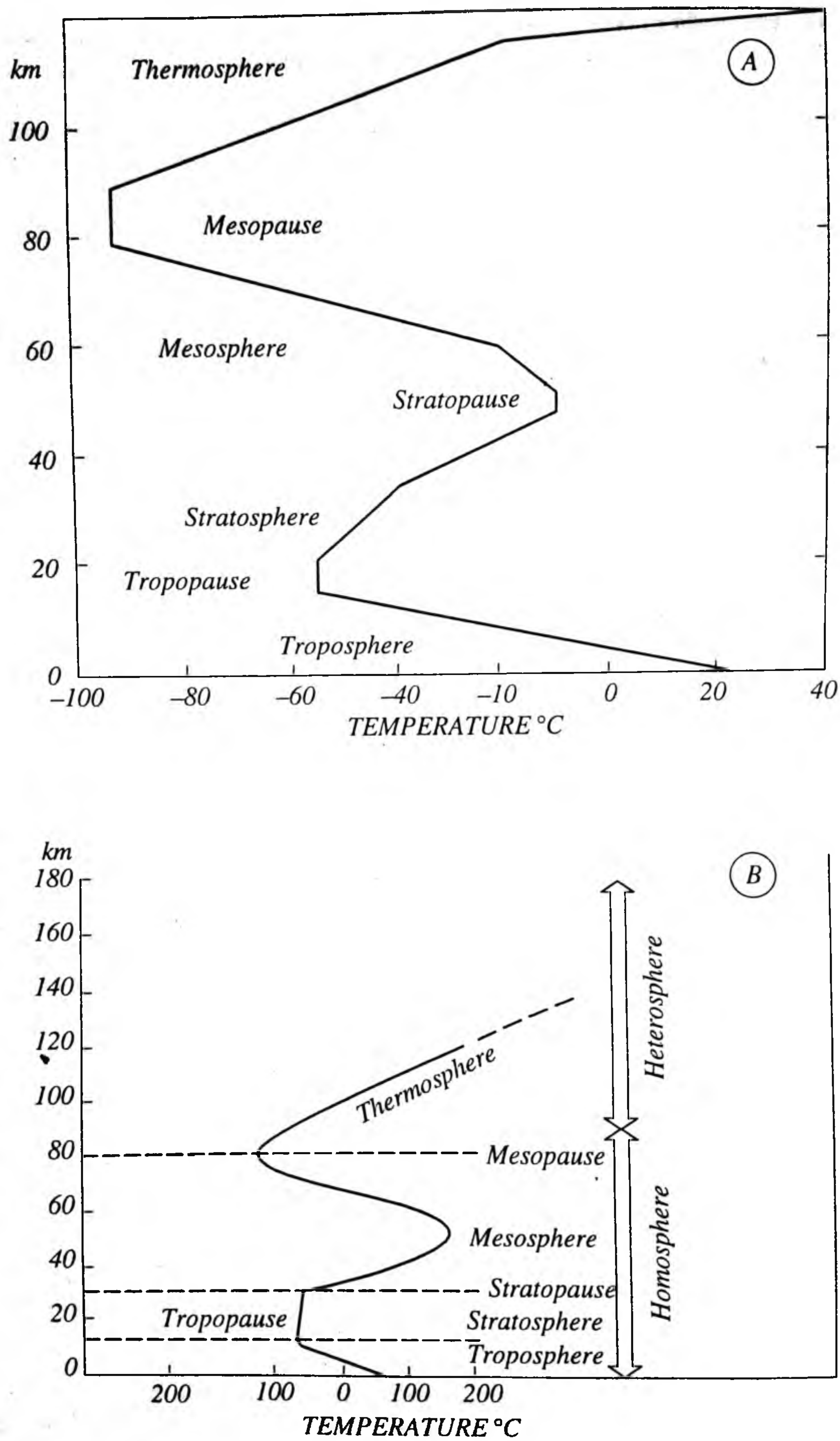


Fig. 2.1: Stratification of the atmosphere. A-according to R.G. Barry and R.J. Chorley. B-according to A.N. Strahler. The temperatures to the left of 0 in the lower figure (B) are in minus degrees.

temperature becomes possible due to absorption of ultraviolet solar radiation by ozone and lesser density of air. This layer is characterized by near absence of weather phenomena because of stable condition, dry air, feable air circulation, rare occurrence of clouds, concentration of ozone etc. Sometime cirrus clouds, knowns as **'mother-of-pearl clouds'** or **'nacreous clouds'** appear in the lower stratosphere. The lower part of stratosphere is very important for life-forms in the biospheric ecosystem because there is concentration of ozone gas (O_3) between the height of 15-35 km, the maximum O_3 concentration being at the height of 22 km, though ozone has been discovered up to the height of 80 km.

The lower portion of the stratosphere having maximum concentration of ozone is called **ozonosphere,** which is confined between the height of 15 km to 35 km from sea level though the upper limit has been fixed at 55 km. Ozone (O_3) defined as 'a three atom isotope of oxygen or merely a triatomic form of oxygen (O_3)' is a faintly blue irritating gas with a characteristic pungent odour. The ozone gas is unstable because the creation and destruction of this gas is a gradual and continuous natural process. It acts as a protective cover for the biological communities in the biosphere because it absorbs almost all of the ultra-violet rays of solar radiation and thus protects the earth's surface from becoming too hot. Recently, the researches have shown that there is gradual depletion of ozone gas in the atmosphere due to human activities. It may be pointed out that combining of atmospheric oxygen (O_2) with individual oxygen molecules results in the creation of ozone ($O_2 + O + M \rightarrow O_3$) whereas the breaking of ozone (O_3) into O_2 and O results in the depletion or destruction of ozone. The main culprits of ozone destruction and halogenated gases called chlorofluorocarbons, popularly known as CFCs, belong to the category of synthetic chemicals and are relatively simple compounds of the elements chlorine, fluorine and carbon and are initially stable compounds which do not have any toxic effect on life processes in the biosphere at ground level. These synthetic chemicals are widely used as propellants in spray can dispensers, as fluids in air conditioners and refrigerators etc. Chlorofluorocarbons, when used as propellants, are released into the air and are transported in the stratosphere by vertical atmospheric circulation. Chlorine when separated from chlorofluorocarbons reacts with water and thus depletes ozone rather breaks ozone into O_2 and O. Besides, nitrogen oxides released by supersonic jets which fly at the height of 18-22 km also depletes ozone. Depletion of ozone would result in the rise of temperature of the ground surface and lower atmosphere. This would cause global warming, acid rain, melting of continental glaciers and rise in sea level, skin cancer to white-skinned people, poisonous smogs, decrease in photosynthesis, ecological disaster and ecosystem instability.

(3) Mesosphere

Mesosphere extends between 50 km and 80 km. Temperature again decreases with increasing height. In fact, the rise of temperature with increasing height in the stratosphere stops at stratopause. At the uppermost limit of mesosphere (80 km) temperature becomes-80°C and may go down as low as-100 to-133°C. This limit is called **mesopause** above which temperature increases with increasing height. In fact, mesopause refers to inversion of temperature after the height of 80 km because there is gradual decrease of temperature in mesosphere from the altitude of 50 km to 80-100 km above which it again rises. **Noctilucent clouds** formed through the process of condensation in association with meteoric dusts and some moisture transported upward by convective mechanism, are noticed during summer season over polar areas. The layer is characterized by very low air pressure ranging between 1.0 millibar at 50 km altitude representing stratopause and 0.01 millibar at mesopause (at 90-100 km).

(4) Thermosphere

The part of the atmosphere beyond mesopause is known as thermosphere wherein temperature increases rapidly with increasing height but air pressure becomes extremely low due to very low atmospheric density. It is estimated that the temperature at its upper limit (height undecided) becomes 1700°C. It may be pointed out that this temperature cannot be measured by ordinary thermometer because the gases become very light due to extremely low density. That is why one does not feel warm when one stretches one's arm in the air. Thermosphere is divided into two layers viz. (i) ionosphere, and (ii) exosphere.

(1) **Ionosphere** extends from 80 km to 640 km. There are a number of ionic layers (with increasing heights) in this sphere e.g. D. layer, E layer, F layer, and G layer. **D. layer** (between the height of 80 km –99 km) reflects the signals of low frequency radio waves but absorbs the signals of medium and high frequency waves. This layer disappears with the sunset because it is associated with solar radiation. E layer, also known as **Kennelly-Heaviside layer,** is confined in the height between 99 km-130 km. This layer reflects the medium and high frequency radio waves back to the earth. This layer is produced due to interaction of solar ultra-violet photons with nitrogen and nitrogen molecules and thus it also disappears with the sunset. **Sporadic E layer** is associated with high velocity winds and is created under special circumstances. This layer reflects very high frequency radio waves. **E_2 layer** is generally found at the height of 150 km and is produced due to reaction of ultra-violet solar photons with oxygen molecules and thus this layer also disappears during nights. **F layer** consists of two sub-layers e.g F_1 and F_2 layers (150 km - 380 km) and are collectively called '**appleton layer**'. These layers reflect medium and high frequency radio waves back to the earth. **G layer** (400 km and above) most probably persists day and night but is not detectable.

(2) **Exosphere** represents the uppermost layer of the atmosphere. In fact, we know very little about the atmosphere extending beyond 640 km height from the sea level. The density becomes extremely low and the atmosphere resembles a nebula because it is highly rarefied. The temperature becomes 5568°C at its outer limit but this temperature is entirely different from the air temperature of the earth's surface as it is never felt.

It may be mentioned that the atmosphere above ionosphere is called **outer atmosphere** having **exosphere** and **magnetosphere**. This zone is characterized by **Van Allen Radiation Belts** having charged particles trapped by earth's magnetic field, **aurora australis** and **aurora borealis.** Aurora means dawn while borealis and australis mean northern and southern respectively. **Auroras are** cosmic glowing lights produced by a stream of electrons discharged from the sun's surface due to magnetic storms. Auroras are seen as unique multicoloured fireworks hanging in the polar sky during mid-night.

(B) Chemical Characteristics

On the basis of chemical composition the atmosphere is divided into two broad zones viz. (1) homosphere, and (2) heterosphere.

(1) **Homosphere** represents the lower portion of the atmosphere and extends upto the height of 90 km from sea level. The main constituent gases are oxygen (20.946%) and nitrogen (78.084%). Other gases are argon, carbon dioxide, neon, helium, krypton, xenon, hydrogen etc. This zone is called homosphere because of the homogeneity of the proportion of various gases. In other words, the proportions of different gases are uniform at different levels in this zone. It may be pointed out that man is increasingly distrurbing the natural proportions of gases through his everincreasing economic activities and modern technologies. For example, the proportion of carbon dioxide is rapidly increasing due to burning of fossil fuels (coal, petroleum and natural gas) and deforestation. The concentration of atmospheric carbon dioxide at the beginning of the industrial revolution (1860 A.D.) was fixed at 280 to 290 ppm (part per million) by volume but now it has increased to 350-360 ppm (1988 A.D.), thus registering an overall increase by 25 per cent from the pre-industrial level. On the other hand, the proportion of ozone gas is rapidly decreasing due to ever-increasing production and consumption of CFCs (chlorofluorocarbons) and halogenated gases. On the basis of thermal conditions the homosphere has been divided into three layers viz. (i) **troposphere,** (ii) **stratosphere,** and (iii) **mesosphere.**

(2) **Heterosphere** extends from 90 km to 10,000 km. Different layers of this sphere vary in their chemical and physical properties. There are four distinct layers of gases in this sphere. (i) **Molecular nitrogen layer** is dominated by molecular nitrogen and extends upward upto the height of 200 km (90 to 200 km). (ii) **Atomic**

oxygen layer extends from 200 to 1100 km. (iii) Further upward there is **helium layer** which extends upto the height of 3500 km. (iv) **Atomic hydrogen layer** is the topmost layer of the atmosphere and extends upto the outermost limit of the atmosphere.

2.6 IMPORTANT DEFINITIONS

Auroras : are cosmic glowing lights produced by a stream of electrons discharged from the sun's surface due to magnetic storms. Auroras (borealis-northern, australis-southern) are seen as unique multicoloured fireworks hanging in the polar sky during mid-night in the exosphere and magnetosphere.

Boyle's gas law : pertains to relationships among air pressure, volume of gas and its density.

Charle's gas law : shows relationship between air pressure and temperature with constant gas volume.

Cold point : the height at which (tropopause) decrease of temperature with increasing altitude stops is called cold point.

Combined gas law : is related to derive any one variable with two known variables.

Lussac's gas law : shows relationship among pressure, volume of gas and temperature.

Mesopause : is the upper limit (80 km) of mesosphere.

Noctilucent clouds : formed through the process of condensation in association with meteoric dusts and some moisture transported upward by convective mechanisms, are noticed during summer season over polar areas.

Stratopause : is the upper limit (50 km) of stratosphere.

Tropopause : is the upper limit (16 km over equator) of troposphere.

3

INSOLATION AND ENERGY (HEAT) BALANCE

3.1 THE ENERGY SYSTEM

The earth and the biospheric ecosystem receives energy from three basic sources viz. (i) **solar radiation**, (ii) **gravity** and (iii) **endogenetic forces** coming from within the earth but the solar radiation is the most significant source of terrestrial heat energy. The endogenetic forces caused by varying thermal conditions deep within the earth create relief features of varying orders and dimensions on the earth's surface which in turn affect waterflow, vegetation cover, development of soils, weather and climate etc. Gravity forces help in the downslope movement of water and ice and thus facilitate in transforming potential energy into kinetic energy.

Solar energy received through solar radiation heats the earth's surface and the atmosphere and thus is responsible for the movement of air and currents through changes in pressure gradients; drives the hydrological cycle through evaporation and precipitation which in turn helps in the cycling and recycling of nutrients and chemical elements in the biosphere through the broader cyclic pathways collectively known as **biogeochemical cycles;** helps the plants to prepare their food through the process of **photosynthesis** which infact changes solar energy into chemical energy which is used by plants, animals and man through different trophic levels of food chains and food webs.

Radiation balance or heat balance is very important for biological communities in the biospheric ecosystem and hence a detailed discussion on global radiation and heat balance and the role of man in the alteration and maintenance of global and regional heat balances of the earth and its atmosphere is not only desirable but is also necessary for future environmental and ecological planning.

It may be pointed out that the solar energy is responsible for the functioning and maintenance of the 'earth-atmosphere system' and the solar energy is received through solar radiation. Different types of weather phenomena which occur on the earth's surface depend on the mode of transfer and exchange of solar energy between the earth's surface and the atmosphere. The energy transfer from place to place takes place through the processes of conduction, convection and radiation.

3.2 FLUX OF SOLAR ENERGY IN THE BIOSPHERE

The flux or inflow of solar energy in the biosphere has been estimated differently by various scientists. Following the estimate of Ian Simmons (1982) the solar energy reaching the top of the earth's atmosphere is 520×10^{22} Joules (which is 1/2 billionth part of total energy radiated from the sun) every year. Out of the total energy (transmitted from the sun in the form of electromagnetic radiation) about 100×10^{22} Joules reach the earth's surface but 40% of the total solar energy entering the earth's atmosphere is reflected back into space by desert, snow and ice and oceans. Thus 60×10^{22} Joules become available to the green plants for photosynthesis. This part of the solar energy is known as **pool for photosynthesis.** This energy is converted by the green plants into food or chemical energy of which a large part is spent by the plants through respiration. Only 170×10^{19} Joules (which is only 0.2% of the total solar energy entering the earth's atmosphere) are stored in the biomass (the total mass of the living plant tissues.) Thus it is obvious that the flora of the biosphere utilize only 0.2% of the total energy present in the light (solar radiation) of the right wavelength (suitable for photosynthesis by green plants). Man utilizes only less than one per cent of the total energy stored in the biomass (as accumuled organic matter, fig 3.1).

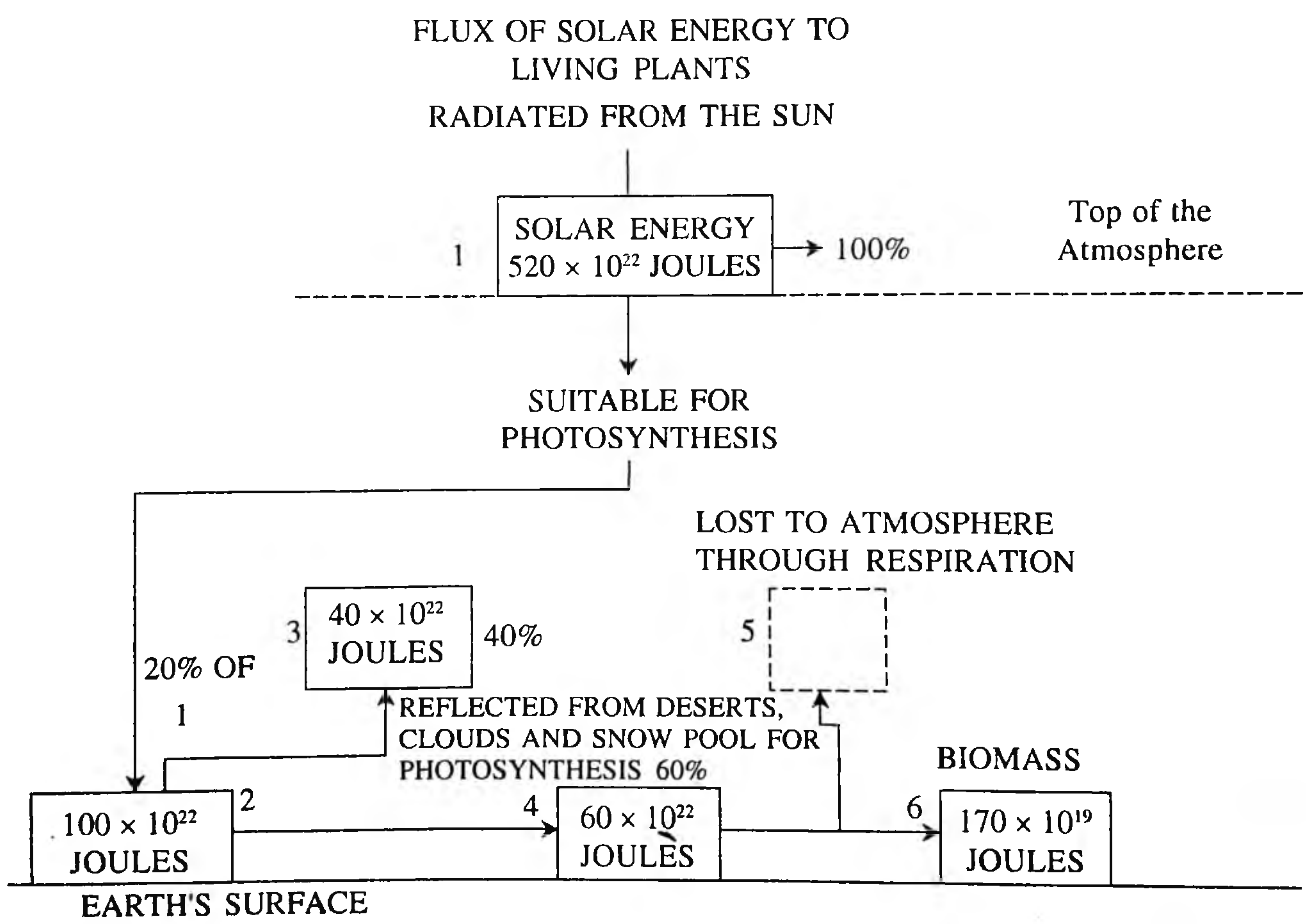


Fig. 3.1 : The flow or flux of solar energy to living plants (Based on Ian Simmons, 1982).

The solar or light energy is transformed into food or chemical energy by the processes of photosynthesis by green plants. Certain part of this chemical energy is lost to the atmosphere through respiration by the plants and the remaining part is stored in the plants as biomass. The energy is further transferred from one level of organisms to the other level of organisms and it is also used and spent at various levels of organisms. Thus the flow of energy is unidirectional and once used and spent is never available for reuse. "Energy is constantly flowing into the biosphere, undergoing various transformations which may involve being stored but ultimately being lost in the form of heat:" (P.A. Furley and W.W. Newey, 1983).

3.3 INSOLATION

The sun is a great engine that drives winds on the earth's surface, ocean currents, exogenetic or denudational processes (weathering and erosion) and ultimately sustains life in the biosphere. 'The radiant energy received from the sun, transmitted in a form analogous to shortwaves (1/250 to 1/6700 mm in length), and travelling at the rate of 1,86,000 miles a second is called **solar radiation** or **insolation'** (G.T. Trewartha).

In fact, the solar energy is radiated from the surface of the sun but the source of energy is the interior of the sun. It may be mentioned that the sun is a big gaseous mass having a diameter of about 13,82,000 km which is about 109 times that of the planet earth. The sun is supposed to have been formed of four major zones, namely **core, photosphere, chromosphere, and corona.** The bright outer surface of the sun is called **photosphere** because of the dominance of **photons** which represent bundle of energy of burning gases within a 300 km thick outer surface. It may be mentioned that the photosphere representing outer surface of the sun is not characterized by even surface of uniform thickness rather it is uneven having numerous small bright areas called as granules surrounded by dark areas having cool gases. The photosphere consists of 90 per cent hydrogen and 10 per cent helium. Within photosphere there are cool and dark spots, known as **sunspots** and hotspots, known as **faculae**. A thin layer of burning gases around photosphere but about 1,000,000 km away from the sun is called **chromosphere** comprising ionized hydrogen and helium atoms. A stream of electrons and protons released from the photosphere into chromosphere and corona is called **solar wind**. The sudden and explosive bursts of burning hot gases are called **solar flares** which release enormous amount of energy and atomic particles which after mixing with solar wind and reaching earth's polar magnetic zones cause **auroral lights. Corona** represents outermost zone of the sun's atmosphere and is characterized by very hot (having a temperature of one to two million^{0}K = Kelvin) and rarefied gases.

The solar energy is radiated from the photosphere in the form of electromagnetic radiation waves of wchich the earth receives only 1/2 billionth part but even this energy (insolation) is equivalent to 23 trillion horse power which is capable for the sustenance of all life-forms in the biosphere and all weather phenomena.

3.4 MECHANISM OF SOLAR RADIATION

The source of energy of the sun is its interior wherein the hydrogen is converted into helium due to enormous confining pressure and very high temperature under the process of nuclear fusion which generates huge quantity of heat. This heat is transported to the outer surface of the sun through convection and conduction from below. It may be pointed out that the rate of generation of heat inside the sun is more or less constant and hence the radiation of energy from the outer surface of the sun (called as **photosphere**) is also more or less constant. Thus, the amount of solar radiation or the solar energy received on a unit area of the surface facing the sun at the average distance between the sun and the earth is also more or less constant and is called as **solar constant**. Thus, it is obvious that the *solar constant refers to the rate of radiation from the sun which is of the value of 2 gram calories per square centimetre per minute (2 cal/cm^2/min)*. It is also expressed in terms of langley (a unit measure of heat energy, one gram calorie per square centimeter is equal to one langely) as 2 langely per minute (2 ly/min).

There are two basic laws which govern the nature and flow of radiation as given below.

(1) Wien's displacement law 'states that the wavelength of maximum radiation is inversely proportional to the absolute temperature of the emitting body.'

Thus, the higher the temperature of radiating body, the shorter the wavelength and vice versa. This law may be explained with the example of wavelengths of the radiation waves of the earth and the sun. It may be mentioned that the average temperatures of the surface of the earth and the sun are 288° K and 6000°K respectively.

λmax (wavelength in micrometer) = K/T
where K is constant (2897)
T is temperature in degrees Kelvin

(i) In the case of the sun the wavelength of solar radiation waves = λmax = 2897/6000°k
= 0.48 micrometer

(ii) In the case of the earth the wavelength of terrestrial radiation waves = λmax = 2897/288°k
= 10 micrometers

It is evident from the above examples that the wavelengths of terrestrial radiation waves are much longer than those of the solar radiation waves.

(2) **Stefan-Boltzman law of radiation** states 'that flow, or flux, of radiation is proportional to the fourth power of the absolute temperature of the radiating body.'

It may be mentioned that **Wien's displacement law, Stefan-Boltzman law, Kirchoff's law, Plank's law** etc. are related to radiation from the **black body**. A black body is that hypothetical body of object which absorbs all incoming electromagnetic radiation without reflecting any amount of incident energy and radiates energy. The sun and the earth, though not perfect black bodies, are approximately black bodies.

Stefan - Boltzman law states :

$$F = \sigma T^4$$

where F = flux of radiation from per square meter surface area of the radiating body

σ = is a constant equivalent to 5.67×10^{-8} W/m^2 K^4 in SI units

T = is the temperature of the radiating body in degree Kelvin

The Stefan-Boltzman law simply states that 'the hotter the radiating body, the greater the amount of energy radiated from that body and vice versa.' This can be explained with the temperatures of the outer surfaces of the sun and the earth. As stated above the temperatures at the surfaces of the earth and the sun are 288°K and 6000°K respectively. Thus, the sun's surface is much hotter than the earth's surface, say the sun's surface is roughly 20 times hotter than the earth's surface. 'Twenty raised to the fourth power is 160,000. Therefore,

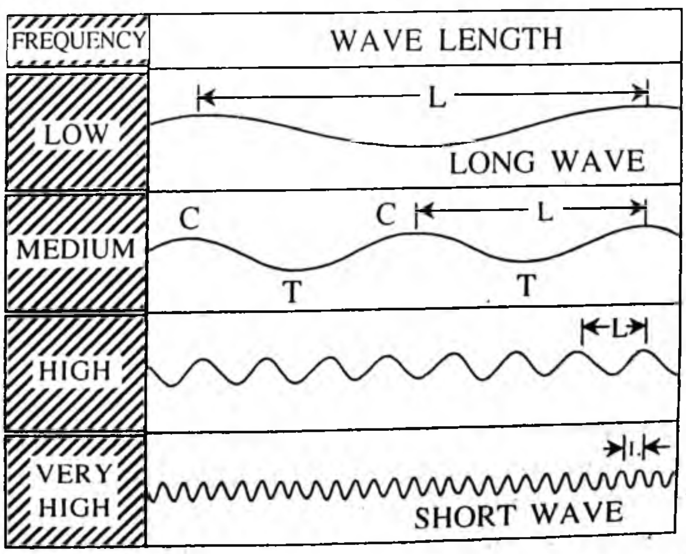


Fig.3.2 : Relationship between wavelength and wave frequency, L = wavelength, C= wave crest, and T= wave trough.

the sun emits 160,000 times as much radiation per unit area as Earth' (Oliver and Hidore, 2003).

The **Kirchoff's law** is related to the absorption of radiation and emission of radiation from a body. The law states, the higher the absorption of radiation of a body, the greater the emission of radiation from that body.

The surface temperature of the sun is 6000°K. The highly incandescent gas of the sun's surface being heated from below emits bundle of energy called **'photon'** which is infact the particle of radiation which has the property of wavelength. Continuous emission of **photons** from the sun's surface causes continuous bands of radiation having certain wavelength which is considered as short wavelength in relation to the earth's outgoing longwave radiation. The solar energy radiated from the outer surface of the sun in the form of electromagnetic wave is called as **electromagnetic radiation,** which travels at the speed of 3,00,000 km per second (1,86,000 miles per second). The solar energy received at the earth's surface is called **insolation** or **solar radiation.**

The energy from the sun is emitted in the form of electromagnetic waves which travel outward in radial manner from the sun almost in straight line and take 8 minutes 20 seconds to reach the earth's surface after covering an average distance of 150 million km (93 million miles) between the sun and the earth. The electromagnetic radiation waves are expressed in terms of **wavelengths** (L). The straight distance between two successive crests or troughs is called wavelength fig (3.2) (L) which is expressed in the length units of meters, centimeters, millimeters, microns etc.

Table 3.1 : Wavelengths of shortest waves

Waves	Wavelength (in angstrom)	Frequency of wavelengths in megahertz
1. Gama Rays	less than 0.03	10^{14}
2. Hard X-Rays	0.03 - 0.6	10^{13}
3. Soft X-Rays	0.6 - 100	10^{12} - 10^{11}
4. Ultra-Violet Rays	100 - 4000	10^{10} - 10^{9}

The number of radiation waves (one radiation wave is equal to one wavelength) passing through a certain point per unit time (usually one second) is called **wave frequency** which varies according to the wavelengths of the radiation waves. There is inverse relationship between the wavelength, and wave frequency i.e. shorter the wavelength, higher the wave frequency and longer the wavelength, lower the wave frequency (fig. 3.2) . In other words, high wave frequency is associated with short wavelength and low wave frequency is associated with long wavelength. Wave frequency is generally expressed as wave cycles per second. The wave cycles are usually expressed by the unit of measure of hertz. For example, one hertz per second represents one wave cycle meaning thereby only one wavelength passes per second from a fixed point. Hertz is further expressed in kilohertz (1,000 hertz) or megahertz (1,000,000 hertz).

The electromagnetic radiation emitted from the outer surface of the sun consists of four spectra of radiation waves having different wavelengths and wave frequencies.

(1) **The first spectrum** of electromagnetic waves includes **gama rays, hard x-rays, soft x-rays** and **uulra violet rays.**The wavelengths of this spectrum of the shortest wavelengths are expressed in the unit measure of angstrom wherein one **angstrom** is, equal to 0.000,000.01 cm or 10^{-8}cm. The wavelengths of the waves of the spectrum of the shortest wavs are given in table 3.1.

(2) **The second spectrum** of the electromagnetic radiation waves is also called as the **spectrum of visible light** or **rays** which includes violet, blue, green, yellow, orange and red rays which carry 41 per cent of the total energy of the solar spectrum of all the electromagnetic radiation waves. The unit of the measure of wavelengths of this spectrum is

micron (one micron is equal to 0.0001 cm or 10,000 angstroms). The wave frequency of these different rays ranges between 10^{10} and 10^{9} megahertz per second. The wavelengths of these visible rays are as given below :

Visible Rays	Wavelengths in microns
1. Violet rays	0.4 -0.43
2. Blue rays	0.43 - 0.49
3. Green rays	0.49 - 0.53
4. Yellow rays	0.53 - 0.58
5. Red rays	0.58 - 0.70

(3) **The third spectrum** of the electromagnetic radiation waves is called as **infrared spectrum** which consists of infrared waves of the wavelengths ranging from 0.7 micron to 300 microns. The wave frequency ranges between 10^{8} and 10^{6} megahertz per second.

(4) **The fourth spectrum** of the electromagnetic radiation wave consists of longwaves including microwaves, radar waves and radio waves. The unit measure of these wavelengths of longwaves is usually centimetre to metre. The wavelengths of microwaves range between 0.03 cm and 1.0 cm. These waves are used to send messages from one place to other distant places. The wavelengths of radar waves vary from 1.0 cm to 100 cm (1 m). The **radar system** is divided into two sub-systems on the basis of frequency viz. (i) **radio system, and** (ii) **television system.** The radar, television and radio waves are divided into 6 categories on the basis of wave frequency and wavelengths.

Frequency	Wavelengths
1. Extremely High Frequency (EHF)	0.1 - 1.0 cm
2, Super High Frequency (SHF)	1.0 cm - 10.0 cm
3. Ultra-High Frequency (UHF)	10.0 - 100.0 cm
4. Very High Frequency (VHF)	1.0 m - 10.0 m
5. High Frequency (HF)	10 m - 100 m
6. Low Frequency (LF)	more than 100 m

3.5 DISTRIBUTION OF INSOLATION

On an average, the amount of insolation received at the earth's surface decreases from equator towards the poles but there is temporal variation of insolation received at different latitudes at different times of the year. Table 3.2 depicts the amount of insolation received at the outer boundary of the atmosphere and at the earth's surface at the time of winter solstice (22 December), vernal equinox (21 March), summer solstice (21 June) and autumnal equinox (23 September) as given by Baur and Phillips.

Table 3.2 : Average Amount of Direct Solar Radiation Received at the outer Boundary of the Atmosphere and at the Earth's Surface (in cal/cm²/min)

Date	Latitudes (northern hemisphere)						
	0-10	10-20	20-30	30-40	40-50	50-60	60-90
	A- Received at the upper limit of the atmosphere						
December, 22	0.549	0.465	0.373	0.274	0.173	0.079	0.006
March, 21	0.619	0.601	0.563	0.509	0.441	0.358	0.211
June, 21	0.579	0.629	0.664	0.684	0.689	0.683	0.703
September, 23	0.610	0.592	0.556	0.503	0.435	0.353	0.208
	B- Received at the earth's surface if cloudiness and turbidity are considered						
December, 22	0.164	0.161	0.134	0.082	0.036	0.013	0.001
March, 21	0.191	0.221	0.206	0.161	0.116	0.096	0.055
June, 21	0.144	0.170	0.216	0.233	0.183	0.159	0.133
September, 23	0.170	0.162	0.201	0.183	0.131	0.079	0.028

Source : Baur and Phillips

It is apparent from table 3.2 that the amount of solar radiation reaching the outer limit of our atmosphere is significantly more at different latitudes (A in table 3.2) than the amount of insolation received at the ground surface. This trend reveals the fact that a sizeable portion of incoming solar radiation is lost while passing through the atmosphere due to cloudiness (reflection), atmospheric turbidity (scattering), reflection, and absorption (through ozone). The data of insolation as portrayed in table 3.2 A further reveal that maximum insolation reaches the outer limit of the atmosphere at north pole at the time of summer solstice while maximum insolation is received at the ground surface between latitudes 30°-40° N on 21st June because of minimum amount of cloudiness due to the presence of subtropical high pressure belt and anticyclonic conditions.

Table 3.3 : Amount of insolation received at the earth's surface from equator towards the poles (in percentage)

Latitudes	0	10	20	30	40	50	60	70	80	90
Insolation in per cent	100	99	95	88	79	68	57	47	43	42

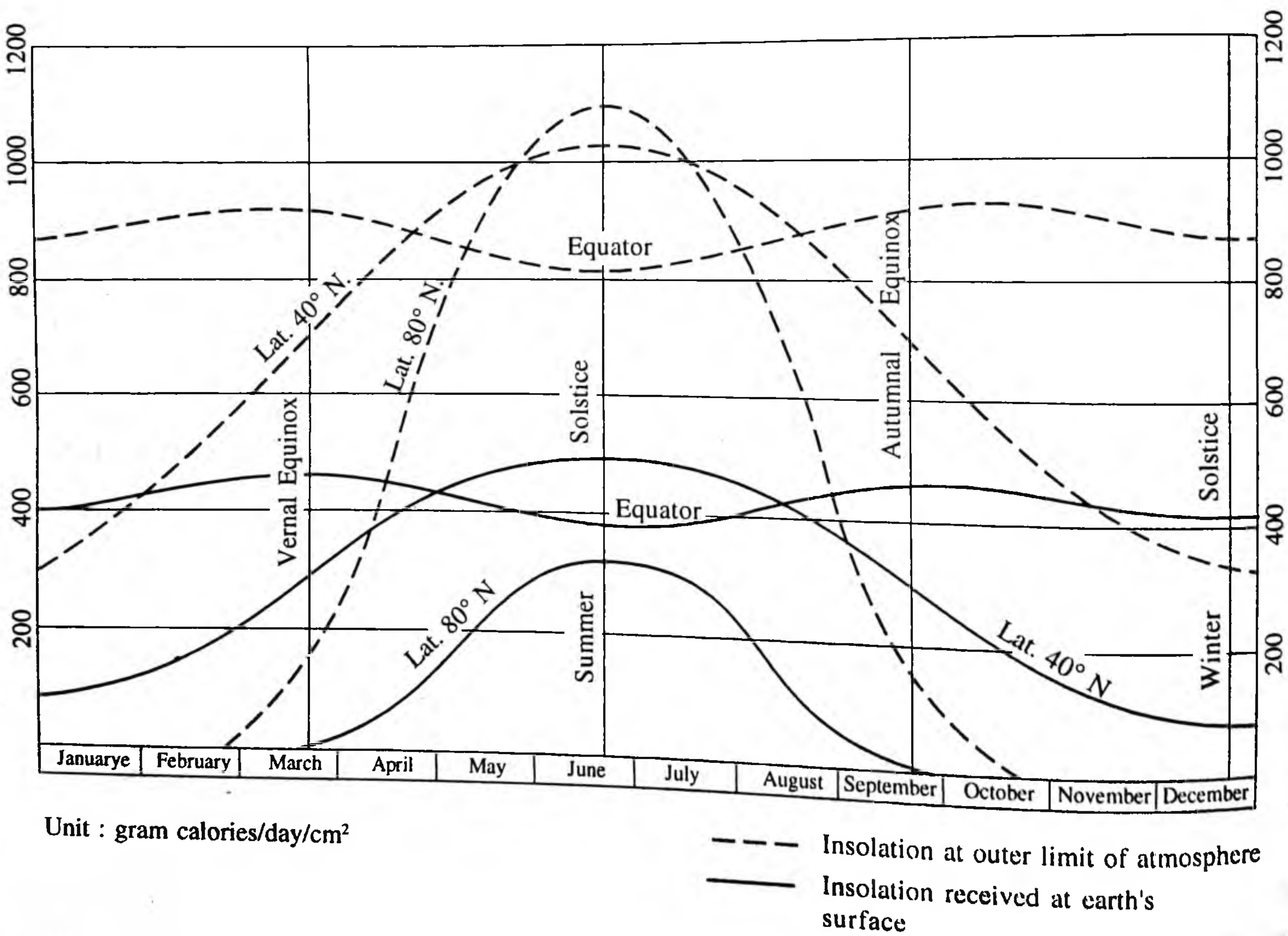


Fig. 3.3 : Latitudinal and seasonal variations in the amount of insolation received at the outer surface of the earth's atmosphere (shown by broken lines) and at the earth's surface (shown by solid lines). After G.T. Trewartha, 1954.

Table 3.3 reveals the fact that total amount of insolation received at the earth's surface decreases from equator towards the poles. The insolation becomes so low at the poles that they receive about 40 per cent of the amount received at the equator. The tropical zone extending between the tropics of Cancer (23.5°N) and Capricorn (23.5°S) receives maximum insolation. Not only this, there is very little variation of insolation during winter and summer seasons because every place experiences overhead sun twice every year. The globe is divided into 3 zones on the basis of the amount of insolation received during the course of a year.

(1) **Low latitude** or **tropical zone** extends between the tropics of Cancer and Capricorn. All places experience overhead sun (sun's rays are vertical) twice during the course of a year due to northward and southward march of the sun. Consequently, every place receives maximum and minimum insolation twice a year. The region receives highest amount of insolation of all other zones and there is little seasonal variation .

(2) **Middle latitude zone** extends between 23.5° and 66° latitudes in both the hemispheres. Within this zone every place receives maximum (at the time of summer solstice-21 June in the northern hemisphere and at the time of winter solstice -22 December in the southern hemisphere) and minimum (at the time of vernal equinox-21 March in the northern hemisphere and at the time of autumnal equinox-23 September in the southern hemisphere) insolation once during the course of a year. Insolation is never absent at any time of the year but seasonal variation increases with increasing latitudes.

(3) **Polar zone** extends between 66° and 90° (poles) latitudes in both the hemispheres. Every place receives maximum and minimum insolation once during the course of a year but some times insolation becomes zero due to absence of direct solar rays.

3.6 FACTORS AFFECTING THE DISTRIBUTION OF INSOLATION

It is apparent from the foregoing discussion that the amount of insolation received at the earths's surface varies considerably (decreases) from equator towards the poles due to certain astronomical and geographical factors viz. (1) angle of the sun's rays or the altitude of the sun, (2) length of days, (3) distance between the sun and the earth, (4) sunspots, and (5) effects of the atmosphere.

(1) Angle of the sun's Rays

The angle between the rays of the sun and the tangent to the surface of the earth at a given place largely determines the amount of insolation to be received at the place. The sun's rays are more or less vertical (maximum angle of 90° between the sun's rays and the tangent to the earth's surface) at the equator and become more and more oblique poleward. In other words, the angle of the sun's rays

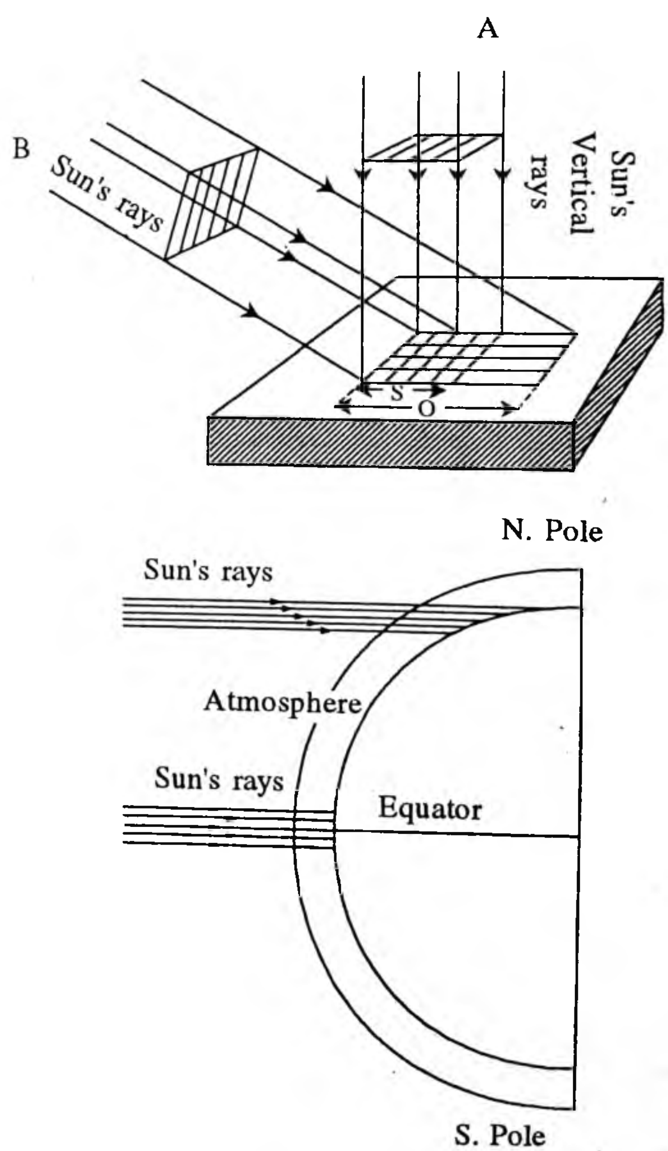


Fig. 3.4 : Effect of the angles of sun's rays on the distribution of insolation.

decreases poleward. As per rule vertical rays bring more insolation than oblique rays. In other wards, as the angle of sun's rays decreases poleward, the amount of insolation received also decreases in that direction. The control of the angle of the sun's rays on the amount of insolation may be explained with the following examples :

(i) Vertical rays are spread over minimum area of the earth's surface and they heat the minimum possible area and thus the energy received per unit area increases. On the other hand, oblique rays are spread over larger area of the earth's surface and hence the amount of energy received per unit area decreases. It is, obvious from fig. 3.4 that A and B bands of the sun's rays are of uniform width and carry equal amount of solar energy but the area (S) covered by A band is much smaller than the area covered by B band (O) and therefore the amount of insolation received per unit area over S surface is greater than over O surface area (fig. 3.4).

(ii) Oblique rays have to pass through thicker portion of the atmosphere than the vertical rays. Thus, the oblique rays have to traverse larger distances than the vertical rays. Consequently, the amount of solar energy lost due to reflection, scattering and absorption increases with increasing distance of travel path covered by the sun's rays through the atmosphere (fig.3.4). It may be summarized that the oblique rays lose more energy than the vertical rays while passing through the atmosphere.

(2) Length of Day

If all the other conditions are favourable and equal then longer duration of sunshine (or length of day) and shorter duration of night enable the ground surface to receive larger amount of insolation. On the other hand, shorter the duration of sunshine and longer the period of night, the lesser the amount of the insolation received at the earth's surface. The length of day varies at all places except at the equator due to inclination of the earth's axis, its parallelism and the earth's rotation and revolution. The length of day is always of 12 hours at the equator because the circle of illumination or light circle always divides the equator into two equal halves. But the length of day increases poleward with northward march of the sun in the northern hemisphere while it decreases in the southern hemisphere at the time of summer solstice (21 June). On the other hand, the length of day increases from the equator poleward in the southern hemisphere but it decreases in the northern hemisphere at the time of winter solstice (22 December) (southward march of the sun.) It is important to note that the duration of day becomes of 6 months at the north pole from 21 March to 23 September during the northward migration of the sun while the night is of the duration of 6 months at the south pole during this period. Conversely, the length of day becomes of 6 months at the south pole (23 September to 21 March) during the southward migration of the sun while the night becomes of 6 months at the north pole during this period. Inspite of increasing length of day from the equator towards the north pole during summer solstice and from the equator to the south pole during winter solstice the amount of insolation received at the ground surface decreases considerably poleward because of decrease in the angle of sun's rays. Inspite of the longest length of day at the poles insolation becomes minimum because (i) the sun's rays become more or less parallel to the ground surface, and (ii) the ice cover reflects most of the solar radiation. It is apparent that the angle of the sun's rays controls the amount of insolation received more effectively than the length of day. It may be, thus, concluded that the places having longer length of day and vertical sun's rays will certainly receive maximum insolation.

Table 3.4 : Maximum length of day at different latitudes.

Latitude	0	17	31	41	49	58.5	63.4	66.5	67.4	69.8	78.2	90
Length of day (hours)	12	13	14	15	16	18	20	24	1 month	2 months	4 months	6 months

(3) Distance between the Earth and the Sun

The distance between the sun and the earth changes during course of a year because the earth revolves around the sun in elliptical orbit. The average distance between the sun and the earth is about 93 million miles (149 million kilometres). At the time of perihelion on January 3 the earth is nearest to the sun, say 91. 5 million miles (147 million kilometres) away while at the time of aphelion on July 4 it is farthest from the sun, say 94.5 miles (152 million kilometres) away (fig 3.5). As per rule, the earth at the time of perihelion, when it is nearest to the sun, should receive maximum insolation while it should receive minimum insolation at the time of aphelion when the earth is at the greatest distance from the sun. In fact, in the month of January, when the earth is nearest to the sun, there is winter season instead of summer season in the northern hemisphere due to low amount of insolation received. On the other hand, in the month of July, when the earth is farthest from the sun, there is summer instead of winter in the northern hemisphere due to high amount of insolation received. It is obvious that factors of the angle of the sun's rays and length of day play more dominant role in the distribution of insolation than the factor of varying distances between the earth and the sun. Of course winters are 7 per cent less severe in January in the northern hemisphere but

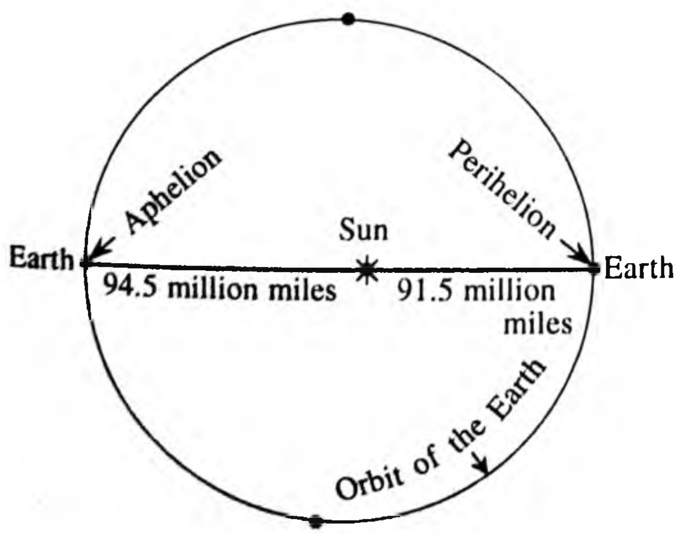


Fig.3.5 : Relative distance between the sun and the earth. **Note** *: The earth's orbit is elliptical, and not circular as shown in this figure.*

summer is 7 per cent more intense in the southern hemisphere at the time of perihelion while summer is 7 per cent less intense in July in the northern hemisphere but winter is 7 per cent more intense in the southern hemisphere at the time of aphelion.

(4) Sunspots

Sunspots, defined as dark areas within photosphere of the sun and surrounded by chromosphere, are created in the solar surface (photosphere) due to periodic disturbances and explosions. These dark areas are cool areas because they are characterized by 1500°C less temperature than the chromosphere which surrounds them. The average size of small sunspot is estimated about of 1600 km diameter which has the life span 'ranging from few days to a few months. Each spot has a black center, or **umbra** and a lighter region, or **penumbra,** surrounding it' (Oliver and Hidore, 2003). It is believed that Galileo was the first to identify sunspots as a feature of the sun.

The number of sunspots varies from year to year. The studies have shows that variation in the number of sunspots is cyclic in nature. . In other words, the increase and decrease of number of sunspots is completed in a cycle of 11 years. 'First, the sunspots increase to a maximum, with 100 or so visible at a given time. Over a period of years, the number diminishes until only a few or none occurs. Change from the maximum to the minimum number takes about 5.5 years, and thus the complete cycle is 11 years' (Oliver and Hidore, 2003). The sunspots activities have been related with the amount of radiation from the earth's surface. It is believed that the energy radiated from the sun increases when the number of sunspots increases and consequently the amount of insolation received at the earth's surface also increases. On the other hand, the amount of insolation received at the earth's surface decreases with decrease in the number of sunspots due to less emission of radiation from the sun. It may be mentioned that due to lack of detailed study of sunspots periodicity as an important attribute of solar activity no precise relationship between sunspots and amount of insolation received at the earth's surface can be established. It may be further pointed out that the period of occurrence of sunspots also coincides with the occurrence of the intensity of **solar wind** and hence it becomes difficult to identify which event is responsible for increased solar radiation.

(5) Effects of the Atmosphere

The electromagnetic solar radiation waves or the incoming shortwave solar radiation waves have to pass through a mean sun-earth distance of 149.5 million kilometers covering the sun's and the earth's atmosphere and hence some portion of solar energy is lost (depleted) through the processes of reflection, diffusion, absorption, scattering etc. It may be mentioned that the amount of the depletion of solar energy depends upon the distance and the depletion is governed by the **inverse square law** which 'states that the area illuminated, and hence the intensity, varies with squared distance from the light or energy source. Thus, if the intensity of radiation at a given distance X is one unit, at a distance of 2 X the intensity of light will be one fourth that X' (Oliver and Hidore, 2003). This is why the earth receives only 1/2 billionth part of energy radiated from the sun.

Reflection

The portion of incident radiation (energy) reflected back from a surface of a body is called **albedo** or **reflection coefficient** or simiply **reflectivity**, which is presented in percentage. For example, 30 per cent albedo (reflectivity) means that a particular surface reflects 30 per cent of total incident energy and absorbs only 70 per cent of total incident energy. The albedo or reflectivity depends on the nature of the surface of the receiving body (e.g. snow-covered, bare rocks, ploughed fields, vegetation cover, cloud cover, water surface etc.). Reflectivity (albedo) is also controlled by the angle of the sun with the earth's surface. Verticality of the sun (90^0) allows minimum reflection while horizontality of the sun (0^0 to 5^0) causes maximum relection from the earth surface. Thus, albedo varies from surface to surface and from morning to evening and from season to season.

Various data of albedo derived so far indicate the earth's albedo as 30 per cent, though it varies between 29 and 34 per cent (including the energy reflected through the mechanism of diffuse reflection by dust particles, water molecules etc. from cloud surface and from the earth's surface). The albedo of the other planet has also been estimated e.g. Moon (7%), Mercury (6%), Mars (16%), Venus (76%), and the remaining other planets (73% to 94%). Table 3.5 depicts albedo of different types of surfaces of the earth's surface.

Table 3.5 : Albedo of different types of earth surfaces to solar radiation (in percentage)

Types of surfaces	Per cent	Types of surfaces	Per cent
Planet Earth	30	**Water Surface**	
Snow Cover		(angle of sun's inclination)	
(a) fresh snow	75-95	(a) near the horizon (0^0)	99 +
(b) old snow	30-40	(b) 10^0	35
Cloud cover		(c) 30^0	06
(a) cumulonimbus	70-80	(d) 50^0	2.5
(b) stratocumulus	25-50	(e) 90^0	2
Forest cover (average)	5-10	Green field crops	3-15
(a) deciduous forest	10-20	Dry ploughed field	5-25
(b) coniferous forest	5-15	Desert areas (sands)	25-30
Dry earth (surface)	1-25	Wet earth (surface)	10

Diffusion or diffuse reflection

The scattering of incoming electromagnetic solar radiation waves by dust particles and molecules of water vapour (clouds), when the diameter of these particles is larger than the wavelengths of incoming solar radiation, is called **diffuse reflection** which sends some portion of incoming solar energy back to space while some portion remains in the lower atmosphere. The diffused and scattered solar energy present in the lower atmosphere enables us to see even the dark portion of the moon. One can also see (if not suffering from cataract) even in the pitch darkness of the night. It may be mentioned that diffuse reflection is non-selective in nature and hence different colours of solar beams are not separated during diffuse reflection and hence diffused light remains white. This is the reason that the sun under cover of thin clouds and fog appears white. Some portion of scattered and diffused solar energy reaches the ground surface. Such diffused energy is called **diffuse blue light of the sky** or **diffuse day light.**

Absorption

Absorption refers to the retaining of a portion of incident energy (radiation) by a substance and its conversion into heat energy (sensible heat). Thus, absorption raises the temperature of the absorbing substance or body. The absorption of incoming solar radiation is selective in nature and is effected by water vapour, different gases (mainly oxygen, nitrogen and ozone), haze, smoke, some dust particles etc. Water vapour is by far the most effective absorber of the wavelengths of incoming solar radiation waves ranging between 0.9 micron and 2.1 microns. Water vapour is a potent absorber of infrared radiation waves of electromagnetic solar radiation and longwave terrestrial radiation but it becomes transparent to shortwave ultraviolet solar radiation and hence no absorption of incoming shortwave ultraviolet solar radiation waves. On the other hand, nitrogen and oxygen gases absorb ultraviolet solar radiation waves of shorter wavelength (less than 0.29 micrometer) while ozone absorbs ultraviolet solar rays of still shorter wavelengths in 3 spectral bands e.g. (i) 0.20-0.31 μm, (ii) 0.31-0.35 μm, and (iii) 0.45-0.85 μm. It may be mentioned that oxygen, nitrogen, ozone and water vapour act as an **atmospheric window** for the spectrum of visible lights (ranging in wavelengths from 0.4 to 0.7 micron) of incoming solar radiation because the visible lights are not absorbed by these gases and hence they escape to reach the earth's surface.

Scattering

The diffusion of a portion of incoming solar radiation in different directions by particulate matter (dust particles) and molecules of gases in the atmosphere is called the **process of scattering.** Lord Rayleigh (1842-1919) studied the process of scattering of solar radiation and its multi-facet effects which is known as **Rayleigh scattering.** The process of scattering is selective because it depends on the ratio between the diameter of the invisible dust particles and gas molecules and the wavelengths of radiation waves. In general, the process of scattering becomes effective when the diameters of the dust particles and gas molecules are smaller than the wavelengths of solar radiation waves. The **law of scattering** states that 'the amount of scatter is inversely proportional to the fourth power of the wavelengths. This means that in a given set of conditions, the shorter wavelengths scatter more readily than does long wave radiations. (Oliver and Hidore, 2003). This can be explained with an example, if the wavelength of a radiation wave is 0.4 micrometer and that of the other radiation wave is 0.8 micrometer, then the amount of scattered energy by the longer wavelength (0.8 micrometer) would be only one sixteenth of the shorter wavelength (0.4 micrometer).

The **second law of scatter** as developed by Gustave Mie in 1908 'states that molecules that have a larger ratio of diameter to wavelengths than those that give rise to Rayleigh scattering results in the scattering of light at all wavelengths. More light scatters in a forward or continuing direction than in a backward direction' (Oliver and Hidore, 2003). The amount of scattering of radiation waves in the spectrum of visible light decreases from increasing wavelengths of violet rays (0.4 - 0.43 micron), blue rays (0.43 - 0.49 micron), green rays (0.49-0.53 micron), yellow rays (0.53-0.58 micron), and red rays (0.58 - 0.70 micron). Thus, the sequence of scattering of visible lights while entering the earth's atmosphere becomes violet rays (first to be scattered), blue rays, green rays, yellow rays, and red rays (the last to be scattered). The **Rayleigh scattering** explains the different colours of the sky at different times. Blue light of the incoming shorter wavelengths of visible light spectrum is more scattered than red light and hence the sky looks blue in colour. The picturesque reddish and orange hue of the sky during sunrise (dawn) and sunset (twilight) is the result of scattering of all colour spectra except red and orange because at the time of sunrise and sunset the oblique rays with very low angle have to pass through the longest path of the atmosphere.

3.7 HEAT BUDGET (ENERGY BALANCE)

'The total solar radiation reaching a horizontal surface on the ground is called **global radiation.** It comprises the direct shortwave radiation from the sun, plus the diffuse radiation scattered by the atmosphere' (J.E. Hobbs, 1980). On an average, there is supposed to exist heat balance between the amount of solar radiation received by the earth's surface and its atmosphere and the amount of heat lost by the outgoing terrestrial longwave radiation from the earth's surface and loss of heat from the atmosphere. It may be pointed out that the solar energy received at the earth's surface is converted into heat energy which heats the outer surface of the earth. Thus, the earth after being heated also radiates energy in the form of longwave radiation. The radiation from the sun towards the earth and from the earth towards the atmosphere and the space is called **incoming shortwave solar radiation** (radiation from the sun) and **outgoing longwave terrestrial radiation** (from the earth) respectively.

The heat budget of the earth and the atmosphere displaying statement of receipt of solar radiation by the atmosphere and the earth's surface and the loss of energy by the earth and the atmosphere known as terrestrial radiation is also called **energy balance of the earth and the atmosphere** or **global radiation balance.**

On an average, the solar radiation reaching the outer boundary of the earth's atmosphere is estimated as follows :

total solar radiation
at the outer boundary of = solar constant × $\pi r^2/4\pi r^2$
the atmosphere

where r = radius of the earth

$4\pi r^2$ = surface area of the earth (both land and sea surfaces)

= 11×10^9 Jm^{-2} yr^{-1}

where J = Joules (the SI unit of energy, equivalent to 10^9 ergs and one watt-second)

10^9J = one GJ (G - giga means one billion)

J = Joules

The total incident solar radiation (energy) reaching the outer margin of earth's atmosphere is taken to be 100 units or 100 per cent for the explanation of heat/energy budget of the earth and the atmosphere. Two examples based on the data of (1) G.T. Trewartha, and (2) Oliver and Hidore are given below to explain the heat/energy budget (balance) :

1. Based on G.T. Trewartha

The total incident radiation at the outer margin of the earth's atmosphere is taken as 100 percent (fig. 3.6) and hence all the data used in the explanation of heat budget are in percentage.

(1) Incoming Shortwave Solar Radiation and the Heat Budget of the earth and the Atmosphere

The earth receives most of its energy from the sun through shortwave solar radiation. The solar energy radiated towards the earth's surface (1/2 billionth part of the total energy radiated from the outer surface (**photosphere**) of the sun which is equivalent to 23 trillion horse power) is taken as 100 per cent or 100 units. Out of the total incoming solar radiation entering the earth's atmosphere 35 per cent is sent back to space through scattering by dust particles (6%), reflection from the clouds (27%) and from the ground surface (2%) , 51 per cent is received by the earth's surface (received as direct radiation), and 14 per cent is absorbed by the atmospheric gases (ozone, oxygen etc.) and water vapour in different vertical zones of the atmosphere. The 51 per cent solar energy received by the earth comprises 34 per cent as direct solar radiation and 17 per cent as **diffuse day light.** The heat budget of the atmosphere comprises 48 per cent of solar radiation wherein 14 per cent is received through absorption of the shortwave incoming solar radiation and 34 per cent is received from the outgoing longwave terrestrial radiation.

Table 3.6 : Simplified global radiation/heat budget of the earth and the atmosphere (based on G .T. Trewartha)

(1) Incoming Shortwave Solar Radiation (in percentage)

Total energy reaching the top of the atmosphere		100
(A) The amount of solar radiation lost (depleted) during its passage through the atmosphere (a + b + c)		35
(a) reflected from the clouds	27	
(b) reflected from the ground surface	2	
(c) scattered and diffused by the dust particles and molecules of water vapour and sent back to space	6	
Remaining amount of solar radition available for the earth and its atmosphere (100-35)		65
(B) Terrestrial heat receipt (gained by the earth's surface) (a+b, 34 + 17 = 51)		51
(a) received through direct radiation	34	
(b) received through diffuse day light	17	
(C) Atmospheric heat receipt (gained by the atmosphere) from incoming solar radiation and outgoing terrestrial radiation , (a + b, 14 + 34)		48
(a) received through absorption of incoming solar radiation by ozone, CO_2, oxygen, water molecules etc.	14	
(b) received through outgoing terrestrial radiation	34	

(2) Outgoing Longwave Terrestrial Radiation and Heat Balance of the Earth and the Atmosphere

(A) Energy received by the earth		(B) Energy lost by the earth (a + b + c, 23 + 9 + 19 = 51)	51
Total energy received by the earth	51	(a) lost through direct radiation	23
		(b) spent in convection and turbulence	9
		(c) spent in evaporation	19

(3) Heat Balance of the Atmosphere

(A) Total energy received by the atmosphere	48	(B) Energy lost from the atmosphere to space	48
(a) received through absorption of incoming shortwave solar radiation	14		
(b) received through effective radiation from the earth	6		
(c) received through convection and turbulence	9		
(d) received as latent heat of condensation	19		
Total amount received by the atmosphere (a +b + c + d)	48	Total amount lost by the atmosphere	48

Atmospheric heat/energy balance = gain (48) – loss (48) = 0

Source of Data : G.T. Trewartha

(2) Outgoing Longwave Terrestrial Radiation and Heat Balance

After receiving energy from the sun (fig. 3.6) the earth also radiates energy out of its surface into the atmosphere through longwaves (fig. 3.6). The terrestrial radiation is also called **'effective radiation'** because it helps in heating the lower portion of the atmosphere. Twenty three per cent energy (out of 51% energy which the earth has gained from the sun) is lost through direct long-wave outgoing terrestrial radiation out of which 6 per cent is absorbed by the atmosphere and 17 per cent goes directly to the space. About 9 per cent of the terrestrial energy is spent in convection and turbulence and 19 per cent is spent through evaporation which is added to the atmosphere as latent heat of condensation. Thus, the total energy received by the atmosphere from the sun (14%) and the earth (34%) becomes 48 per cent which is reradiated to the space in one way or the other.

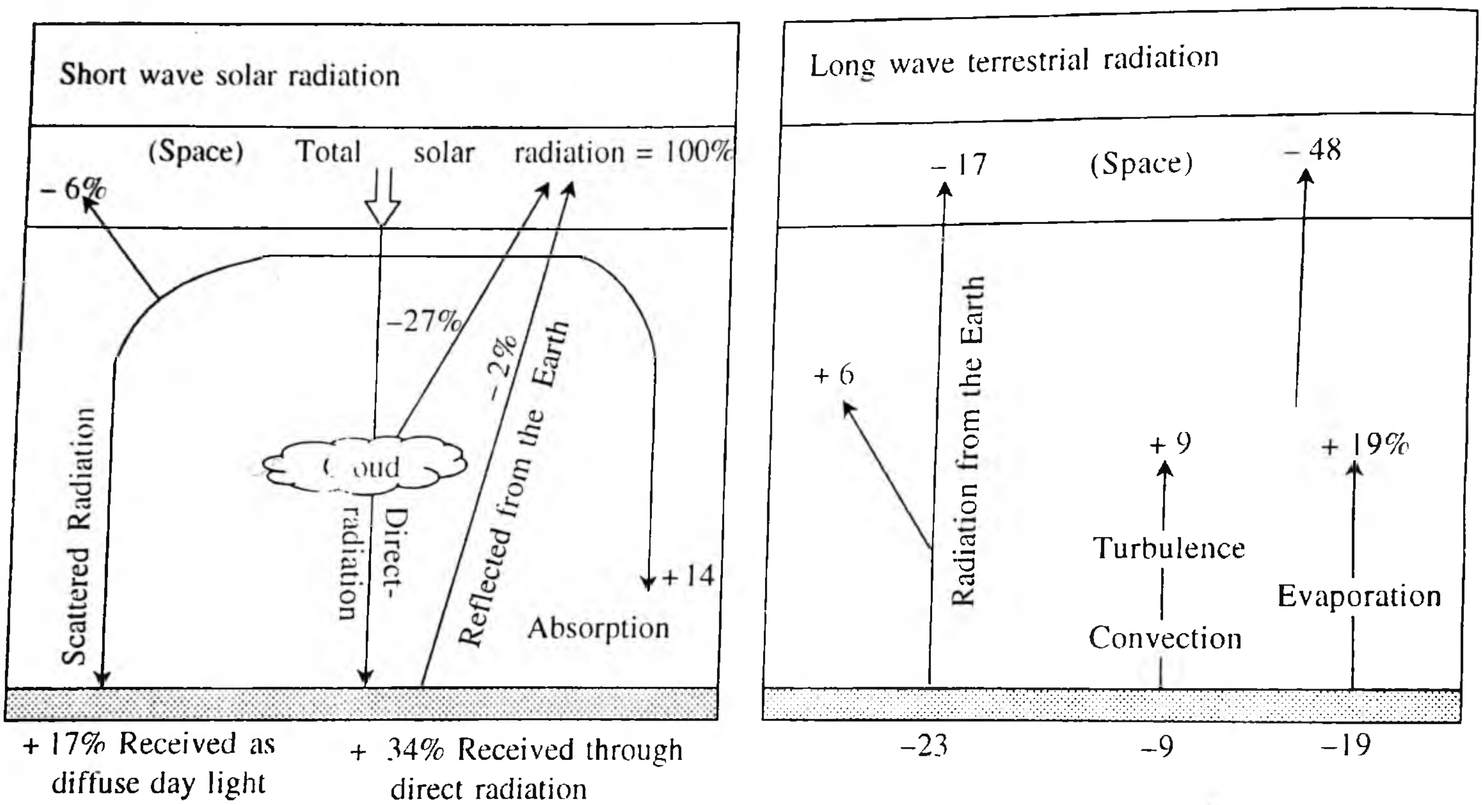


Fig. 3.6 : Radiation or heat balance of the earth and the atmosphere.

It may be mentioned, that the model of heat balance of the earth and the atmosphere as presented by G.T. Trewartha is over simplified because it does not consider the counter radiation (reradiation) of terrestrial radiation by the atmospheric vapour and clouds. It is significant to note that a sizeable portion of heat radiated from the earth is returned back to the earth's surface by water vapour, carbon dioxide etc. after absorbing terrestrial radiation. In fact, a part of ground radiation after being absorbed by the atmosphere is radiated back to the earth's surface. This process of reradiation of terrestrial heat energy from the atmosphere back to the earth's surface is called **counter-radiation** which is effected mainly by water vapour and atmospheric carbon dioxide. This mechanism known as greenhouse effect keeps the lower atmosphere and ground surface relatively warmer. Thus, it is imperative to include reradiation of terrestrial energy back to the earth's surface and again its escape to the atmosphere and the space in the consideration of heat/energy budget (balance) of the earth and the atmosphere. So, the second example of a comprehensive model of Oliver and Hidore is presented below.

2. Based on Oliver and Hidore

Oliver and Hidore have included counter-radiation by the atmospheric water vapour and gases in their model of heat/energy balance of the earth and the atmosphere and have referred counter-radiation as skyradiation. They have used units to explain the solar energy, earth energy and atmospheric energy wheerin one unit is equal to 1/100 of the total solar radiation which reaches the top of the earth's atmosphere. Table 3.7 explains the heat/energy balance of the earth and the atmosphere.

Table 3.7 : Energy (heat) balance (budget) of the Earth and the Atmosphere (number indicates unit)

Total Solar Radiation Reaching the outer Boundary of the Earth's Atmosphere		100
Gain of energy by the earth (inflow)		
(a) through direct radiation absorbed by the earth's surface	50	
(b) through longwave sky- radiation (counter-radiation or reradiation from the lower atmosphere) absorbed by the earth's surface)	96	
(A) **Total energy gained by the earth** (a + b, 50 + 96 = 146)	146	
Loss of energy from the earth's surface (outflow)		
(a) radiation loss in the form of sensible heat	12	
(b) longwave radiation from the earth's surface to the atmosphere	107	
(c) loss in the form of latent heat	20	
(d) longwave radiation from the earth's surface to space	7	
(B) **Total loss of energy from the earth** (a + b + c + d) (12 + 107 + 20 + 7)	146	
1. **Heat Balance of the Earth's surface** (A – B) (146 – 146 = 0)	146-146 = 0 (balance)	
Gain of heat energy by the atmosphere (inflow)		
(a) solar radiation directly absorbed by the atmosphere	20	
(b) latent heat of condensation	20	
(c) longwave radiation from the earth's surface	107	
(d) through conduction from the earth's surface as sensible heat	12	
(A) **Total energy gained by the atmosphere** (a + b + c + d) (20 + 20 + 107 + 12)	159	
Loss of heat energy from the atmosphere (outflow)		
(a) longwave radiation from the atmosphere to space	63	

(b) longwave sky radiation (counter - radiation to the earth's surface)	96
(B) Total loss of heat energy from the atmosphere (a+b, 63+96)	159
2. Heat Balance of the Atmosphere (A – B, 159 – 159 = 0)	159 – 159 = 0 (balance)
3. Heat Balance of the Earth-Atmosphere	
(A) **Inflow of energy**	
solar radiation reaching the outer limit of the atmosphere	100
Total inflow	100
(B) **Outflow of energy**	
(a) sent back to space by reflection and scattering	30
(b) longwave radiation from the atmosphere to space	63
(c) longwave radiation from the earth's surface to space	7
Total outflow (a + b + c, 30 + 63 + 7)	100

Source of Data : Oliver and Hidore, 2003

It is evident from table 3.7 that out of the total solar radiation (100 units) reaching the outer limit of the earth's atmosphere 30 units are sent back to space by the atmosphere through the processes of reflection and scattering while 7 units are sent back to space from the earth's surface as direct longwave radiation. Thus, 37 units (30+7) of incoming solar radiation, sent back to space by the atmosphere and the earth's surface, are of no use in heating the earth's surface and the atmosphere. Only 63 units (100-37) of energy are available to the earth's surface and the atmosphere.

The inflow of solar radiation to the earth surface comprises 146 units of energy which are received through direct solar radiation and scattered energy (50 units) and through counter-radiation or sky radiation from the atmosphere (due to greenhouse effect) (96 units). Thus, the total gain of solar radiation by the earth's surface becomes 146 units. The heat energy received by the earth's surface (146 units) is spent in evapotranspiration (20 units), conduction (as sensible heat, 12 units), direct radiation to the atmosphere (107 units) and the space (7 units). Thus, the total loss of energy from the earth's surface becomes 146 units (20 + 12 + 7 + 107 = 146 units). This demonstrates a steady state balance of heat energy of the earth's surface (gain of 146 units - loss of 146 units = 0, balance).

The atmosphere receives 159 units of heat energy comprising 20 units through direct absorption of incoming solar radiation by atmospheric gases (mainly carbon dioxide and ozone) and water vapour, another 20 units from condensation and latent heat, 107 units from longwave radiation from the earth's surface and 12 units through conduction (sensible heat) from the earth's surface. Thus, the total gain of heat energy by the earth's atmosphere becomes 159 units. The heat energy from the atmosphere is lost through (i) longwave radiation of 63 units to space and (ii) longwave sky radiation (counter-radiation) of 96 units to earth's surface. Thus, total loss of heat energy from the atmosphere becomes 159 units (63 + 96 = 159 units). This demonstrates balance between the gain of heat energy (159 units) and loss of heat energy (159 units) from the atmosphere.

The 100 units of incoming solar radiation is balanced by 30 units of energy sent back to space by scattering and reflection by the atmosphere, 63 units sent back to space by atmospheric longwave radiation and 7 units sent back to space from the earth's surface (30 + 63+7 = 100 units).

Oliver and Hidore (2003) maintain that ' the earth is in a steady-state balance of incoming and outgoing energy. The temperature (average) of the earth undergoes small changes, but the mean temperature stays nearly the same. It varies only slightly around 15°C (59°F) at the surface, although there are daily, seasonal and year to year changes...... There is a built-in-storage mechanism known as the greenhouse effect that raises the temperature such that life can exist' (Oliver and Hidore, 2003).

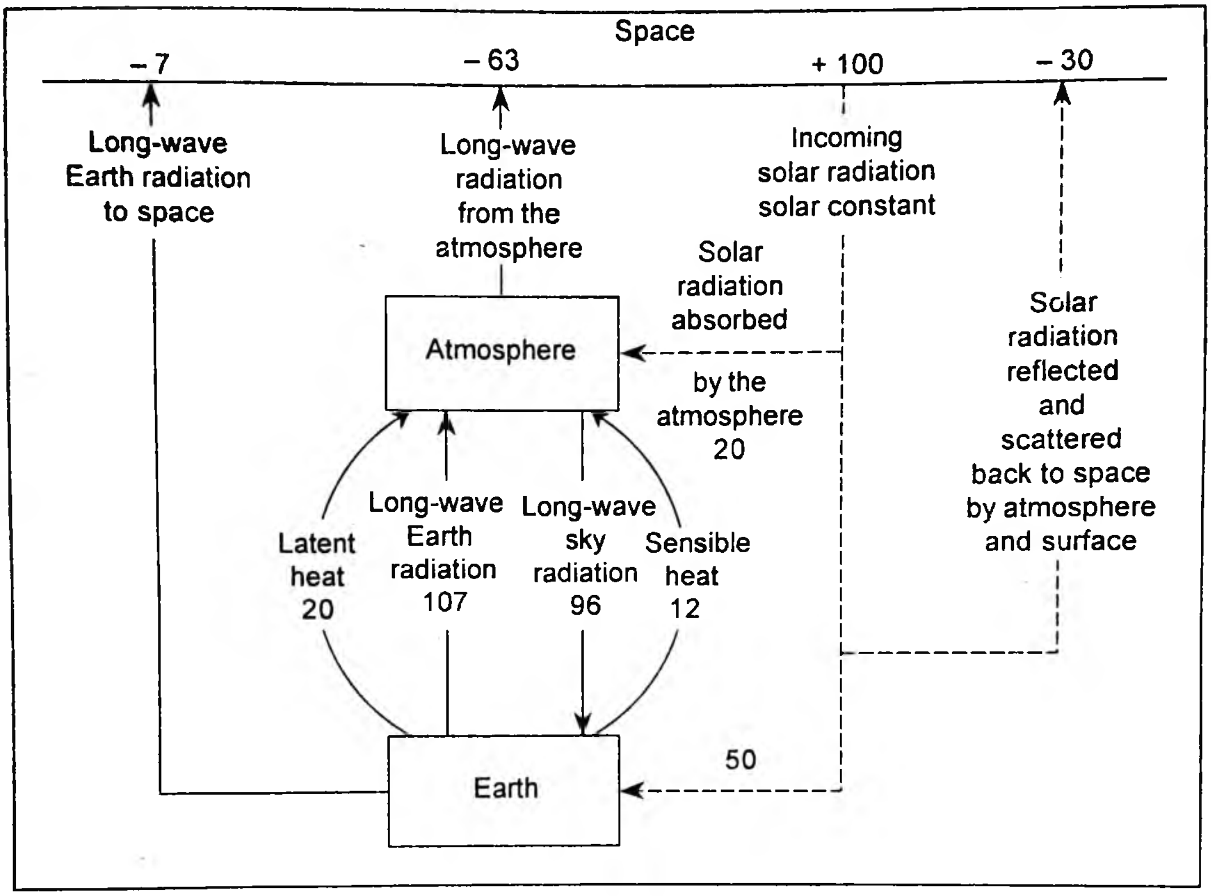


Fig. 3.7 : Heat (energy) balance of the earth and the atmosphere. After-J.E. Oliver and J.J. Hidore, 2003.

3.8 NET RADIATION AND LATITUDINAL HEAT BALANCE

The difference between all incoming solar energy and all outgoing terrestrial energy by both shortwave and longwave radiation is called **net radiation**. It is apparent from the aforesaid discussion that the net radiation from the whole globe is at least theoretically zero but this is far from truth if we look at the regional distribution of insolation. There are some places where the receipt of solar

Table 3.8 : Annual Meridional Heat Transport

Latitudes (northern hemisphere)	Heat transport (kilo calories per year × 10^9)	Latitudes (northern hemisphere)	Heat transport (kilocalories per year × 10^9)
90	0.00	40	3.91
80	0.35	30	3.56
70	1.25	20	
60	2.40	10	2.54
50	3.40	0 (equator)	–0.26

Source : W.E. Sellers, 1965

energy is more than the energy lost because the solar energy comes at faster rate than the terrestrial energy goes out. Similarly, in some areas the loss of energy through outgoing terrestrial radiation is faster than the gain of incoming solar radiation. This mechanism results in the development of areas of **energy surplus** (where incoming solar radiation exceeds outgoing terrestrial radiation) **and energy deficit** (where outgoing terrestrial radiation exceeds incoming solar radiation).

The energy surplus and energy deficit areas may be identified and studied at two levels viz. (i) **at the earth's surface**, and (ii) **in the atmosphere**, latitudinal base being common in both the cases. .(i) The distribution of net radiation at the earth's surface from equator towards the poles shows that (a) there is large **energy surplus area** between the zones of 20°N and 20°S where energy gain from the incoming solar radiation is more than the loss of energy through outgoing longwave terrestrial radiation and the annual surplus energy amounts to 100 kilo langleys per year; (b) net radiation rapidly decreases from the energy surplus areas of low latitudes towards mid-latitudes; (c) net radiation becomes practically zero near 70° latitude in the northern and southern hemispheres, and (d) the polar areas are the zones of perennial **energy deficit.**

(ii) The latitudinal distribution of net radiation in the atmosphere shows that 'the atmosphere is itself a net loser of radiation at all latitudes' (J.E. Hobbs, 1980). Thus, the atmosphere is the zone of perennial energy deficit because the deficit of energy always exceeds 60 kilo langleys per year. If the data of net radiation of both, the earth's surface and the atmosphere, are combined together, the net radiation value for the combined '**earth's surface--atmosphere system**' may be calculated. Based on the combined data the following energy zones are identified, (a) large region of surplus radiation extending between 40°N and 30°S latitudes, (b) northern high- latitudes of deficit radiation and (c) southern high- latitudes of deficit radiation' (A. N. Strahler, 1978).

It means that "there must exist a two-way heat transfer; from the earth's surface to the atmosphere and from the equator to the poles" (J.E. Hobbs, 1980). This can be achieved if heat is transported from the earth's surface to the atmosphere and from the tropical and subtropical areas of surplus radiation to the high latitude zones of deficit radiation. The transport of heat from equatorial area towards the poles is called '**meridional transport of heat**'.

The meridional transport of heat energy in the form of **sensible heat** is accomplished by the atmospheric circulation and ocean currents which transport heat energy from the 'low latitude surplus energy areas' to the 'high latitude deficit energy areas.' The vertical transport of heat in the atmosphere is accomplished by ascending air in the form of sensible heat and latent heat. Table 3.8 portrays latitudinal transfer of sensible heat.

3.9 HUMAN INFLUENCE ON RADIATION (HEAT) BALANCE

Radiation balance or heat balance is very important for biological communities including both plants and animals together with micro-organisms and man. The changes in the radiation balance may be grouped in two classes viz. (i) **natural changes** and (ii) **man-induced changes** or **anthropogenic changes**. Natural changes in the global radiation/heat balance take place due to (i) periodic changes in **solar constant**, (ii) alteration of the transparency of the atmosphere through the addition of enormous quantity of dust and smoke to the atmosphere ejected through volcanic eruption (volcanic dust in the atmosphere reduces the shortwave solar radiation reaching the earth's surface), (iii) the global climate changes due to movement of continents and ocean basins in relation to poles due to the mechanism of plate tectonics.

Besides these and many more natural changes of solar radiation balance and weather and climate, man is also capable of changing and altering the radiation balance and weather and climate from local through regional to global scales.

(i) **At local scale:** man has largely been responsible to affect and modify the radiation balance through his activities e.g. increasing urbanisation and expanding industrialisation. Increasing urbanisation means covering of more and more bare ground surface by 'pucca structure' which sets off a chain of effects and counter-effects viz. sprawling urban areas change the thermal properties of the ground surface, reduce the albedo, change the aerodynamic character of the surface, alter the pattern of air circulation, lower the speed of wind, reduce total insolation, increase mean annual temperature and create **heat island** in the city centre and **pollution dome** in the lower atmosphere above the major urban centres. Expanding industrialization causes addition of enormous quantity of dust and gases (mostly toxic and piosonous) through **human volcanoes** (factories) to the lower atmosphere and thus changes the heat balance at local level which is also extended to regional level in the highly urbanised and industrialized countries where several industries of large industrial belts intensify the greenhouse effects.

Two case studies of Budapest city (Hungary) and Hamilton (Ontario, Canada) industrial area may illustrate the influences of urbanisation and industrialization on radiation balance at local level. D. Greenland (1981) has reported that there is decrease in the annual mean incoming shortwave solar radiation upto the tune of 7 to 8 per cent near the city centre of Budapest whereas F. Probald (1972) has maintained that the decrease in the incoming solar radiation in the city centre of Budapest during winter months (November to March) caused by polluted air over the city rises to 15 per cent or even more. The conversion of larger ground area into 'pucca structure' has markedly reduced the albedo of the city. This reduced albedo compensates the loss of reduced incoming solar radiation because decrease in surface albedo means decrease in the loss of heat through reflection from the surface. The study of Budapest city further reveals that the longwave radiation from the surface has also increased but the effect of this process is negated because of increased longwave radiation from the atmosphere back to the surface as a result of **counter-radiation** which is because of accumulating greenhouse gases (carbon dioxide) in the lower atmosphere over the city of Budapest. W.R. Rouse and J.G. McCutcheon (1972) have reported similar situation in the industrial city of Hamilton as they have reported an overall decrease of 9% to 17% in the incoming solar radiation and 11% increase in the longwave downward radiation from the atmosphere as counter radiation. D. Greenland (1981) has concluded that 'it is interesting to note, however, that the changes in the various radiant flows tend to balance each other out, leaving the net radiation of the urban surface rather similar to that of the surrounding surfaces. The effect of increased longwave radiation countering decreased shortwave radiation was seen in both Budapest and Hamilton.'

(ii) The change of radiation balance at **regional level** is caused due to weather modification programmes viz. cloud seeding to induce more precipitation, prevention of hailstorms, dispersion and diversion of clouds and other human activities like melting of ice through the use of carbon-black dusts on the ice-covered surface, diversion of atmospheric storms etc. Land use changes affect the radiation balance in a variety of ways at regional scale. According to the report of SMIC (1971, Study of Man's Impact on Climate, Massachusetts, U.S.A.) 18 to 20 per cent of land surface of the earth has been changed by man for agricultural purposes. The change in land use, mainly through deforestation for increase in cropland, changes the albedo (reflection of incoming solar radiation) of the earth's surface which then changes the radiation balance. According to the report of SMIC the clearance of coniferous forest (of which the albedo is 12 per cent) or decidous forest (albedo being 18 per cent) for agricultural land (albedo being 20 per cent) results in increase of surface albedo and hence decrease in the absorption of solar radiation. Thus land use changes from forest cover to agricultural land reduce the net radiation balance. The irrigated land in dry areas reduces albedo by 5 per cent in comparison to the surrounding desert areas.

(iii) The radiation balance at **global level** is changed in the following manner- (i) Emission of carbon dioxide through the burning of hydrocarbon fuels (coal, petroleum, natural gas etc.) and its concentration in the atmosphere raises the temperature of the earth's surface by retarding the loss of heat from the ground surface through outgoing longwave terrestrial radiation, and (ii) The introduction of chlorofluorocarbon and nitrogen oxides in the stratosphere depletes ozone layer and thus allows more ultraviolet solar rays to reach the earth's surface. This results in the increase of incoming shortwave solar radiation which raises the temperature of the ground surface and the lower atmosphere. This in turn changes the heat balance of the earth and its atmosphere.

It may be pointed out that the effects of human activities in changing the radiation balance are so complex and involve negative feedback mechanisms that it is not easy to build any adequate model which can well explain the impact of human activities on radiation balance. Any change in radiation balance effected by man would certainly cause changes and alteration in other environmental processes because radiation balance is a key factor to weather and climate of the planet earth. Any change in the natural state of radiation balance may change the weather and climatic conditions from local through regional to global levels which in turn would affect the hydrological cycle and processes, flow of sediments and chemical elements in the biospheric ecosystem and food chains affecting all forms of life in the biosphere.

3.10 IMPORTANT DEFINITIONS

Albedo : The portion of incident radiation (energy) reflected back from a surface of a body is called albedo or reflection coefficient or simply reflectivity.

Absorption : Absorption refers to the retaining of a portion of incident energy (radiation) by a substance and its conversion into heat energy (sensible heat).

Atmospheric window : Atmospheric window refers to any of the wavelengths at which electromagnetic solar radiation can pass through the atmosphere and reach the earth's surface.

Auroral lights : The lights in the sky over the polar areas caused by the mixing of enormous amount of atomic particles released by solar flares with solar wind and reaching the earth's polar magnetic zone are called auroral lights. These are of two types e.g. aurora borealis and aurora australis. Aurora means dawn while borealis and australis mean northern and southern respectively. Auroras are cosmic glowing lights produced by a stream of electrons discharged from the sun's surface due to magnetic storms.

Chromosphere : A thin layer of burning gases around photosphere but about 1 million kilometers away from the sun is called chromosphere.

Corona : The outermost zone of the sun's atmosphere characterized by very hot (having a temperature of one to two million degree Kelvin) and rarefied gases is called corona.

Counter-radiation : The process of reradiation of terrestrial heat by the atmosphere back to the earth's surface is called counter-radiation or reradiation or sky radiation.

Diffuse blue light : The portion of scattered and diffused solar radiation reaching the earth's surface is called diffuse blue light or **diffuse day light.**

Diffuse reflection : The scattering of incident radiation waves by dust particles and molecules of water vapour, when the diameter of these particles is larger than the wavelength of incident radiation waves, is called diffuse reflection which sends some portion of incident radiation back to space while some portion remains in the lower atmosphere.

Effective radiation : The longwave radiation from the earth's surface is called effective radiation because it helps in the heating of the lower atmosphere.

Faculae : The cool and hot spots within the photosphere of the sun are called faculae.

Insolation : The radiant energy received by the earth and its atmosphere from the sun is called insolation.

Inverse square law : related to the depletion of solar energy by the atmosphere 'states that the area illuminated, and hence intensity, varies with squared distance from the light of energy source.'

Law of scattering : states that 'the amount of scatter is inversely proportional to the fourth power of the wavelengths'.

Net radiation : is the difference between total incoming solar radiation and total outgoing terrestrial energy (radiation).

Photosphere : The bright outer surface of the sun is called photosphere because of the dominance of photons.

Photons : represent bundle of energy of burning gases within a 300-km thick outer surface of the sun.

Scattering: refers to the process of diffusion of a portion of incoming solar radiation in different directions by particulate matter (dust particles) and molecules of gases including vapour in the atmosphere.

Rayleigh scattering : refers to the process of scattering', its multi-faceted effects e.g. blue colour of the sky, red and orange colours during sunrise and sunset. The process was studied by Lord Rayleigh.

Solar wind : refers to a stream of electrons and protons released from the photosphere into chromosphere and corona of the sun.

Stefan- Boltzman law : states 'that flow or flux of radiation is proportional to the fourth power of the absolute temperature of the radiating body'.

Sunspots : are dark and cool areas within the photosphere of the sun and are surrounded by chromosphere.

Wien's displacement law : 'states that the wavelength of maximum radiation is inversely proportional to the absolute temperature of the emitting body.'

4

TEMPERATURE

4.1 INTRODUCTION

Here, temperature means atmospheric temperature. Indirectly the sun is the major source of atmospheric temperature. In fact, the atmosphere receives very low amount of heat energy from the sun as it receives most of its energy from the longwave terrestrial radiation. Atmosphere receives energy from the sun and the earth in different ways. On an average, the heating and cooling of the atmosphere is accomplished through direct solar radiation and through transfer of energy from the earth through the processes of conduction, convection and radiation. It may be pointed out that **'heat' and 'temperature'** generally appear synonym to common people but these two terms differ considerably as regards their real meaning. Heat is a form of energy while temperature denotes the intensity of hotness or coldness of any substance. In other words, heat denotes the quantity of energy present in any substance while temperature refers to the degree of hotness of that substance or measure of the quantity of energy or heat per unit volume of the substance of a body. Thus, the temperature of any substance may be raised or lowered with the addition or substraction of heat. The transfer of heat from one body to the other is accomplished through conduction, convection, and radiation.

Temperature of a substance also determines the direction of flow of energy of heat. There is outflow of heat from a body having higher temperature towards a body having relatively low temperature. In this way temperature is also a measure of kinetic energy. Air temperature of a unit volume of air at a given time is measured in degree F (Fahrenheit scale) or degree C (Celsius or centrigrade scale) by thermometer. The feezing point (ice point) for Fahrenheit and Celsius scales are 32^0 and 0^0 respectively.

4.2 TRANSFER OF HEAT ENERGY

The transfer of heat energy from a body or a system, having highest temperature, to the other body or system having lowest temperature, is accomplished through the processes of radiation, conduction and convection. The transmission of heat energy from one body to the other body without any medium is called radiation. The energy from the photosphere of the sun is transmitted to the earth's surface by electromagnetic radiation waves. The earth after getting heated from the electromagnetic solar radiation also radiates heat from its outer surface in the form of longwaves. The atmosphere receives major part of longwave terrestrial radiation and reradiates it back to the earth's surface as counter-radiation. Thus, the process of radiation from the sun to the earth's surface, from the earth's surface to the atmosphere, from the atmosphere back to the earth's surface is very much complicated. Some portion of heat energy from the earth's surface is transmitted to the atmosphere through the molecules of lower atmosphere. This process of transfer of heat energy is called **conduction**. The third process of transfer of energy from one body to the other body is **convection** which involves heat transfer through the movement of a mass of substance (in the case of earth-atmosphere system the mass of substance is air) from one place to another place.

4.3 HEATING AND COOLING OF THE ATMOSPHERE

The solar energy received by the earth's surface including both ground surface and water surface (of the seas and the oceans) is converted into heat energy in the form of **sensible heat** (heat that can be measured by thermometer) and is temporarily stored. This stored energy is radiated from the ground and water surface in the form of longwaves into the atmosphere. The process of radiation of heat energy from the earth's surface is called ground radiation (including radiation from both, ground surface and water surface). The part of this ground radiation after being absorbed by the atmosphere is again radiated back to the earth's surface. This process of radiation of terrestrial heat energy from the atmosphere back to the earth's surface is called counter-radiation. The counter-radiation is effected mainly by water vapour and atmospheric carbon dioxide. The heating and cooling of the atmosphere is accomplished through the processes of direct absorption of solar radiation, conduction, terrestrial radiation, convection, condensation, adiabatic mechanism etc.

1. Heating of the Atmosphere by Direct Solar Insolation

The heat energy is radiated from the outer surface of the sun (photosphere) in the form of longwaves. The atmosphere absorbs 14 per cent of incoming shortwave solar radiation through ozone, oxygen, water vapour etc. present therein. Seven per cent of this energy is spread in the lower atmosphere up to the height of 2 km. It is apparent that this amount is too low to heat the atmosphere significantly.

2. Conduction

The transfer of heat through the molecules of matter in any body is called conduction. The transfer of heat under the process of conduction may be accomplished in two ways viz. (i) from one part of a body to the other part of the same body, and (ii) from one body to the other touching body. Conduction may be effective only when there is difference in temperatures in different parts of a single body or in two bodies and the process continues till the temperatures of all parts of a body or of two touching bodies become same. It is obvious that heat moves from warmer body to the cooler body through molecular movement. The rate of transfer of heat through molecular movement depends on the heat conductivity of the substance. The substance or a body which allows transfer of heat through conduction at a very fast rate is called **good conductor of heat** while the substance or a body which retards conduction of heat is called **bad or poor conductor of heat.** Metal is a good conductor of heat while air is very poor conductor of heat. The earth's surface is heated during daytime after receiving solar radiation. The air coming in contact with the warmer ground surface is also heated because of transfer of heat (conduction of heat) from the ground surface through the molecules to the air. Since air is very poor conductor of heat and hence the transfer of heat from the ground surface through conduction is effective only upto a few metres in the lower atmosphere and thus the lower atmosphere is heated. The ground surface becomes colder than the air above during winter nights and thus heat is transferred from the lower portion of the atmosphere to the ground surface and thus the atmosphere is cooled.

3. Terrestrial Radiation

The process of transfer of heat from one body to the other body without the aid of a material medium (e.g. solid, liquid or gas) is called radiation. There are two basic laws which govern the nature of flow of heat energy through radiation.

(a) **Wien's displacement law** 'states that the wavelength of the radiation is inversely proportional to the absolute temperature of the emitting body'.

(b) **Stefan-Boltzmann law** 'states that flow, or flux of radiation is proportional to the fourth power of the absolute temperature of the radiating body'.

The earth's surface after receiving insolation from the sun through shortwave electromagnetic radiation gets heated and radiates heat to the atmosphere in the form of longwave or infrared radiation throughout 24 hours. It may be remembered that the atmosphere is more or less transparent for incoming shortwave solar radiation but it absorbs more than 90 per cent of outgoing longwave terrestrial radiation through water vapour, carbon dioxide, ozone etc. Thus, the terrestrial radiation is the most important source of heating of the atmosphere. The process of radiation of heat from the earth's surface is called **ground radiation.** The part of this ground radiation after being absorbed by the atmosphere is radiated back to the earth's surface. This process of radiation of terrestrial heat energy from the atmosphere back to the earth's surface is called **counter-radiation** which is effected mainly by water vapour and atmospheric carbon dioxide. This mechanism known as **greenhouse effect** keeps the lower atmosphere and the ground surface relatively warmer. Thus, the atmosphere acts as window glasspane which allows the shortwave solar radiation to come in and prevent the longwave terrestrial radiation to escape into space.

It is obvious that the increase in the concentration of carbon dioxide in the atmosphere will increase the greenhouse effect and thus the temperature of the earth's surface would increase. It may be pointed out that carbon dioxide also absorbs longwave terrestrial radiation and helps in keeping the lower atmosphere and the ground surface warmer. Water vapour absorbs both the incoming shortwave solar radiation and outgoing longwave terrestrial radiation. Since most of water vapour is concentrated in the lower atmosphere (90 per cent of the total atmospheric water vapour is found upto the height of 5 km in the lower atmosphere) and hence both the incoming solar radiation and outgoing terrestrial radiation increase with increasing height. This is the reason that high mountains are called **radiation windows.**

4. Convection

The transfer of heat energy through the movement of a mass of substance from one place to another place is called convection. The process of convection becomes effective only in fluids or gases because their internal mass motion activates convection of heat energy. The earth's surface gets heated after receiving heat energy (insolation) from the sun. Consequently, the air coming in contact with the warmer earth's surface also gets heated and expands in volume. Thus, warmer air becomes lighter and rises upward and a vertical circulation of air is set in. Conversely, the relatively colder air aloft becomes heavier because of contraction in volume and thus descends to reach the earth's surface. The descending air is warmed because of dry adiabatic rate and warm ground surface. This warm air again ascends because of increase in volume and decrease in density. The whole mechanism of ascent of warmer air and descent of colder air generates convection currents in the lower atmosphere. This convective mechanism transports heat from the ground surface to the atmosphere and thus helps in the heating of the lower atmosphere. Similarly, horizontal convection currents are also generated on the ground surface.

5. Adiabatic Heating and Cooling

The adiabatic heating and cooling of the atmosphere takes place through the ascent and descent of a parcel of air respectively. It is a general trend that temperature decreases with increasing height at the rate of 6.5°C per 1000 m or 3.6°F per 1000 feet. This rate of decrease of temperature with increasing height is called **normal lapse rate.** A definite ascending air with given volume and temperature expands due to decrease in pressure and thus cools. For example, an air with the volume of one cubic foot and air pressure of 1016 mb at sea level if rises to the height of 17,500 feet, its volume is doubled because of expansion. On the other hand, a descending air contracts and thus its volume decreases but its temperature increases. It is apparent that there is change in temperature of air due to ascent or descent but without addition or substraction of heat. Such type of change of temperature of air due to contraction or expansion of air is called **adiabatic change of temperature.**

Adiabatic change of temperature is of two types viz. (i) **dry adiabatic change** and (ii) **moist adiabatic change.** The temperature of unsaturated ascending air decreases with increasing height at the rate of 5.5°F per 1000 feet or 10°C per 1000 m. This type of change of temperature of unsaturated ascending or descending air is called dry adiabatic rate. It may be pointed out that if an air descends its temperature increases at the above mentioned rate. The rate of decrease of temperature of an ascending air beyond condensation level is lowered due to addition of latent heat of condensation to the air.

This is called moist adiabatic rate wherein temperature of a parcel of ascending air beyond condensation level decreases (and hence air cools) at the rate of 3°F per 1000 feet or 6°C per 1000 meters. This is also called retarded adiabatic rate and cooling. Conversely, the descending parcel of air contracts in volume due to increase of pressure and hence is warmed at the rate of 10°C per 1000 meters.

4.5 MEAN TEMPERATURES

All types of average temperatures *e.g.* monthly, seasonal and annual means, depend on daily temperatures and their averages. The earth receives energy (insolation) through the electromagnetic shortwaves radiated from the photosphere (outer surface of the sun) of the sun during day time. This radiant energy is transformed into heat. The earth's surface receives maximum energy at 12 noon but the maximum temperature never occurs at 12 noon because the transformation of solar energy into heat requires time. The energy received by the earth from solar radiation continues to exceed the energy lost by outgoing longwave radiation from the earth's surface from 6 A.M. to 2-4 P.M. Thus, the curve of air temperature also rises upto 4 P.M. This is why maximum temperature is recorded between 2 P.M.- 4 P.M. The highest temperature recorded within 24 hours is called **maximum daily temperature.** On the other hand, the loss of energy through longwave radiation from the earth's surface exceeds the energy received from the sun from 4 P.M. to the sunrise and hence there is gradual fall of the curve of temperature but the lowest (minimum) temperature is recorded between 4-5 A.M. instead of midnight. The lowest temperature within 24 hours is called **minimum daily temperature.** Thus, there is no coincidence between the time of maximum and minimum amount of insolation received from the sun and maximum and minimum temperatures of the air. This is called **lag of temperature.** The average of maximum and minimum temperatures within 24 hours is called **mean daily temperature.** Similarly, the mean of daily maximum and minimum temperatures of a month is called mean monthly maximum temperature and mean monthly minimum temperature. Mean of maximum and minimum temperatures of 12 months is called mean annual maximum and mean annual minimum temperature. The differences between the maximum and minimum temperatures of a day (24 hours) is called daily or diurnal range of temperature. Similarly, the differences between the monthly maximum and minimum temperatures on one hand and between annual maximum and minimum on the other hand are called monthly range and annual range of temperatures respectively.

4.6 RANGE OF TEMPERATURE

The difference between the highest and the lowest temperatures per unit time (a day, a month, a season or a year) at local, regional or global level is called range of temperature. Daily and annual ranges of temperature are more significant from weather and climate point of view though monthly and seasonal ranges of temperatures are also considered.

Diurnal Range of Temperature

The difference between the highest (maximum) and the lowest (minimum) temperatures of a day (24 hours) is called **diurnal or daily range of temperature** which depends on the daily cycle of heating and cooling of the earth's surface and the air above it. The heating of the earth's surface begins with the sunrise due to the receipt of solar radiation and the amount of insolation goes on increasing with rising sun and it becomes maximum when the sun is at the zenith (overhead). There is gradual transfer of heat from the surface through conduction to the layer of air, though very thin, which is just in touch with the earth's surface. It may be mentioned that if the summer day is characterized by clear sky (cloudless), calm air and sunny day, the transfer of heat in the air layer is exceedingly faster and hence a steep thermal gradient upto 20^{0}C between the lower and upper boundaries of 2-3 meter thick air layer is developed but if the day is cloudy and windy, a gentle thermal gradient develops because of slow rate of transfer of heat in the air upward. The inflow of incoming solar radiation starts decreasing after noon which is characterized by maximum insolation but temperature of the earth's surface and surface air continues to increase upto 4 P.M. The maximum temperature is generally recorded between 2-4 P.M. Thus, there is significant time lag between the time of maximum insolation (at 12 noon) and maximum temperature (between 2-4 P.M.). It is also significant that the equilibrium between incoming solar radiation and outgoing terrestrial radiation does not occur at the time of maximum temperature, rather it (equilibrium) occurs about 90 minutes before sunset. It may be mentioned that there is also lag in daily maximum temperature. In other words, daily maximum temperature varies between 2 to 4 P.M. depending on the nature of sky (clouded or cloudless), nature of air movement (still air or movement in air), moisture condition (moist day or dry day) etc. The time lag of maximum temperature in a weather condition of still and dry air, cloudless sky, thin aerosol, becomes larger but it becomes minimum when the weather is characterized by windy and moist air, cloudy sky and thick aerosol.

The ground surface and the surface air begin to cool after sunset because the loss of energy by outgoing longwave terrestrial radiation far exceeds the incoming shortwave solar radiation. Thus, the air coming in touch with the ground surface is also cooled but the temperature increases above cool air due to transfer of heat from the ground surface to the lower layer of troposphere. The cooling of ground surface depends on the length of night, moisture content in the air and the movement of air. The cooling becomes rapid when the sky is clear, velocity of wind is high, air is dry due to minimum moisture content and the night is of longer duration but the cooling is retarded when the air movement is very slow i.e. calm air, sky is clouded, moisture content in the air is high. The coolest ground surface and hence lowest (minimum) temperature of a day (within 24 hours) is recorded between 4-5 in the early morning. This mechanism of heating and cooling of the earth's surface and boundary layer of air within 24 hours is called **daily cycle of air temperature.**

It is, thus, evident that daily range of temperature is the net result of daily heating and cooling during day time and night time respectively. There are periodic, non-periodic, seasonal, annual, local and regional variations in daily range of temperatures depending on the conditions of sky (whether clear or cloudy), air movement (whether still air or high velocity wind), moisture content in the air (whether dry air or moist air) etc. Overcast sky, moist air, and significant air movement cause low daily range of temperature while clear sky, dry and calm air are responsible for high daily range. Even there is a spatial variation is diurnal range of temperature as it becomes high in low latitudes (equatorial zone) but becomes very low in high latitudes (polar areas). Similarly, there is low daily range of temperature over sea surface in comparison to ground surface. Daily range of temperature increases with increasing altitudes because air density decreases upward.

In the equatorial region daily range of temperature exceeds annual range of temperature as daily range of temperature usually varies between 5^0-10^{0}C which is obviously much more than annual range of 2^0-3^{0}C. The island areas record still low annual range of temperature (0.5-1.0^{0}C). In tropical hot deserts daily range of temperature varies between 22^0 to 28^{0}C while annual range remains between 17^0 to 22C. Very high daily and annual range of temperatures is because of open and clear skies, vegetation free ground surface, very low relative humidity, dominance of sands etc.. In the polar areas daily range of temperature is very low, some time it reaches zero.

Annual Range of Temperature

The difference between the highest (warmest month) and the lowest (coldest month) temperatures of a year is called annual range of temperature. Like daily lag of temperature there is also seasonal lag of temperature. In other wards, there is no coincidence in the month of maximum insolation and the month of maximum temperature. Similarly, the month of minimum insolation does not coincide with the month of minimum (lowest) temperature. For example, the maximum insolation is received at the earth's surface in the months of June and December in the northern and the southern hemispheres respectively, but the maximum (highest) temperature is recorded in the months of July (northern hemisphere) and January (southern hemisphere). Similarly, the minimum (lowest) insolation is received in the months of December (northern hemisphere) and June (southern hemisphere) but the minimum (lowest) temperature (coldest month) is recorded in the months of January (northern hemisphere) and July (southern hemisphere). It is evident that there is a lag of one month between the month of maximum insolation and the hottest month (maximum temperature) and between the month of minimum insolation and coldest month. This is called **seasonal temperature lag.**

Table 4.1 : Seasonal Temperature lag (temperature in °C)

Location (Latitudes)	Average Temperature at Solstice		Average Monthly Temperature	
	June (max. insolation)	December (min. insolation)	Warmest month (July)	Coldest month (January)
30^0N (Charleston, USA)	26	11	28	10
40^0 N (Urbana, USA)	22	0	25	–1
41^0N (Naples, Italy)	22	11	25	9
43^0N (Moscow, Russia)	19	–6	21	–8
53^0N (Edmonton, Canada)	14	–8	17	–14

Source of Data : J.E. Oliver and J.J. Hidore, 2003.

The mean annual temperature range is characterized by spatial variations both horizontally and vertically. The annual temperature range, decreases from the equator poleward. Spatial variations in mean annual temperature range are noted even along the same latitude because of contrasting nature of land and sea surfaces. The continents record higher annual range than the oceans on the same latitude. The distance from the sea coast determines the magnitude of annual range. In other wards, the annual range increases from the coastal areas towards the inner parts of the continents. For example, mean annual range of temperature on the west coast of Europe along 60^0N latitude is around 20^0C while it becomes more than 56^0C in the western Siberia along the same latitude. The mean annual range varies along the same latitude on the eastern and western coasts of a continent. For example, along 40^0N latitude the eastern coast of North America records an annual range of 20^0C while it is only 8^0C on the western coast. This is because of the prevalence of Gulf Stream warm current along the eastern coast and the presence of cool California current on the western coast. The annual range considerably varies over oceans and continents in the Arctic Circle as the mean annual range of temperature is only 11^0C over North Atlantic Ocean (within Arctic Circle) while it becomes as large as 45^0C in Canadian Arctic Circle and more than 66^0C in the Siberian Arctic Circle. It is, thus, evident that the annual range of temperature is controlled by a host of factors e.g. distance from the equator (latitude), altitude (height from sea level), moisture content in the air (relative humidity), nature of sky (whether clear or clouded), distance from the sea coast, ocean currents, topography etc. The effects of these factors on annual range of temperature will be discussed later in this chapter.

4.7 DISTRIBUTION OF TEMPERATURE

The spatial and temporal distribution of temperatures is very significant because different types of weather, climates, vegetation zones, animals and human life etc., basically depend on the distribution of temperature, whether horizontal or vertical. The study of distribution of temperature is attempted in several ways viz. (i) temporal distribution, and (ii) spatial distribution. The spatial distribution is studied in two ways e.g. (a) vertical distribution, and (b) horizontal distribution of temperature. The horizontal distribution of temperature is also termed as regional distribution of temperature. The spatial distribution of temperature is controlled by a variety of factors e.g. latitudes or distance from the equator, height from sea level or altitude, distance from the sea coast, nature of land and water, properties of ground surface, nature of slopes, prevailing winds, oceans currents etc.

Factors Controlling the Distribution of Temperature

As elaborated above the following factors control the distribution of temperature on the earth's surface :

1. Latitudes

The temperature of the atmosphere of a particular place near the ground surface depends on the amount of insolation received at the place. Since the amount of insolation received by the ground surface decreases poleward from the equator *i.e.* from low latitudes towards high latitudes because the sun's rays become more and more oblique (slanting) poleward and hence air temperature also decreases polewards. It may be noted that though sun's rays are almost vertical over the equator throughout the year but there is no maximum temperature on it rather maximum temperature is recorded along 20^0N latitude in July because major portion of insolation is reflected by clouds and sizeable amount of heat is lost in evaporation in the low latitude zone (equatorial zone) while tropics are characterized by clear skies and high pressure due to subsidence of air from above.

The maximum heating of ground surface occurs around tropics of Cancer and Capricorn and hence maximum temperatures are also recorded near the tropics. The polar zones record lowest temperatures. The highest temperature of 58^0C was recorded in Al Aziz of Libya in September, 1922, whereas the second highest temperature of 57^0C was recorded in July, 1913 in the Death Valley of California, USA. These extreme temperatures are the result of extreme heating of sandy surface near the tropics. The lowest temperature recorded till now is -89^0C which was recorded in 1983 at Vostock of Antarctica whereas the second lowest temperature of -68^0C was recorded at Verkhoyansk of Russia. These extreme low temperatures are the result of minimum amount of insolation received from the sun and maximum loss of energy through ground radiation to the atmosphere and space due to perpetually snow-covered ground surface which also allow maximum reflection (albedo) of solar radiation.

2. Altitude

The temperature decreases with increasing height from the earth's surface at an average rate of 6.5^0C per kilometre because of the following reasons. (i) The major source of atmospheric heat is the earth's surface from where heat is transferred to the atmosphere through the processes of conduction, radiation and convection. Thus, the portion of the atmosphere coming in direct contact with the earth's surface gets more heat from the ground surface than the portion lying above because as we ascend higher in the atmosphere the amount of heat to be transported above decreases and hence temperature decreases aloft. (ii) The layers of air are denser near the earth's surface and become lighter with increasing altitudes. The lower layer of air contains more water vapour and dust particles than layers above and hence it absorbs larger amount of heat radiated from the earth's surface than the upper air layers.

3. Distance from the Coast

The marine environment moderates the weather conditions of the coastal areas because there is more mixing of temperatures of the coastal seas and oceans and coastal lands due to daily rythm of land and sea breezes. Thus, the daily range of temperature near the coastal environment is minimum but it increases as the distance from the sea coast increases. Minimum daily range of temperature is the characteristic feature of marine climate while extremely high daily range of temperature characterizes continental climate.

4. Nature of Land and Water

The contrasting nature of land and water surfaces in relation to the incoming shortwave solar radiation largely affects the spatial and temporal distribution of temperature. It may be pointed out that land becomes warm and cold more quickly than the water body. This is why even after receiving equal amount of insolation the temperature of land becomes more than the temperature of the water body. The following reasons explain the differential rate of heating and cooling of land and water.

(i) The sun's rays penetrate to a depth of only one meter in land because it is opaque but they penetrate to greater depth of several metres in water because it is transparent to solar radiation. The thin layer of soils and rocks of land, thus, gets heated quickly because of greater concentration of insolation in much smaller mass of material of ground surface. Similarly, the thin ground layer emits heat quickly and becomes colder. On the other hand, the same amount of insolation falling on water surface has to heat larger volume of water because of the penetration of solar rays to greater depth and thus the temperature of ground surface becomes higher than that of the water surface though the amount of insolation received by both the surfaces may be equal.

(ii) The heat is concentrated at the place where insoalation is received and there is very slow process of redistribution of heat by conduction because land surface is static. It may be noted that downward distribution of temperature in the land surface within a day (24 hours) is effective upto the depth of only 10 centimetres. Thus, the land surface becomes warm during day and cold during night very rapidly. On the other hand, water is mobile. The upper surface of water becomes lighter when heated by insolation and thus moves away horizontally to other places and the solar rays have to heat fresh layer of cold water. Secondly, heat is redistributed in water bodies by sea waves, ocean currents and tidal waves. All these extend the period of warming of water surface.

(iii) There is more evaporation from the seas and the oceans and hence more heat is spent in this process with the result oceans get less insolation than the land surface. On the other hand, there is less evaporation from the land surface because of very limited amount of water.

(iv) The specific heat (the amount of heat needed to raise the temperature of one gram of a substance by 1^0C) of water is much greater (five times) than the land (specific heat of water and land surface is 1.0 cal/g/^{0}C and 0.19 cal/g/^{0}C respectively) because the relative density of water is much lower than that of land surface. It means more heat is required to raise the temperature of one gram of water by 1^0C than one gram of land. More specifically, the heat required to raise the temperature of one cubic foot of water by 1^0C is two times greater than the heat required for the equal volume of land (one cubic foot). It is apparent that same amount of insolation received by same mass of water and land would increase the temperature of land more than the temperature of equal mass of water.

(v) The reflection (albedo) of incoming solar radiation from the oceanic water surface is far more than from the land surface and thus water receives less insolation than land. It may be mentioned that this is the generalized statement because the nature of ground surface varies from low latitudes to higher latitudes because the percentage of snow–covered surface increases beyond 60^0 latitude and therefore the albedo also increases in the same proportion.

(vi) Oceanic areas are generally clouded and hence they receive less insolation than land surface. But clouds absorb outgoing terrestrial radiation and counter-radiate heat back to the earth's surface. This process retards the loss of heat from the oceanic surfaces and hence slows down the mechanism of cooling of the air lying over the oceans. On the other hand, land surfaces receive more insolation at faster rate because of less cloudiness and simultaneously lose more heat through outgoing terrestrial radiation very quickly.

5. Nature of Ground Surface

The nature of ground surface in terms of colour, vegetation, land use practices etc. affects the distribution of temperature. The snow covered surfaces receive very low amount of insolation because they reflect 70 to 90 per cent of incoming shortwave solar radiation and thus polar and arctic areas are characterized by extremely low temperature throughout the year. On the other hand, sandy surfaces record high temperature during day time in the tropical and subtropical areas because they absorb most of solar radiation very quickly as they reflect only 20 to 30 per cent of solar radiation. Table 4.1 depicts the albedo of different kinds of surfaces.

Table 4.1 : Albedo of different kinds of surfaces

Surface	Per cent of radiation being reflected	Surface	Per cent of radiation being reflected
Snow cover	70-90	Forest	5-10
Sand	20-30	Water	3-5
Grass	14-37	Thick cloud	70-80
Dry ground	15-25	Thin cloud	25-80
Wet ground	10	Black soils	8-14

Dark coloured ground surfaces receive more solar radiation than light coloured surfaces. The temperature of ground surface of forested areas never becomes very high because sizeable amount of heat is spent in the process of evapotranspiration from plant leaves.

6. Nature of Ground Slope

The ground slope facing the sun receives more insolation because the sun's rays reach the surface more or less straight and hence sun-facing ground surfaces record higher temperature than the leeward slopes where sun's rays reach more obliquely. In the northern hemisphere the southward facing slopes of east-west stretching mountains receive greater amount of insolation than the north-ward facing slopes because of their exposure to the sun for longer duration. This is why most of the valleys situated on the southern slopes of the Alpine mountains have settlements and cultivation. The coastal windward slope of the mountains and hills have relatively low temperature because of oceanic influences and ascending air (temperature decreases at the rate of 10^{0}C/km of an ascending air) than the leeward slope which is characterized by relatively high temperature because the descending air is warmed at dry adiabatic rate (10^{0}C/km). This is why there is much difference of temperature along the western and eastern slopes of the western Ghats of India.

Topographic features in terms of relief also determine the variations in spatial distribution of temperature. The west-east location of the lofty Himalayas and their extensions protect south Asia in general and India in particular from Siberian extremely cold winds and hence becoming too cold. Conversely, the absence of any west-east stretching mountain barrier in the USA allows cold powdery polar winds from Arctic Canada to reach as far south as the Gulf Coast during winter and the temperature of New Orleans, Houstan and Galveston falls below freezing point. On the other hand, during summer warm tropical airmasses enter the country and raises the temperature.

7. Prevailing Winds

The prevailing winds help in redistribution of temperature and in carrying moderating effects of the oceans to the adjacent coastal land areas. The winds blowing from low latitudes to high latitudes raise the temperature of the regions where they reach while winds blowing from high latitudes to low latitudes lower the temperature. The winds blowing from oceans to coastal lands bring in marine effects and thus lower the daily range of temperature. The winds coming from higher parts of the mountains lower the temperature in the valleys. The temperature rises at the time of arrival of temperate cyclones while it falls sharply after their passage or their occlusion. The winds associated with warm oceanic currents raise the temperature of coastal lands while the winds coming in contact with cold currents lower the temperature of affected coastal lands. For example, the North Atlantic Drift (extension of Gulf Stream) raises the temperature of coastal areas of north-western Europe and Labrador cold current lowers the temperature in the neighbourhood of New Foundland. Some times, local winds change the temperature dramatically. For example, the warm **Chinook winds** raise the temperature by 30 to 40^{0}F within a few minutes along the eastern slopes of the Rockies in the USA and the snow melts as by magic at the arrival of Chinook. This is why pastures are open throughout the year along the eastern slopes of the Rockies. **Loo**, a local hot wind, raises the temperature in the Ganga Plain of North India to such an extent (maximum temperature ranges between 40^{0}C to 48^{0}C during the day) that **heat waves** prolong for several days in continuation and several people die of sun stroke.

8. Ocean Currents

The warm ocean currents flowing from tropical areas to temperate and cold zones raise the average temperature in the affected areas. For example, Gulf Stream raises the average temperature of the coastal areas of north-western Europe while Kuroshio warm current raises the temperature of Japanese coasts. Labrador, Peru, California, Kurile etc. cold currents lower the temperatures of affected areas. In fact, ocean currents moving from one place to another equalize the temperatures.

9. Cloud Cover

The cloudiness affects the local, daily and seasonal temperatures and hence the ranges of temperature. It is experienced fact that night time temperature during clear sky is much less than clouded nights. Similarly, cloudy nights and days are warmer than cloudless nights and days. This is because of the fact that cloud cover reflects a portion of incoming shortwave solar radiation and hence lowers the amount of solar radiation reaching the earth's surface. On the other hand, cloud cover retards the loss of heat energy from the earth through outgoing longwave terrestrial radiation and reradiates it back to the ground surface and thus cloud cover keeps the ground surface and boundary layer of air warm. Conversely, cloudless clear sky allows more solar radiation waves to reach the earth's surface during daytime while it allows rapid rate of loss of heat from the ground surface through longwave radiation during nights and hence daily range of temperature becomes large but the daily range of temperature during cloudy day and night becomes low. The cloudy oceanic zones of low latitudes, mid-latitudes and high latitudes are characterized by low range of temperature whether diurnal or annual.

4.8 VERTICAL DISTRIBUTION OF TEMPERATURE

Temperature decreases with increasing height in the troposphere but the rate of decrease varies according to seasons, duration of sunshine and location. On an average, the rate of decrease of temperature with increasing altitudes in a stationary column of air with absence of any vertical motion is 6.5^{0}C per 1000 meters. This decrease of temperature is called vertical temperature gradient or **normal lapse rate** which is 1000 times greater than the horizontal lapse rate (decrease of temperature with increasing latitudes). It may be mentioned that normal lapse rate is average but actual lapse rate varies both spatially and temporally. Actual lapse rate is called **environmental lapse rate**. In the lower troposphere (1.5 to 2 km) there are frequent hourly changes of lapse rate while it is less variable in the upper troposphere (2 km to tropopause). Summer registers higher lapse rate than winter and daytime lapse rate scores over night time lapse rate. The decrease of temperature upward in the atmosphere proves the fact that the atmosphere gets heat from the earth's surface through the processes of conduction, radiation and convection. It is, thus, obvious that as the vertical (height) distance from the earth's surface (the source of direct heat energy to the atmosphere) increases (*i.e.* as the altitude increases), the air temperature decreases. The following are the reasons for decrease of temperature with increasing altitudes in the troposphere.

(i) Heat is transferred to the atmosphere from the earth's surface through the processes of conduction, radiation and convection. Thus, as the altitude increases the amount of heat transported upward decreases. Consequently, every air layer receives less heat than the air layer laying below.

(ii) The air pressure is higher in the lower portion of the atmosphere near the earth's surface because of weight of all the air layers lying above and thus the air density is maximum in the lower atmosphere but it decreases rapidly upward and the air becomes thin.

(iii) The quantity of water vapour, dust particles, water droplets, carbon dioxide etc. which absorb outgoing longwave terrestrial radiation, is more concentrated in the lower portion of the atmosphere and decreases rapidly with increasing altitude. Thus, the temperature of lower atmosphere becomes more than the air layers lying above because of more and more absorption of terrestrial radiation in the lower air layers. In other words, the temperature decreases upward because of decrease of absorption of terrestrial radiation with increasing height in the troposphere.

It may be pointed out that the decrease of temperature with increasing height is confined to the troposphere only. The height of troposphere is 16 km and 6 km over the equator and the poles respectively but this height also varies in different seasons *i.e.* it becomes higher in summer than in winter. The upper limit of troposphere is called **tropopause.**

It is interesting to note that the temperature at tropopause increases from over the equator towards the poles because the height of tropopause decreases from over the equator towards the poles. The height of tropopause during July and January over the equator is 17km while temperature at the top of tropopause is -70^0C. The height of tropopause decreases to 15 km in July and 12.5 km in January over 45^0N latitude but the temperature at the top of tropopause increases to -60^0C in July and -58^0C in January. The height of tropopause further decreases to 10 km in July and 9 km in January over the poles but the temperature increases to -45^0C in July and -58^0C in January.

Upward from tropopause the temperature is reported to increase with increasing height in the **stratosphere** wherein it becomes 0^0C or 32^0F at the height of 50 km from sea level. This is the upper limit of the stratosphere and is called **stratopause.** Temperature again decreases with increasing height in the **mesosphere** (50 km-80 km). The temperature becomes -80^0C at **mesopause,** the upper limit of the mesosphere. Beyond mesopause temperature again increases with increasing height in the **thermosphere.** It is estimated that the temperature at its upper limit (height undecided) becomes 1700^0C. It may be pointed out that this temperature cannot be measured by ordinary thermometer because the gases become very light due to very low air density.

Some times, temperature increases with increasing height in the troposphere. In other words, some time warm air lies over cold air. This phenomenon is called **inversion of temperature.**

Inversion of temperature, though is a part of vertical distribution of atmospheric temperature, is being discussed in a separate section because it is a very significant atmospheric phenomenon and has immese climatic and economic significance.

4.9 INVERSION OF TEMPERATURE

1. Meaning of Temperature inversion

As stated above temperature decreases with increasing altitudes in the troposhere at an average rate of 6.5°C per 1000 metres (normal lapse rate) but some times this normal trend of decrease of temperature with increasing heights is reversed under special circumstances *i.e.* temperature increases upward upto a few kilometres from the earth's surface. This is called **negative lapse rate.** Thus, warm air layer lies over cold air layer. This phenomenon meterologically is called inversion of temperature. Such situation may occur near the earth's surface or at greater height in the troposphere but the inversion of temperature near the earth's surface is of very short duration because the radiation of heat from the earth's surface during daytime warms up the cold air layer which soon disappears and temperature inversion also disappears. On the other hand, upper air temperature inversion lasts for longer duration because the warming of cold air layer aloft through terrestrial radiation takes relatively longer period of hours.

2. Types of Temperature inversion

Inversion of temperature occurs in several conditions. Some times, it occurs at ground surface while some times, it occurs at greater height. Some times, it is caused in the static atmospheric conditions while some times, it occurs due to horizontal or vertical movement of air. Thus, temperature inversion is classified into the following types on the basis of relative heights from the earth's surface at which it occurs and the types of air circulation.

(1) **Non-advectional inversion**
- (i) Ground or surface inversion or radiation inversion.
- (ii) Upper air inversion.

(2) **Advectional inversion**
- (i) Frontal inversion or cyclonic inversion.
- (ii) Valley inversion due to vertical air movement.
- (iii) Surface inversion due to horizontal air movement.

(3) **Mechanical inversion**
- (i) Subsidence inversion.
- (ii) Turbulence and convective inversion.

(1) **Ground surface inversion** also called as **radiation inversion** occurs near the earth's surface due to radiation mechanism. This is also called as non-advectional inversion because it occurs in static atmospheric condition characterized by no movement of air whether horizontal or vertical(it may be noted that air is never static). Such inversion normally occurs during the long cold winter nights in the snow-covered regions of the middle and high latitudes. In fact, surface inversion is caused due to excessive nocturnal cooling of the ground surface due to rapid rate of loss of heat from the ground through outgoing longwave terrestrial radiation. Thus, the air coming in contact with the cool ground surface also becomes cool while the air layer lying above is relatively warm. Consequently temperature inversion develops because of cold air layer below and warm air layer above (fig. 4.1). The ground surface inversion occurs under the following conditions :

(i) Long winter nights, so that the loss of heat by terrestrial radiation from the ground surface during night may exceed the amount of insolation received from the sun through incoming shortwave electromagnetic radiation waves and thus the ground surface becomes too cold.

(ii) Cloudless and clear sky, so that the loss of heat through terrestrial radiation proceeds more rapidly without any obstruction. Clouds absorb terrestrial radiation and hence retard loss of heat from the earth's surface.

(iii) Presence of dry air near the ground surface, so that it may not absorb much heat radiated from the earth's surface as moist air is capable of absorbing much of the radiant heat from the earth's surface.

(iv) Slow movement of air, so that there is no transfer and mixing of heat in the lower layers of the atmosphere.

(v) Snow-covered ground surface, so that there is maximum loss of heat through reflection of incoming solar radiation. Snow, being bad conductor of heat retards the flow of heat from the ground surface lying below the snow-layers to the lower atmosphere.

Since such inversion of temperature occurs in the static atmospheric condition (very little movement of air) and hence it is also called **static** or **non-advectional inversion.** Ground inversion occurs in the low latitude areas (tropical and subtropical areas) during winter nights only and

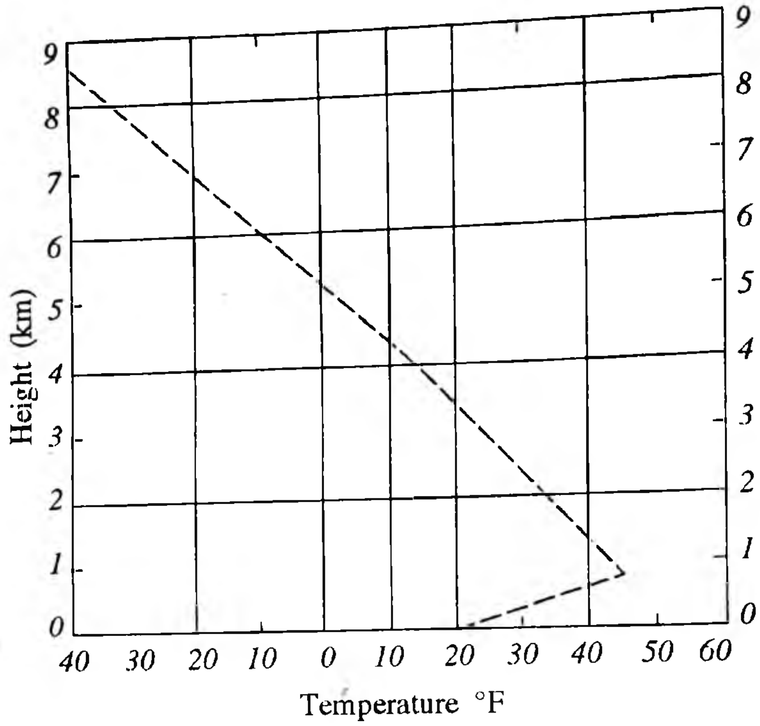


Fig. 4.1: Ground surface inversion of temperature.

the inversion generally disappears with sunrise but some time it persists upto noon. The inversion occurs upto the height of 30-40 feet in the low latitudes, a few hundred feet in the middle latitudes and half a mile in the high latitudes. It is apparent that the duration and height of surface inversion increase poleward. This inversion promotes stability in the lower portion of the atmosphere and causes dense fogs.

(2) **Upper air inversion** is of two types viz. (i) thermal upper air inversion, and (ii) mechanical upper air inversion. The thermal upper air inversion is caused by the presence of ozone layer lying between the height of 15 to 35km (even upto 80km) in the stratosphere. The ozone layer absorbs most of the ultraviolet rays radiated from the sun and thus the temperature of this layer becomes much higher than the air layers lying above and below ozone layer. This inversion occurs only when there is no vertical movement of air (either ascent or descent of air). The **mechanical inversion** of temperature is caused at higher heights in the atmosphere due to subsidence of air and turbulence and convective mechanism. Such inversion occurs in a number of ways *e.g.* (a) Some times, warm air is suddenly transported upward (due to eddies formed by frictional forces) to the zone of cold air and thus cold air being denser lies under the warm air and inversion of temperature is caused. (b) The descending air is warmed at the dry adiabatic rate of 10^0C per 1000m because of compression. This situation causes the existence of warm air above the cold air. Such mechanical inversion caused by the subsidence of air currents is generally associated with the anticyclonic conditions. Such inversion of temperature is of very common occurrence in the middle latitudes where high pressures are characterized by sinking air. The poleward regions of trade winds are also characterized by high pressure caused by the subsidence of air and thus there is also frequent mechanical inversion of temperature. Since the temperature inversion

causes stability in the atmosphere and thus there is dry condition. This is the reason that the poleward parts of trade winds are characterized by arid conditions.

The temperature inversion in the poleward regions of trade winds is called **trade wind inversion** which occurs upto the height of one kilometer and the temperature difference between upper and lower limits of inversion layer ranges upto ten degree centigrade. This temperature inversion is associated with subtropical anticyclones and becomes more prominent during winter months. The trade wind inversion weakens equatorward and becomes non-existent in the inter-tropical convergence (ITC) zone.

(3) **Advectional inversion of temperature** is also called as **dynamic inversion** because it is always caused due to either horizontal or vertical movement of air. Strong wind movement and unstable conditions of the atmosphere are prerequisite conditions for advectional inversion of temperature. This type is further divided into 3 subtypes on the basis of the nature of air movements e.g. (i) frontal or cyclonic inversion, (ii) valley inversion due to vertical movement of air, and (iii) surface inversion due to horizontal movement of air.

(i) **Frontal or cyclonic inversion** is caused in the temperate zones due to temperate cyclones which are formed due to the convergence of warm westerlies and cold polar air and thus the warm air overlies the cold polar winds in the northern hemisphere. The warm air is pushed up by the cold air because it is lighter than the cold air. Thus, the existence of warm air above and cold air below reverses the normal lapse rate (decrease of temperature with increasing height) and inversion of temperature occurs. It may be pointed out that contrary to other types of temperature inversion, the inversion layer associated with frontal or cyclonic inversion is always sloping because the **coriolis force** causes the boundary zone (front) between the warm westerlies and cold polar air masses to become slopy. It is also interesting to note that air moisture increases upward in frontal inversion of temperature while it decreases upward in other types of temperature inversion.

(ii) **Surface inversion** of temperature caused by horizontal movement of air occurs in several situations. Such inversion is caused when warm air invades the area of cold air or cold air moves into the area of warm air because warm air being lighter is pushed upward by relatively dense cold air. When the warm air moves, such inversion is caused over the continents during winter and over the oceans during summer but when the cold air becomes active and invades the areas of warm air, such inversion occurs over the continents during summer and over the oceans during winter. Such surface inversion occurs generally in the low latitudes. The convergence of cold and warm ocean currents also causes such inversion of temperature.

(iii) **Valley inversion** generally occurs in the mountainous valleys due to radiation and vertical movement of air. This is also called vertical advectional inversion of temperature. The temperature of the upper parts of the valleys in mountainous areas becomes exceedingly low during winter nights because of rapid rate of loss of heat from the surface through terrestrial radiation. Consequently, the air coming in contact with the cool surface also becomes cool. On the other hand, the temperature of the valley floor does not fall considerably because of comparatively low rate of loss of heat through terrestrial radiation. Thus, the air remains warmer than the air aloft and hence the warm and light air of the valley floor is pushed upward by the descending cold and heavier air of the upper part of the valley. Thus, there is warm air aloft and cold air

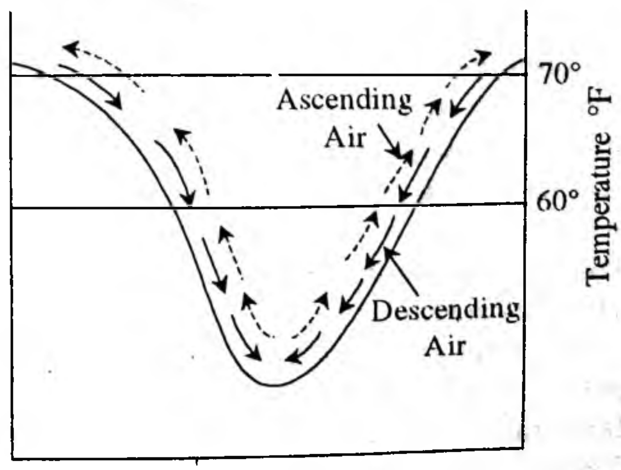


Fig. 4.2 : Valley inversion of temperature.

in the valley floor and inversion of temperature is caused. This situation is responsible for severe frost in the valley floors causing great damage to fruit orchards and vegetables and agricultural crops whereas the upper parts of the valleys are free from frost. This is why the valley floors are avoided for human settlements while the upper parts are inhabited in the mountainous valleys of middle latitudes. Fig 4.2 explains the mechanism of valley inversion of temperature.

Significance of Inversion of Temperature

Though inversion of temperature denotes local and temporary conditions of the atmosphere but there are several climatic effects of inversion which are of great significance to man and his economic activities.

(1) Fog is formed due to the situation of warm air above and cold air below because the warm air is cooled from below and resultant condensation causes the formation of tiny droplets around suspended dust particles and smokes during winter nights. The smokes coming out of houses and chimneys intensify fogs and become responsible for the occurrence of **urban smogs**. When smog is mixed with air pollutants such as sulphur dioxide it becomes poisonous and deadly health hazard to human beings. The incidents of deadly urban smogs of December, 1930 in Meuse Valley of Belgium (600 people fell ill and 63 people died), of October 26, 1948 at Donora in Pennsylvania (USA), and of 1952 in London (causing 4000 human deaths) tell the ordeal of urban smogs. Fogs are also formed at the convergence of warm and cold ocean currents. For example, dense and extensive fogs are formed near Newfoundland due to convergence of warm Gulf Stream and cold Labrador current. Fogs reduce atmospheric visibility and thus they are responsible for several cases of accidents of air crafts while taking off and landing and ships in the oceans. Road and rail transport is also badly affected by the occurrence of dense fogs. Though generally fogs are unfavourable for many agricultural crops such as grams, peas, mustard plants, wheat etc. but some times they are also favourable for some crops such as coffee plants in Yemen hills of Arabia where fogs protect coffee plants from direct strong sun's rays.

(2) Inversion of temperature causes frost when the condensation of warm air due to its cooling by cold air below occurs at temperature below freezing point. Frost is definitely economically unfavourable weather phenomenon mainly for crops because fruit orchards and several agricultural crops such as potatoes, tomatoes, peas etc. are totally damaged overnight. There are frequent cases of destruction of fruit orchards in the lower parts of valleys due to severe frost caused by inversion of temperature in California (USA). Fruit orchards were severelly damaged in California in the year 1913, 1917 and 1923 due to severe frosts. The valley floors in the hills of Brazil are avoided for coffee cultivation because of frequent frosts. Alternatively, coffee is planted on the upper slopes of the valleys. The upper parts of the valleys are inhabited in Switzerland while lower parts are avoided. In fact, the upper slopes of valleys are characterized by fruit orchards, hotels and motels (for tourists), various resort centres etc. while the lower slopes are deserted.

(3) Inversion of temperature causes atmospheric stability which stops upward (ascent) and downward (descent) movements of air. The atmospheric stability discourages rainfall and favours dry condition. The inversion of temperature caused by the subsidence of air resulting into anticyclonic conditions increases aridity. This is why the western parts of the continents situated between 20^0-30^0 latitudes and characterized by anticyclonic condition represent most widespread tropical deserts of the world.

4.10 HORIZONTAL DISTRIBUTION OF TEMPERATURE

On an average, temperature decreases from the equator towards the poles and thus low latitudes are characterized by highest temperature corresponding to maximum insolation received within the tropics whereas high latitudes record lowest temperature in response to minimum insolation received in the polar areas. It may be mentioned that the highest temperature of the earth's surface is never recorded at the equator, instead it is recorded near the tropics of Cancer and Capricorn during northern and southern summers respectively because (i) the sun's rays are near vertical for only 30 days in a year within equatorial zone, demarcated by 6^0N and 6^0S latitudes, whereas sun's rays are near vertical for 86 days in a year within the latitudinal zone of 17.5^0 and 23.5^0 in both the hemispheres, and hence the zone near the tropics (23.5^0) receives the highest amount of insolation resulting into highest temperature; (ii) almost clear skies for the most part of the year allow more inflow of solar radiation and consequent heating of the ground surface whereas cloud cover reflects a portion of incident solar radiation ; and (iii) more heat energy is spent in evaportion and convection as latent heat in equatorial belt while there is least evaporation near the tropics and very little amount of heat energy is spent as latent heat.

Besides above mentioned deviation generally temperature decreases from the equator towards the poles. This change of temperature rather decrease of temperature poleward is called **temperature gradient.** The rate of decrease of temperature (thermal gradient) between the tropics of Cancer and Capricorn is rather low and therefore temperature gradient is insignificant but temperature decreases more rapidly from the tropics poleward and hence temperature gradient becomes steep. Horizontal distribution of temperature over the earth's land-sea surfaces is studied with the help of **isotherms.**

Isotherms are the imaginary lines drawn on the maps joining places of equal temperature reduced to sea level. It is necessary to reduce the actual temperatures of all places at sea level before drawing isotherms. It is, thus, obvious that isotherms do not represent the real temperature of the places through which they pass rather they show temperature of the places at seal level. This is why the isotherm maps are not useful for farmers because they need real temperature of a particular place for growing crops. Normally, isotherms run east-west and are generally parallel to latitudes. This trend shows strong control of latitudes on the horizontal distribution of temperature. Generally, isotherms are straight but they bend at the junction of continents and oceans due to differential heating and cooling of land and water. Isothermal lines are more irregular in the northern hemisphere because of large extent of continents but they are more regular in the southern hemisphere due to over-dominance of oceans. Isotherms are generally closely spaced in the northern hemisphere but they are widely spaced in the southern hemisphere. The closely spaced isotherms denote rapid rate of change of temperature and steep temperature gradient. On the other hand, widely spaced isotherms indicate slow rate of temperature change and low temperature gradient. On an average, isotherms trending from land towards the ocean bend equatorward during summer and poleward during winter. On the other hand, isotherms trending from the oceans to the continents bend poleward during summer and equatorward during winter. The isotherms during the months of January and July are taken as representatives for the study of horizontal distribution of temperature during winter and summer seasons respectively because they represent seasonal extremes.

Seasonal Horizontal Distribution of Temperature

As stated earlier, the months of maximum (June, northern hemisphere) and minimum (December, northern hemisphere) insolation do not coincide with the months of hottest and coldest months (July and January in the northern hemisphere) respectively and hence the months of July (hottest in the northern hemisphere and coldest in the southern hemisphere) and January (coldest in the northern hemisphere and hottest in the southern hemisphere) are taken as representatives to describe the seasonal (and also annual) distribution of average temperature. Figs. 4.3 and 4.4 illustrate distribution of average temperature in July (representing temperature during summer season) and January (representing temperature during winter season). The two isotherm maps reveal the following trends :

(1) The months of July and January are warmest and coldest in the northern hemisphere whereas the warmest and coldest months in the southern hemisphere are January and July respectively.

(2) Both the maps (Figs. 4.3 and 4.4) show latitudinal shifts of isotherms in accordance with seasonal shifting of overhead sun but this shifting of isotherms is more pronounced on the continents.

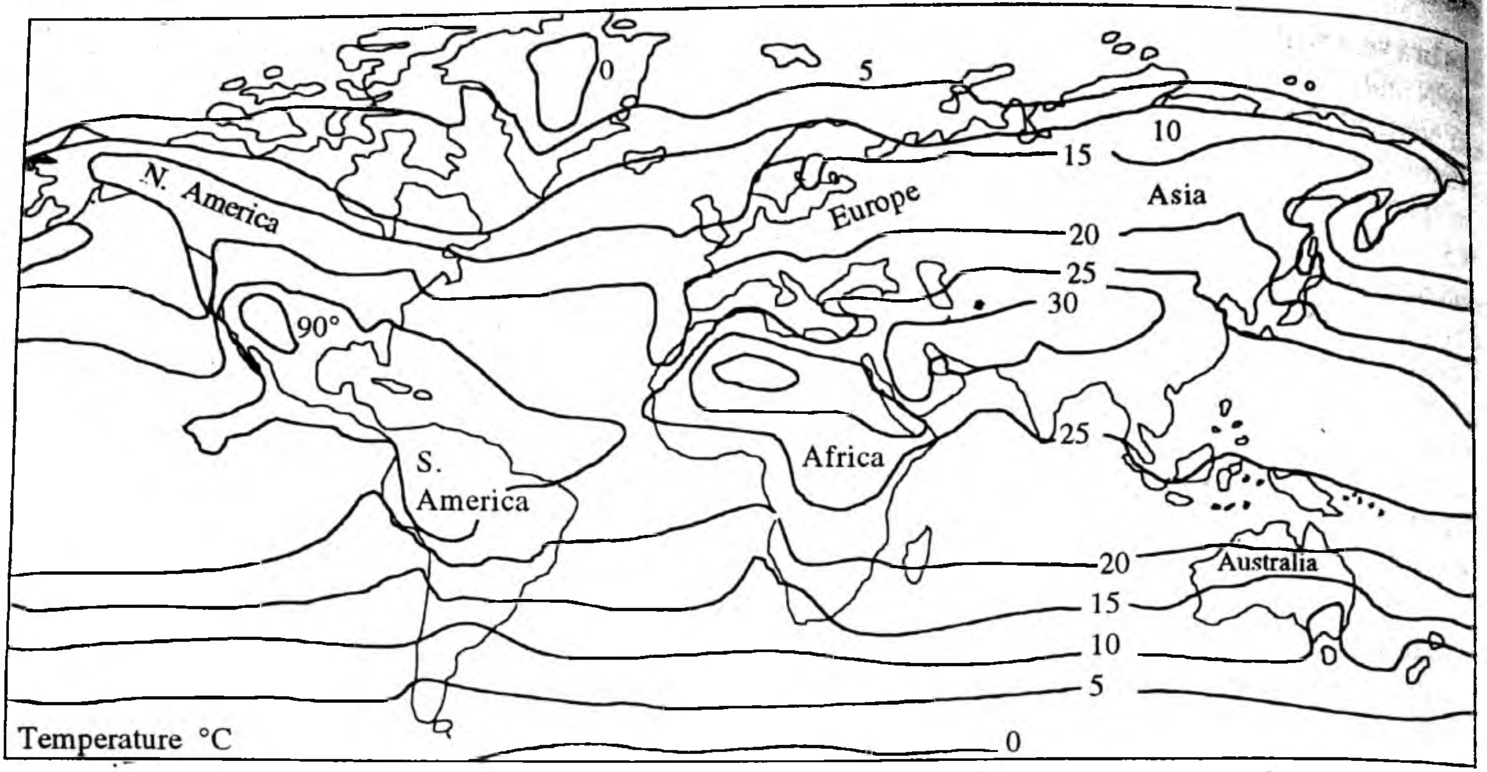


Fig. 4.3 : Isotherms representing horizontal distribution of temperature in July.

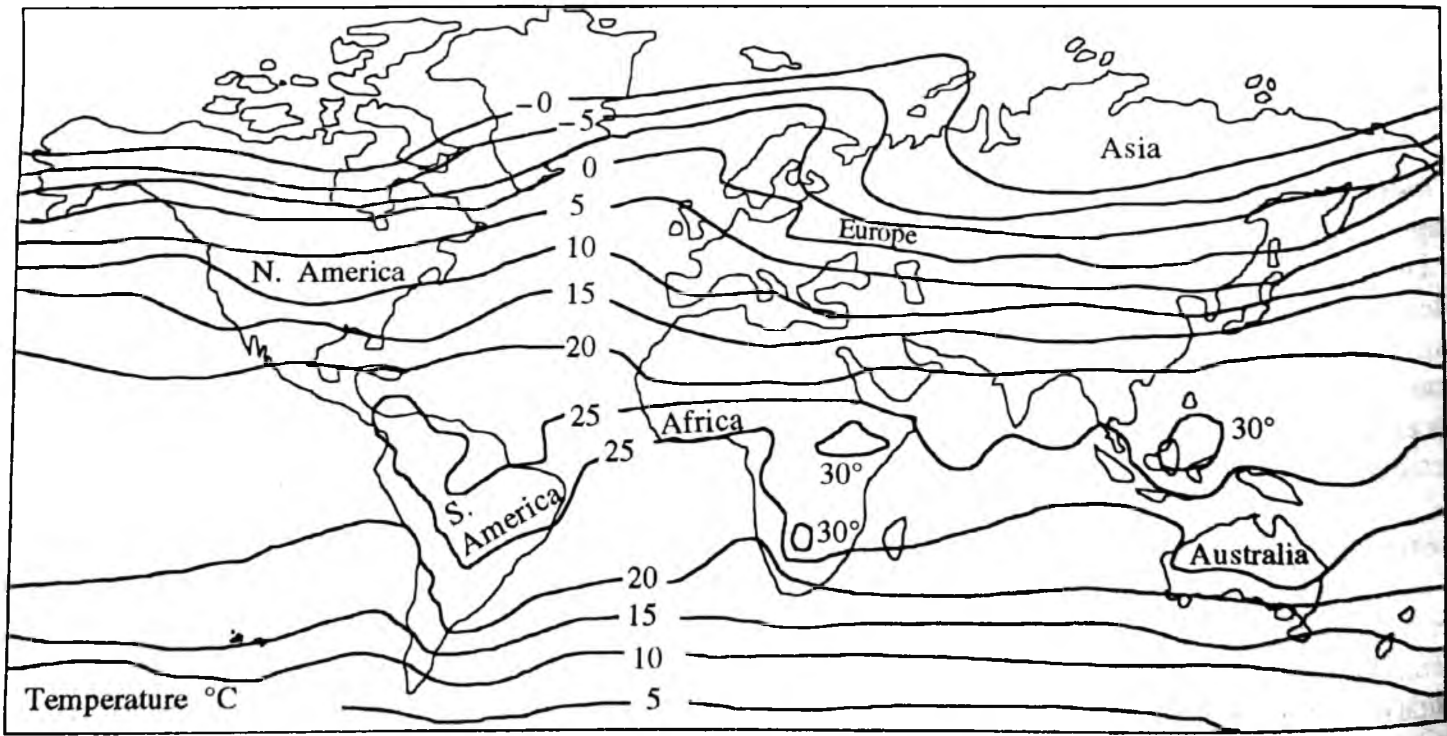


Fig. 4.4 : Isotherms representing horizontal distribution of temperature in January.

(3) The maximum temperatures in January and July are always recorded on the continents. Minimum temperature in January is observed in Asia and North America.

(4) January isotherms suddenly bend poleward while passing through warm portions of the oceans and bend equatorward while passing through the cold portions of the oceans in January in the northern hemisphere while the trend is opposite in July. On the other hand, the isotherms are more or less regular and straight in the southern hemisphere because of over-dominance of oceans.

(5) Temperature gradient is more pronounced during winter than summer.

(6) The January isotherms denote steep temperature gradient in the northern hemisphere as revealed by their closer spacings (Fig. 4.4) while relatively widely spaced isotherms in the southern hemisphere denote gentle (low) temperature gradient because of the dominance of the oceans. In the northern hemisphere the eastern coasts register steeper temperature gradient (1.5^{0}C per latitude) than the western coastal areas (0.5^{0}C per latitude).

Regional Distribution

Horizontal temperature distribution is also described following regional approach wherein the globe is divided into temperature zones.

According to ancient Greek thinkers the globe is divided into three temperature zones on the basis of latitudes (Fig. 4.5) e.g. (1) tropical zone, (2) temperate zone, and (3) frigid zone.

Tropical zone extends between the tropics of Cancer (23.5^{0}N) and Capricorn (23.5^{0}S). The Sun's rays are more or less vertical on the equator throughout the year. The remaining areas are also characterized by vertical sun's rays at least once every year.

There is no winter around the equator because of high temperature prevailing throughout the year but as one approaches the tropics of Cancer and Capricorn summer and winter are clearly observed and differentiated.

(2) **Temperate zone** extends between 23.5^0 and 66.5^0 latitudes in both the hemispheres. Though the duration of day and night is longer in this zone but it is never more than 24 hours. There are marked seasonal contrasts with the northward and southward (summer and winter solstices) migration of the overhead sun and thus the range of temperature between summers and winters becomes exceptionally very high.

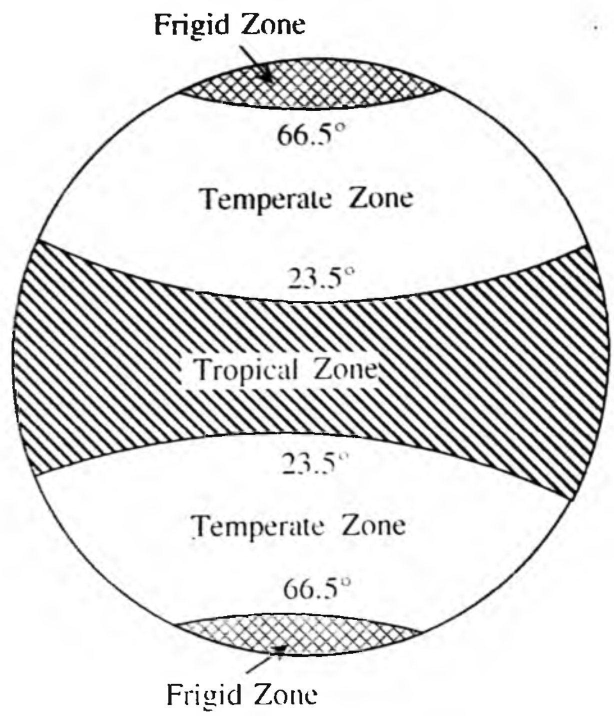


Fig. 4.5 : Temperature zones according to the views of ancient Greek thinkers.

(3) **Frigid zone** extending between 66.5^0 latitude and the poles in both the hemispheres is characterized by more oblique sun's rays throughout the year resulting into exceptionally very low temperature. The length of day and night is more than 24 hours. Days and nights are of 6 months duration at the poles. Sun is never vertical and the ground is covered with snow as temperature more or less remains below freezing point.

It may be pointed out that the Greeks gave undue importance to latitudes in determining different temperature zones and overlooked the controls of contrasting nature of continents and oceans in terms of their heating and cooling, prevailing winds, ocean currents, nature of ground surface etc. Taking all these factors in consideration Soupan divided the globe into temperature zones on the basis of isotherms. According to him the outer limit of tropical zone should be determined on the basis of annual isotherm of 68⁰F (20⁰C). The boundary between temperate and frigid zones in the northern hemisphere should be demarcated by 50⁰F (10⁰C) isotherm of July while January isotherm of 50⁰F (10⁰C) should separate temperate zone from the frigid zone in the southern hemisphere.

Isanomalous Temperature

The discussion of isanomalous temperature is also a part of horizontal distribution of temperature wherein temperature difference is more emphasized. Oliver and Hidore (2003) have defined asanomalous temperature as anomalies (which) represent deviations from temperatures that would only result from solar energy. Generally, the difference of observed temperature of a place and the mean temperature of the latitude passing through that place is called **thermal anomaly**. For example, if the average temperature of 30⁰N latitude is 20⁰C and the temperature of 'A' place located on that latitude is 30⁰C, then the thermal anomaly is of 10⁰C. If the observed temperature of a particular place is more than the mean temperature of the latitude of that place, the thermal anomaly is called **positive thermal anomaly** but if the observed temperature of a given place is less than that of the latitude of that place then it becomes **negative thermal anomaly**. The equal thermal anomaly of several places is called **isanomalous temperature** and the isolines drawn on the world map joining places of equal thermal anomaly are called **isonamals.**

Thermal anomalies are controlled by distributional pattern of land and water and seasons of the year. The mode of effects of land and water in heating and cooling of the earth's ground surface and surface air has already been discussed in section 4.7. During northern winter season positive thermal anomalies are noted over oceans while continents are characterized by negative thermal anomalies in the northern hemisphere. The southern hemisphere denotes reversed trend. During northern summer season the above trend of thermal anomalies of winter season is reversed as continents record positive thermal anomalies while negative anomalies, are noted above oceans. The largest thermal anomalies both positive and negative anomalies are found in the northern hemisphere because of the dominance of land area while moderate anomalies are noted in the southern hemisphere because of overdominance of oceans.

4.11 IMPORTANT DEFINITIONS

Counter radiation : refers to radiation of heat energy from the atmosphere back to the earth's surface.

Ground radiation : denotes radiation of heat energy from the earth's surface to the atmosphere.

Inversion of temperature : the increase of temperature with increasing altitude in the troposphere is called inversion of temperature. It is also called **negative lapse rate.**

Isanomalous temperature : refers to equal thermal anomaly of several places and the isolines drawn on the world map joining places of equal thermal anomaly are called isanomals. Thermal anomaly refers to difference of actual temperature from average temperature of a latitude. If the actual temperature is more than average temperature of a place at the same latitude, it becomes positive thermal anomaly, and vice versa.

Isotherms : are the imaginary lines drawn on the maps joining places of equal temperature reduced to sea level.

Rediation window : the mountains are called radiation window because both incoming solar radiation and outgoing terrestrial radiation increase with increasing height of the mountains.

Sensible heat : is that which can be measured by thermometer and is temporarily stored.

5

ATMOSPHERIC PRESSURE AND MOTION

5.1 ATMOSPHERIC PRESSURE

Air being a physical substance is an admixture of several gases present in the atmosphere and hence it has its own weight. Thus, the air exerts pressure through its weight. Air pressure is defined as the force per unit area or total weight of mass of column of air above per unit area at sea level (unit area being one square inch, one square foot, one square centimeter, one square meter etc.). The atmospheric pressure is maximum at sea level. It exerts the weight of 14.7 pounds on the area of one square inch at sea level or 1034 grams (about one kilogram) per square centimeter. One can imagine as to how much weight of overlying air is being carried by every man daily but he does not feel such enormous weight on his head and shoulders because the air present inside human body exerts equal amount of outward pressure which balances the inward atmospheric pressure. Since the atmospheric pressure decreases with increasing altitudes and therefore the balance between the outward pressure exerted by the air of human body and inward pressure exerted by the atmosphere is disturbed, with the result man suffers from nose and ear bleed at higher altitudes on the mountains.

Air pressure is measured in terms of height of mercury in the glass tube in a mercurial barometer. The standard air pressure at sea level is 1013.25 mb (millibars, millibar is a force equal to 1000 dynes per cm^2 whereas a dyne is a unit of force approximately equal to the weight of one milligram) or 29.92 inches or 76 cm at a temperature of 15^0C at the latitude of 45^0. The height of mercury upto 0.1 inch in the glass tube is equivalent to 3.4 mb. Air pressure is measured with the help of mercurial barometer (Fortin's barometer), aneroid barometer, altimeter (altitude barometer), barograph, microbarograph etc. The lines joining the places of equal pressure at sea level are called **isobars.** Air pressure decreases with increasing altitudes at the rate of 0.1 inch or 3.4 mb per 600 feet but this rate of decrease is confined to the altitude of a few thousand feet only. Normally, half of the total atmospheric pressure is confined to the altitude of 1800 feet.

The standard atmospheric air pressure varies both horizontally and vertically (table 5.1), seasonally, and diurnally. It is apparent from table 5.1 that atmospheric pressure decreases with increasing height. The sea level air pressure is 1013.25 mb which decreases to 540 mb at 5 km height, 264.99

mb at 10 km height, 121.11 mb at 15 km height, 55. 29 mb at 20 km height, 11.97 mb at 30 km height etc. On an average, air pressure spatially (at sea level) varies from 982 mb to 1033 mb but there are also extreme cases. The highest sea level pressure of 1083.8 mb was recorded at Agata of Russia on December 31, 1968 while lowest air pressures of 870 mb and 877 mb were recorded at Typhoon Tip, near Guam in the Pacific Ocean on 12 October, 1979 and in Marina Islands. The other extreme air pressures were recorded at Irkutsk in Siberia, Russia (1075.2 mb, 14 January, 1893), at Northway, Alaska, USA (1078.2 mb, January 31, 1989), at Miles city, Montana, USA, (December 24, 1983, 1063.9 mb) etc. As regards seasonal changes in air pressure, there is pronounced variation from summer to winter seasons. The seasonal changes of air pressure are in proportion to the size of the continents and air temperatures. In fact, there is inverse relationship between air temperature and air pressure i.e. if temperature increases, pressure decreases and vice versa. It is very often said that if thermometer is high, barometer is low (pressure is low) and if thermometer is low, barometer is high (pressure is high). Day to day changes in the atmospheric pressure are very often caused due to occurrence of atmospheric storms. The daily variations in air pressure are marked by maximum pressure at 10 a.m. and 10 p.m. and minimum pressure at 4 a.m. and 4 p.m.

The distribution of atmospheric pressure is controlled by altitude, atmospheric temperature, air circulation, earth's rotation, water vapour, atmospheric storms etc.

Table 5.1 : Standard Atmospheric Pressure and Temperature

Altitude (km)	Temperature (^{0}C)	Air Pressure (millibars, mb)	Density (kg/m^3)
30	–46.5	11.97	0.02
20	–56.5	55.92	0.09
15	–56.5	121.11	0.20
10	–49.9	264.99	0.41
5	–17.5	540.48	0.74
4	–11.0	616.60	0.82
3	–4.5	701.21	0.91
2	2.0	795.01	1.01
1	8.5	898.76	1.11
0	15.0	1013.25	1.23

Source : J.M. Morgan and M.D. Morgan, 1991, referred by Oliver and Hidore, 2003.

5.2 PRESSURE GRADIENT

Generally, pressure gradient is defined as decrease of pressure between isobars of different values *i.e.* from high pressure to low pressure. It may be mentioned that high and low pressures are always used in relative terms and not in absolute terms. More precisely air pressure gradient refers to the rate of change of pressure per unit horizontal distance between two points. Pressure gradient denotes change of direction of air pressure which is always from high to low pressure and perpendicular to the isobars. Pressure gradient is also called as **barometric slope.** Closely spaced isobars denote steep pressure gradient while widely spaced isobars are indicative of gentle or low pressure gradient. It may be mentioned that wind velocity depends on pressure gradient.

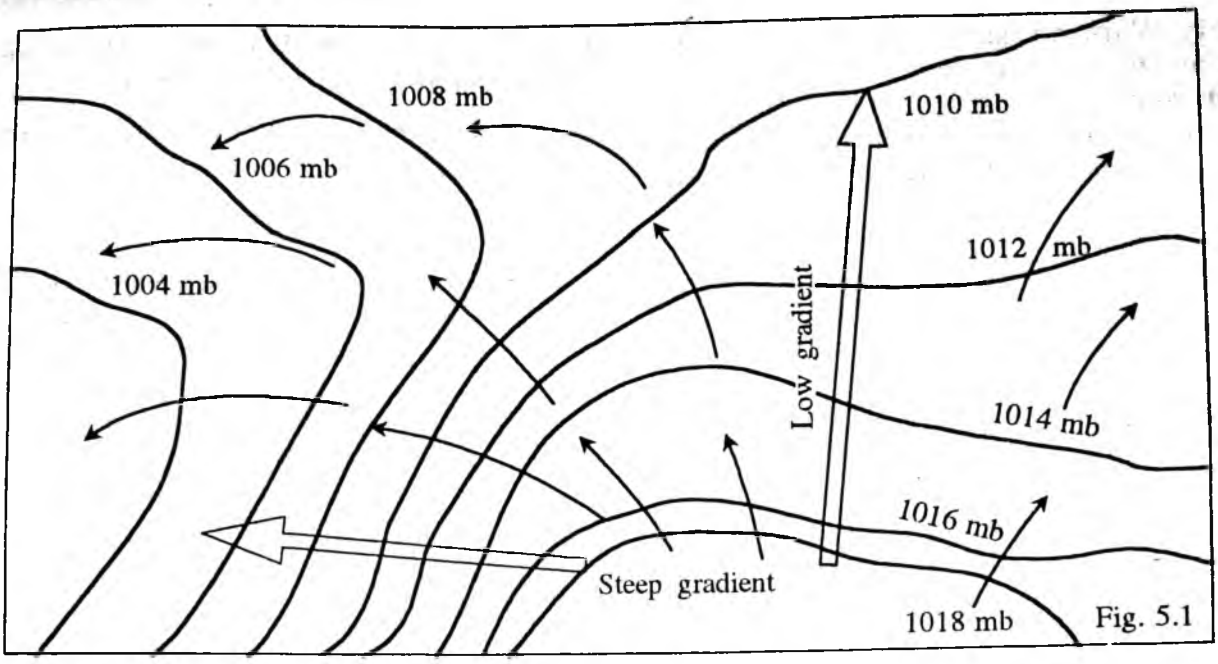


Fig. 5.1 : Pressure gradient and wind direction.

5.3 PRESSURE TYPES

Air pressure is generally divided into two types, namely (1) **high pressure**, and (2) **low pressure** which are indicated by the shapes of isobars. These are simply known as **Highs** and **Lows.** Since there are much variations in the size and duration of high and low pressures displayed by almost closed isobars and hence these are termed as **pressure systems** which are again divided into (1) **high pressure systems**, and (2) **low pressure systems.** They are further divided into (1) semi-permanent high and low pressure systems, (2) temporary and short-lived high and low pressure systems, and (3) migratory high and low pressure systems. It may be mentioned that semi-permanent pressure systems are large-scale weather phenomena and cover larger area and are indicative of monthly, seasonal and annual weather conditions as revealed by their location on the monthly, seasonal (summer and winter seasons) and annual weather maps whereas temporatory or shortlived high and low pressure systems are very small in size and of short duration, generally of less than 24 hour duration. They indicate daily weather conditions. Since their size and location change very frequently, and hence they become very important indicators of daily weather conditions and thus are displayed in daily weather maps.

(1) **High pressure systems** are characterized by highest air pressure in the center of almost closed isobars wherein pressure decreases from the center outward and the lowest pressure is found at the outer margin of the high pressure system. The high pressure in the center is called **high** and is displayed by H on the weather maps. This system is also called as **anticyclone.** In fact, anticyclones are high pressure systems and more common in the subtropical high pressure belts but are practically absent in the equatorial zone. The 'highs' or 'anticyclones' are characterized by divergent wind circulation wherein winds blow from the center outward in clockwise direction in the northern hemisphere and anti-clockwise in the southern hemisphere. The high pressure systems are indicative of dry weather conditions and hence anticyclones are called weatherless phenomena. It may be mentioned that high pressure systems are caused both thermally (excessive cooling) and dynamically (subsidence of air from above e.g. in the areas surrounding tropics of Cancer and Capricorn) and hence they are also classified into (1) **cold high pressure system** (high pressure in the polar regions due to very low temperature and snow covered surface), and (2) **warm high pressure system** (developed due to subsidence of air from above in the subtropical areas). It is, thus, apparent that cold and warm high pressure systems are developed due to thermal and dynamic factors

respectively. Warm pressure systems (warm anti-cyclones) are large in size but very sluggish in movement. Some time, they become stationary over a place for several days and weeks. On the other hand, cold high pressure systems (cold anti-cyclones) are smaller than warm high pressure systems in size but move more rapidly than the latter.

The outward elongated extension of high pressure displayed by elliptical isobars in low

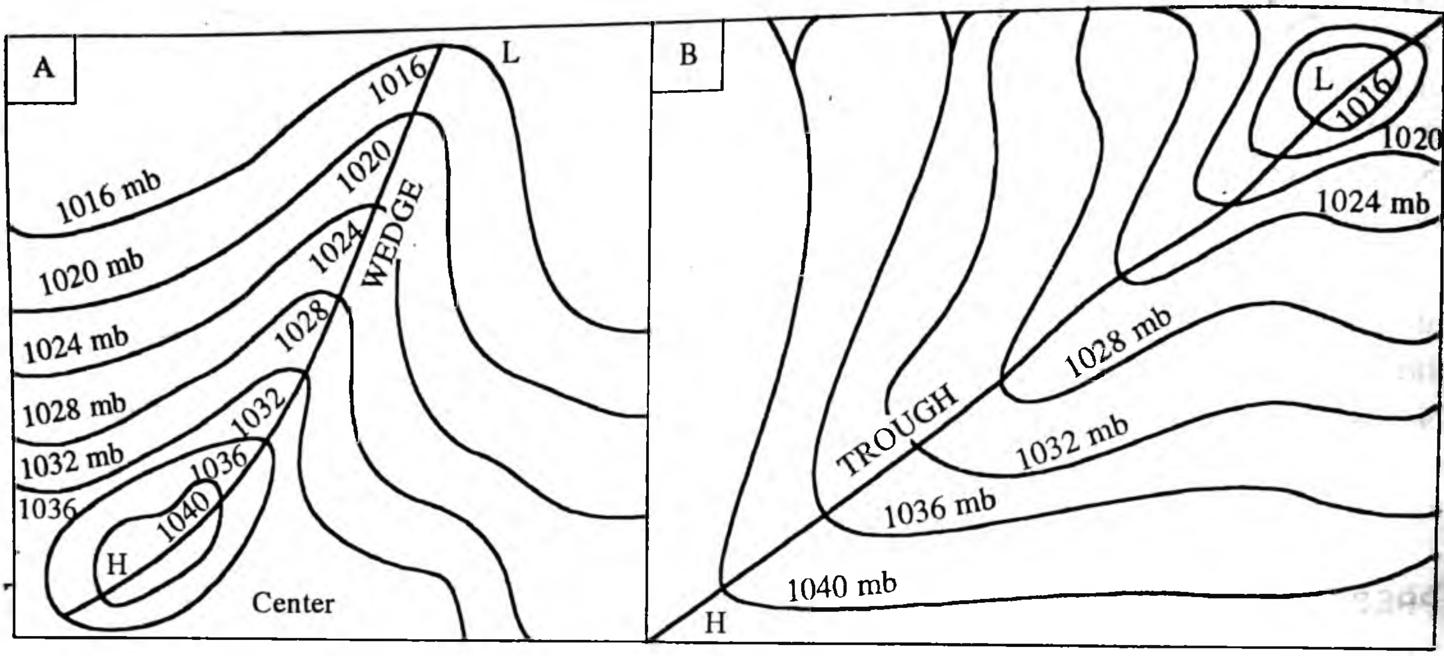


Fig. 5.2 : (A) Ridge (wedge) of high pressure system, and (B) trough of low pressure system).

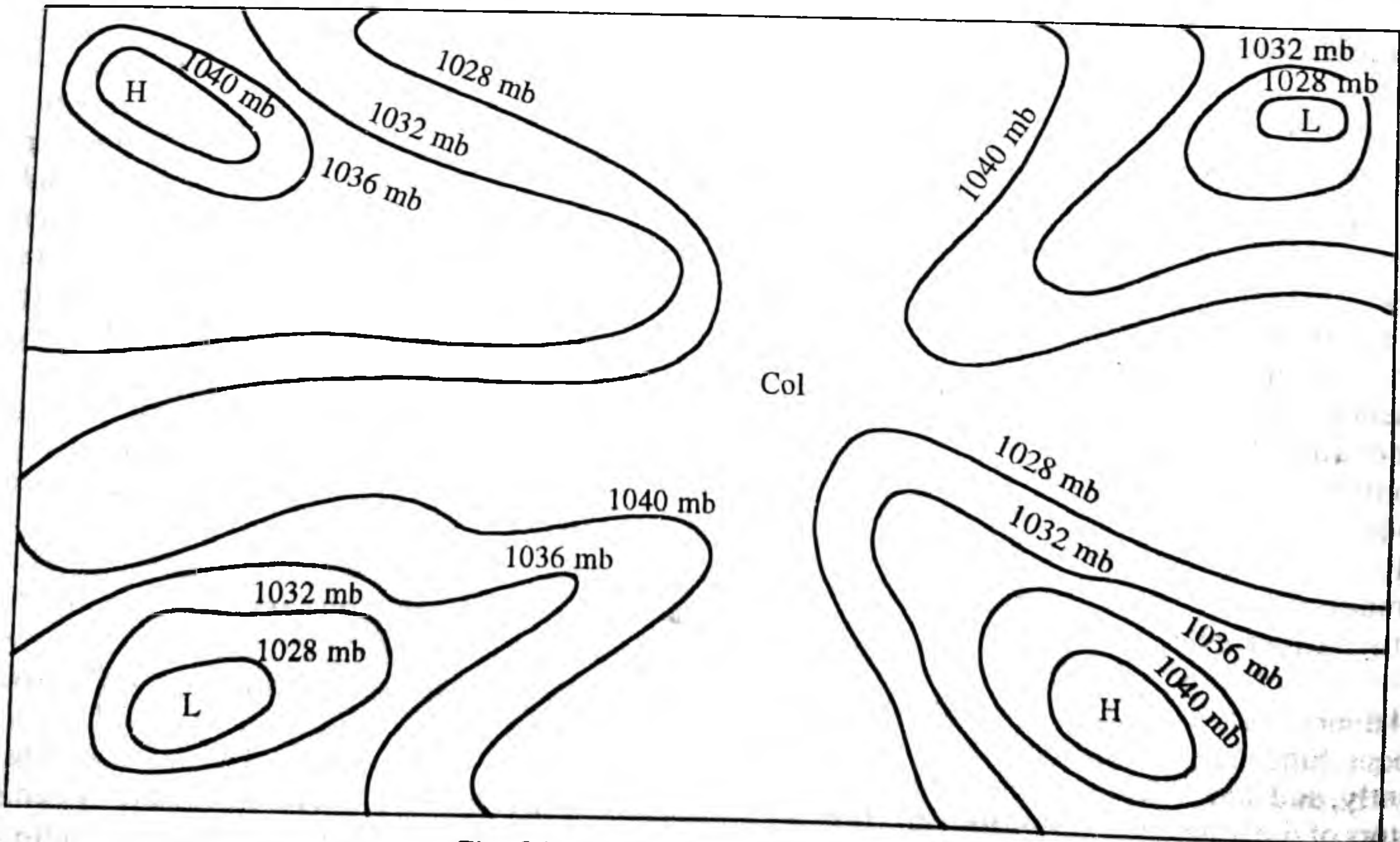


Fig. 5.3 : Formation of a barometric col.

pressure region is called a **high pressure ridge** or **wedge** (Fig. 5.2). On the other hand, the outward extension of low pressure into a region of high pressure as displayed by elliptical isobars is called **low pressure trough** or **trough of low pressure.** An area of uniform pressure developed between two high pressure systems and two low pressure systems is called **Col** (a barometric col).

(2) **Low pressure systems** are also called **Low** or simply **L** or **cyclones** or **depressions.** These are centers of low pressure having increasing pressures outward and closed air circulation from outside towards the central low pressure in such a way that air blows inward in anti-clockwise in the northern hemisphere and clockwise in the southern hemisphere (fig 11.5). Cyclonic low pressure systems are also termed as atmospheric disturbances. They range in shape from circular, elliptical to V shape. The elongated outward extension of low pressure displayed by elliptical isobars is called **low pressure trough** or **cyclonic trough** (Fig. 5.2B). The pressure gradient is from periphery to the center which allows air circulation from outer margin to the central point of lowest pressure. Due to coriolis force and Ferrel's law the winds are deflected to their right in the northern hemisphere and cross the isobars at very low angle and the spiral pattern of wind circulation becomes anti-clockwise in the northern hemisphere while the trend is reversed in the southern hemisphere. Low pressure systems may be further subdivided into (1) **heat lows.** and (2) **dynamic lows.** Heat lows represent those low pressure systems which are thermally induced (due to heating of ground surface from solar radiation). Such heat lows generally develop in the tropical areas. The dynamic lows are dynamically induced (due to rotation of the earth and convergence of warm and cold air masses) and generally develop in temperate regions *i.e.* mid-latitudes. Low pressure systems or cyclones are indicative of humid weather condition.

The heat lows or thermal lows generally develop during summer days due to intense heating of ground surface in the tropical and subtropical zones. Such lows are more or less stationary or move very sluggishly from the place of their origin. Thermal lows also develop in those temperate areas during summers which are not characterized by the activity of polar front and the formation of temperate cyclones.

5.4 VARIATIONS IN ATMOSPHERIC PRESSURE

As stated in section 5.1 of this chapter air pressures vary both spatially and temporally, horizontally and vertically. As regards temporal variations in atmospheric pressures, diurnal and seasonal variations are climatically more important. The 24-hourly average of atmospheric pressure at sea level is called daily mean pressure which is more or less constant.

(1) **Daily variation** of air pressure is controlled by heating of the ground surface and boundary air layer by solar radiation, called as insolational heating, and cooling of the ground surface and boundary air layer by outgoing terrestrial radiation, called as radiational cooling. The insolational heating results in the development of low pressure due to ascent and expansion of warm air while radiational cooling results in high pressure due to descent and contraction of cold air. It is apparent that daily cycle of low and high pressure of a place is of thermal origin but the maximum and minimum (highest and lowest) pressures do not correspond to the time of daily maximum and minimum temperatures. This difference of time between the occurrence of daily maximum temperature and lowest pressure on one hand, and minimum daily temperature and highest pressure may be termed **pressure lag.** It may also be mentioned that daily temperature record is marked by single maximum temperature and single minimum temperature while daily pressure is characterized by two maxima at 10 a.m. and 10 p.m. and two minima at 4 a.m. and 4 p.m. This is called semi-diurnal variation of pressure or **semi-diurnal oscillation.** Diurnal variations are so rhythmic that these are more or less regular. The daily variation in air pressure is more pronounced in the tropical and subtropical areas and are weakened poleward mainly in higher latitudes. The regularity of pressure variation is disturbed by the occurrence of atmospheric disturbances (different forms of cyclones) in the mid-latitude areas.

(2) **Seasonal pressure variations are related** to changes in pressures during summer and winter

seasons. Seasonal pressure variation is also called annual pressure variation. Since the air pressure is mostly the function of insolational heating and terrestrial radiational cooling at global, regional and local levels and there is vast variation in the amount of insolation received at the ground surface during winter and summer seasons, and hence it is natural to observe seasonal variations in air pressure. The equatorial zone displays smallest seasonal variation in the pressures because the amount of insolation received at the ground surface remains almost constant throughout the year. The tropical and subtropical areas record largest seasonal variation of atmospheric pressure due to extreme weather conditions during summers and winters. The size of the continents also determines the magnitude of seasonal pressure variations. Central Asia is characterized by large seasonal pressure variations because of large seasonal contrasts in thermal conditions due to long distance from the sea coast and hence continentality becomes the major control of seasonal pressure conditions. There is also seasonal shifting in pressure belts over the globe due to revolution of the earth around the sun. The seasonal shifting of global pressure belts will be discussed in section 6.6 of the 6th chapter.

(3) **Vertical pressure variation** denotes decrease of air pressure with increasing altitude because of decrease in air density with increase in height from sea level. The density depends on volume of air and the volume depends on expansion (decrease in density) and contraction (increase in density) of air which are the result of heating and cooling of air respectively. The ascending air expands aloft and becomes less dense resulting in the decrease of air pressure but the rate of decrease of air pressure is not constant, rather the rate of decrease also varies with altitude. It is evident from tables 5.1 and 5.2 that the rate of decrease of air pressure with increasing elevation also decreases. The net decrease of air pressure from sea level (1013.25 mb) to 500 m altitude (954.61mb) is 58.64 mb. For every 500m increase in altitude the net decrease is 55.83 mb (at 1 km), 53.17 mb (at 1.5 km), 50.58 mb (at 2 km), 48.10 mb (at 2.5 km), 45.70 mb (at 3 km), 43.41 mb (at 3.5 km), 41.2 mb (at 4 km), 39.08 mb (at 4.5 km), and 37.04 mb (at 5 km). It is evident that the rate of decrease of air pressure also decreases with increasing altitude. It is also clear from tables 5.1 and 5.2 that the atmospheric pressure reduces to about half after every 5 km increase in elevation.

Table 5.2 : Trend of Atmospheric Pressure with Altitude.

Altitude (km)	Air Pressure (mb)	Net Decrease (mb)
0.0 (sea level)	1013.25	—
0.5	954.61	58.64
1.0	898.76	55.85
1.5	845.59	53.17
2.0	795.01	50.58
2.5	746.91	48.10
3.0	701.21	45.70
3.5	657.80	43.41
4.0	616.60	41.20
4.5	577.52	39.08
5.0	540.48	37.04
10.0	264.99	275.49
15.0	121.11	123.88
20.0	55.29	65.82
25.0	25.49	29.80
30.0	11.97	13.52

Source : J.M. Morgan and M.D. Morgan, 1991, in Oliver and Hidore, 2003. The net decrease in air pressure is after every 0.5 km increase in altitude upto 5 km height, thereafter the net decrease has been shown after every 5 km height.

5.5 HORIZONTAL DISTRIBUTION OF AIR PRESSURE AND PRESSURE BELTS

The horizontal distribution of air pressure on the globe is studied on the basis of **isobars.** Air pressure is generally divided into two types viz. (1) high pressure, also called as **'high'** or **anticyclone,** and (2) low pressure, also called as **'low'** or **cyclone** or **depression.** If we look at the globe then it appears that there is certain definite system of high and low pressure. If, for generalization, the globe is considered to be homogeneous (either of land or water), then there should be regular and

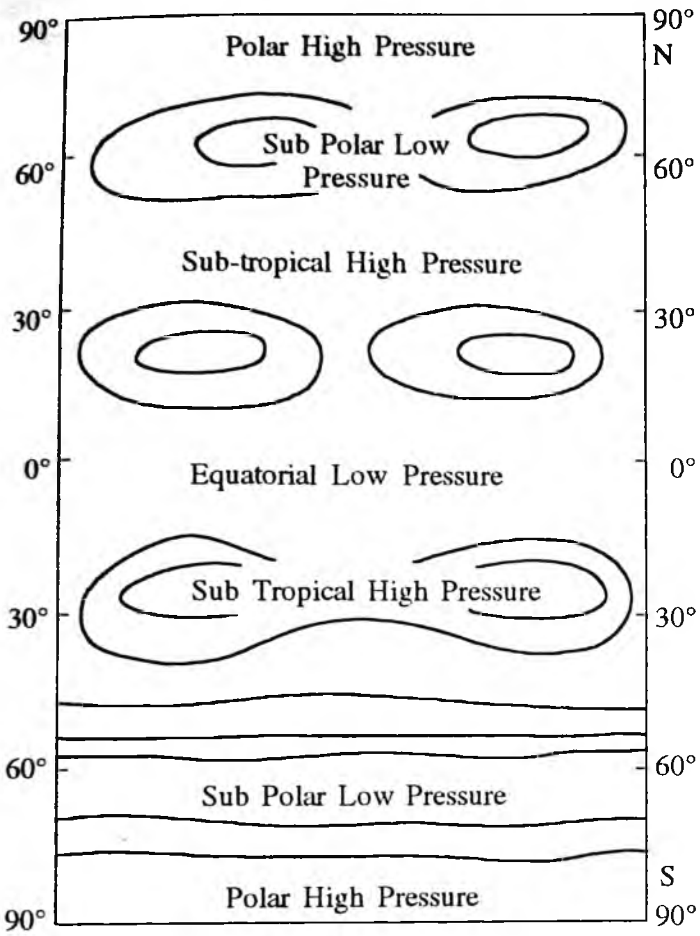


Fig. 5.4 : Generalized distribution of air pressure.

systematic zonal distribution of high and low pressure but the regularity of pressure belts is disturbed due to unequal distribution of land and water on the globe. The pressure belts are discontinued in the northern hemisphere and several centres of pressure belts are developed but the pressure belts are found more or less in regular pattern in the southern hemisphere.

(A) Latitudinal Distribution of Pressure

There is no definite trend of distribution of pressure from equator towards the poles. If the air pressure would have been the function of air temperature alone there should have been regular increase of pressure poleward because temperature regularly decreases from the equator towards the poles but this is not the case. There is low pressure near the equator due to high mean annual temperature but the existence of high pressure belts near the tropics of Cancer and Capricorn cannot be explained on the basis of temperature because the tropics record very high temperature and hence there should have been low pressure if the temperature would have been the only control of air pressure. The air pressure should increase poleward from the tropics of Cancer and Capricorn because there is rapid rate of decrease of temperature poleward but we find low pressure belt near 60^0 latitude. Again we find high pressure belts near the poles due to exceedingly low temperature throughout the year. It is obvious that pressure belts are not only induced by thermal factor but they are also induced by dynamic factors.

In all, there are seven pressure belts on the globe. On the basis of mode of genesis pressure belts are divided into two broad categories *e.g.* (1) thermally induced pressure belts (*e.g.* equatorial low pressure belt and polar high pressure belt), and (2) dynamically induced pressure belts (*e.g.* subtropical high pressure belt and subpolar low pressure belt (fig 5.4).

1. Equatorial Low Pressure Belt

The equatorial low pressure belt is located on either side of the geographical equator in a zone extending between 5^0N and 5^0S latitudes but this zone is not stationary because there is seasonal shift of this belt with the northward (summer solstice) and southward (winter solstice) migration of the sun. During northern summer this belt extends upto 20^0N in Africa and to the north of tropic of Cancer in Asia while during southern summer this low pressure belt shifts to 10^0 to 20^0S latitude. The equatorial low pressure belt is thermally induced because the ground surface is intensely heated during the day due to almost vertical sun's rays and thus the lowermost layers of air coming in contact with the heated ground surface also gets warmed. Thus, warmed air expands, becomes light, and consequently rises upward causing low pressure. The equatorial low pressure belt represents the zone of convergence of north-east and south-east trade winds. There are light, feeble and variable winds within this convergence belt. Because of frequent calm conditions this belt is called a **belt of calm or doldrum.**

This belt is characterized by pronounced diurnal pressure variation.

2. Sub-Tropical High Pressure Belt

Sub-tropical high pressure belt extends between the latitudes of 25°-35° in both the hemispheres. It is important to note that this high pressure belt is not thermally induced because this zone, besides two to three winter months, receives fairly high insolation throughout the year. Thus, this belt owes its origin to the rotation of the earth and sinking and settling down of winds. It is, thus, apparent that the sub-tropical high pressure belt is dynamically induced. The convergence of winds at higher altitude above this zone results in the subsidence of air from higher altitudes. Thus, descent of winds results in the contraction of their volume, increase in density, and ultimately causes high pressure. This is why this zone is characterized by anticyclonic conditions which cause atmospheric stability and aridity. This is one of the reasons for the presence of hot deserts of the world in the western parts of the continents in a zone extending between 25°-35° in both the hemispheres. This zone of high pressure is called **'horse latitude'** because of prevalence of frequent calms. In ancient times, the merchants carrying horses in their ships, had to throw out some of the horses while passing through this zone of calm in order to lighten their ships. This is why this zone is called horse latitude. It is interesting to note that this zone of high pressure is not continuous belt but is broken into a number of high pressure centres or cells (fig. 5.4)

3. Sub-Polar Low Pressure Belt

This belt of sub-polar low pressure is located between 60°-65° latitudes in both the hemispheres. The low pressure belt does not appear to be thermally induced because there is low temperature throughout the year and as such there should have been high pressure belt instead of low pressure belt. It is, thus, obvious that this low pressure belt is dynamically produced. In fact, the surface air spreads outward from this zone due to rotation of the earth and low pressure is caused. It may be pointed out that this factor should be more effective at the poles but the effects of the rotation is negated or say overshadowed due to exceptionally low temperature prevailing throughout the year at the poles. The sub-polar low pressure belt is more developed and regular in the southern hemisphere while it is broken in the northern hemisphere (fig. 5.4) because of over dominance of water (oceans) in the former. Instead of regular and continuous belt there are well defined low pressure centres or cells over the oceans in the northern hemisphere e.g. in the neighbourhood of Aleutian Islands in the Pacific Ocean and between Greenland and Iceland in the Atlantic Ocean. It may be noted that due to great contrasts of temperatures of the continents and oceans during northern summer the low pressure belt becomes discontinuous and is found in a few low pressure cells while the temperature contrast between the continents and oceans is much reduced during winter and hence low pressure belt becomes more or less regular and continuous in the northern hemisphere. The mid-latitude low pressure belt (subpolar low pressure belt) is regular and unbroken because of vast extent of oceans and hence the contrast of heating and cooling of the continents and oceans is minimized in the southern hemisphere.

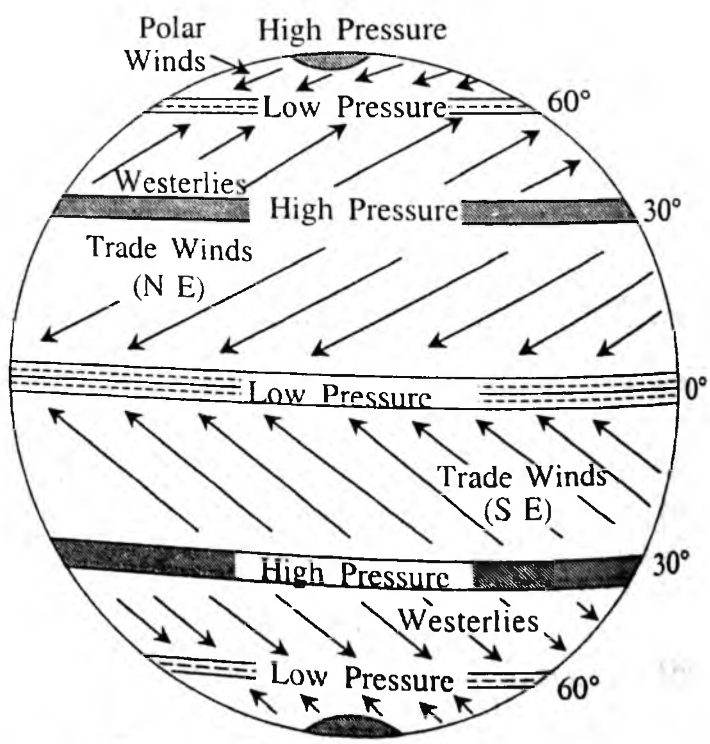


Fig. 5.5 : Air pressure and wind belts.

4. Polar High Pressure Belt

High pressure persists at the poles throughout the year because of prevalence of very low temperature (below freezing point) all the year round. In fact, both the factors, thermal and dynamic, operate at the poles. There is thinning out of layers of air due to diurnal rotation of the earth as the air spreads outward due to this factor but this is overshadowed by thermal factor and hence high pressure is produced due to very low temperature.

Isobaric horizontal distribution of air pressure :

Isobars are imaginary lines on a map joining places of equal pressure at sea level. The seasonal

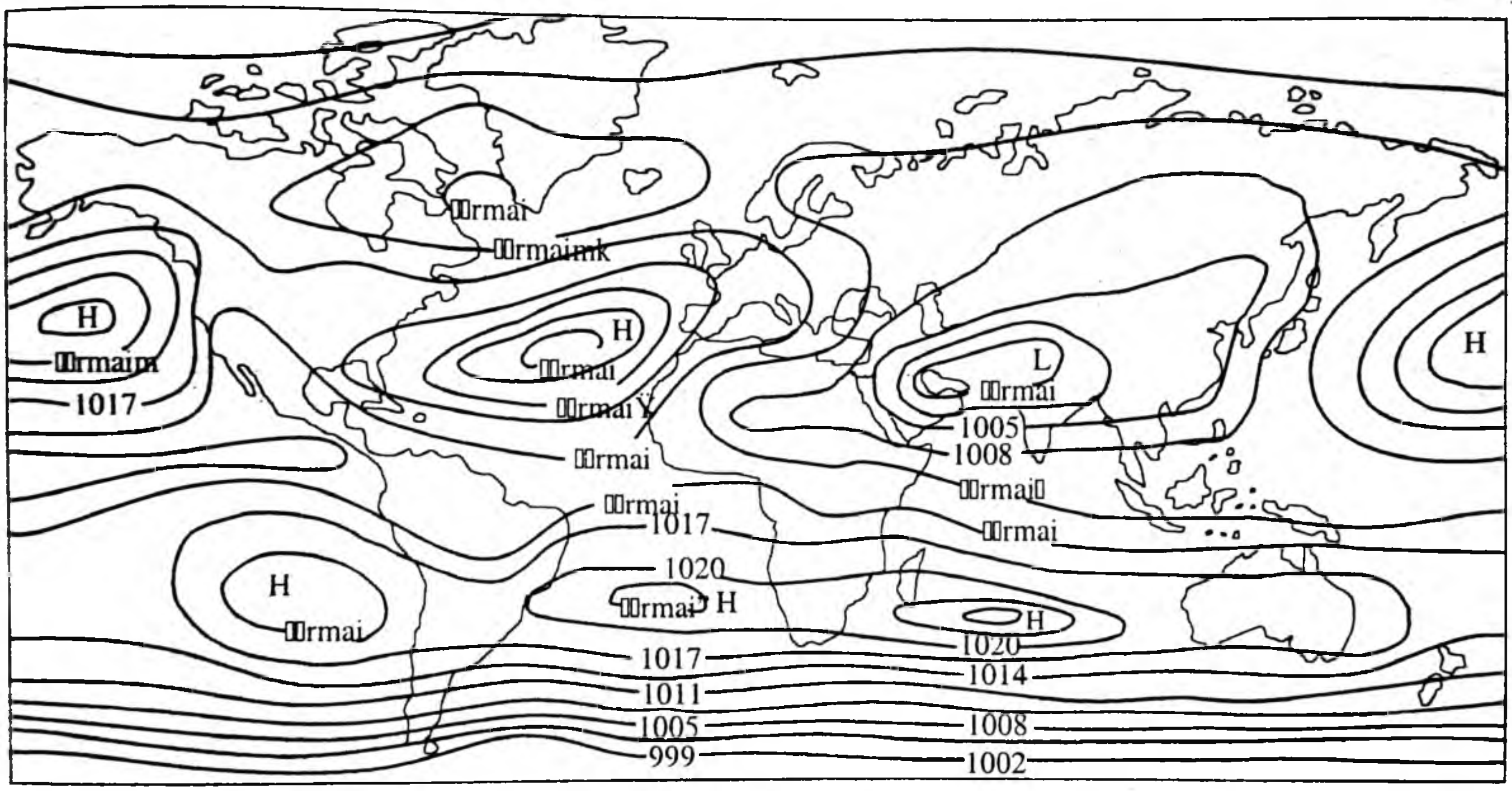


Fig. 5.6 : Isobars and world distribution of air pressure in July, figures in millibars.

(annual) horizontal distribution of air pressure is represented and studied through isobars for the months of July (to represent pressure conditions during summer season) and January (to represent air pressure during winter season) in the northern hemisphere. It may be mentioned that July isobars represent pressure conditions of winter season and January isobars display summer pressure conditions in the southern hemisphere. Figs. 5.6 and 5.7 display the world distribution of air pressure through isobars in July and January respectively. The class interval of isobars is 3 mb.

(1) Northern summer pressure and the **southern winter** pressure conditions are represented **by July isobars.** It is apparent from fig. 5.6 that there are a few pressure cells displayed by closed isobars in the northern hemisphere while the isobars are more or less regular and straight in the southern hemisphere. Equatorial low pressure is found in a narrow zonal stretch while subtropical high pressure assumes discontinuous stretches marked by a few cells of high pressure as displayed by closed isobars. The subtropical high pressure cells have been pushed northward due to northward migration of the overhead sun (summer solstice) and are located between 20^0-40^0 N latitudes. A well marked low pressure cell has developed in the south-west Asia due to excessive insolational heating of ground surface and hence dynamic factor has been negated by thermal factor. It is interesting to note that all the subtropical high pressure cells in the northern and the southern hemispheres have

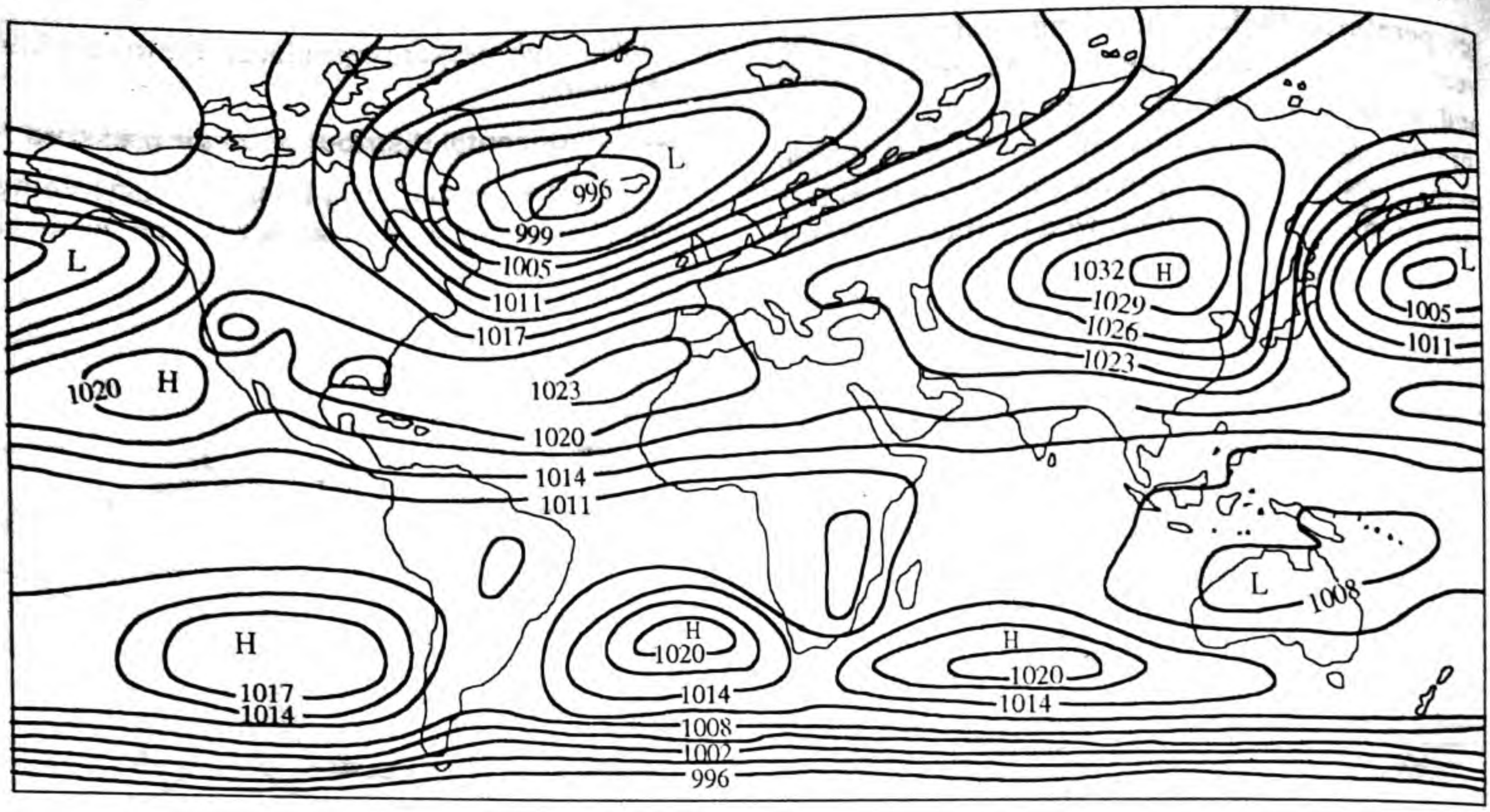


Fig. 5.7 : Isobars and world distribution of air pressure in January, figures in millibars.

developed over the oceans. The subpolar low pressure almost disappears due to northward migration of the sun. As is evident from fig. 5.6 the Icelandic low pressure is maintained but the Aleutian low pressure has disappearred. Subpolar low pressure in the southern hemisphere also shifts northward due to northward migration of the sun (summer solstice) and is located to the north of 60^0 S latitude but unlike northern hemisphere it is continuous zonal in character because of the absence of landmasses and overdominance of oceanic surfaces.

(2) **The northern winter and southern summer** pressure conditions are shown by **January isobars** (fig. 5.7). The conditions of July have almost reversed in January. The continuity of subpolar low pressure belt is broken in the northern hemisphere because of vast stretches of continents and hence it is broken into well developed Aleutian low pressure cell (50 N latitude) and Icelandic low pressure cell (60^0-65^0N latitude). The subtropical high pressure zone is also fragmented into weak high pressure cells over the oceans (e.g. high pressure cell of over 1020 mb off the Californian coast in the Pacific Ocean and 1023 mb cell off the north-western coast of Africa in the Atlantic Ocean) and into strongly developed extensive stretches over the continents mainly over Asia (Fig. 5.7). The equatorial low pressure belt shifts to the south of the equator. The subtropical high pressure zone in the southern hemisphere also shifts to the south of 30^0S latitude. Fig. 5.7 shows well developed high pressure cells (between 30^0-40^0S latitudes) over the Pacific, the Atlantic, and the Indian Oceans. The subpolar low pressure belt in the southern hemisphere develops in continuous zone between 60^0-70^0S latitudes.

(B) Meridional Distribution of Pressure

Meridional pressure distribution means average seasonal sea level pressure for all the longitudes. It may be mentioned that sea level pressures of all the longitudes for a latitude are averaged to show the meridional seasonal pressure profiles (fig. 5.8) for the study of seasonal variations in pressure belts in summer and winter hemispheres (it may be clarified that northern and southern hemispheres become summer hemispheres during July and January respectively while the southern and the northern hemispheres become winter hemispheres during July and January respectively). Fig. 5.8 reveals that (1) the three pressure belts (e.g. equatorial low pressure belt, subtropical high pressure belt, and subpolar low pressure belt) are well marked, (2) seasonal shifting of pressure belts (latitudinal or north-south shifting) becomes effective during two extreme seasons of summer and winter, (3) subpolar low pressure in the southern hemisphere

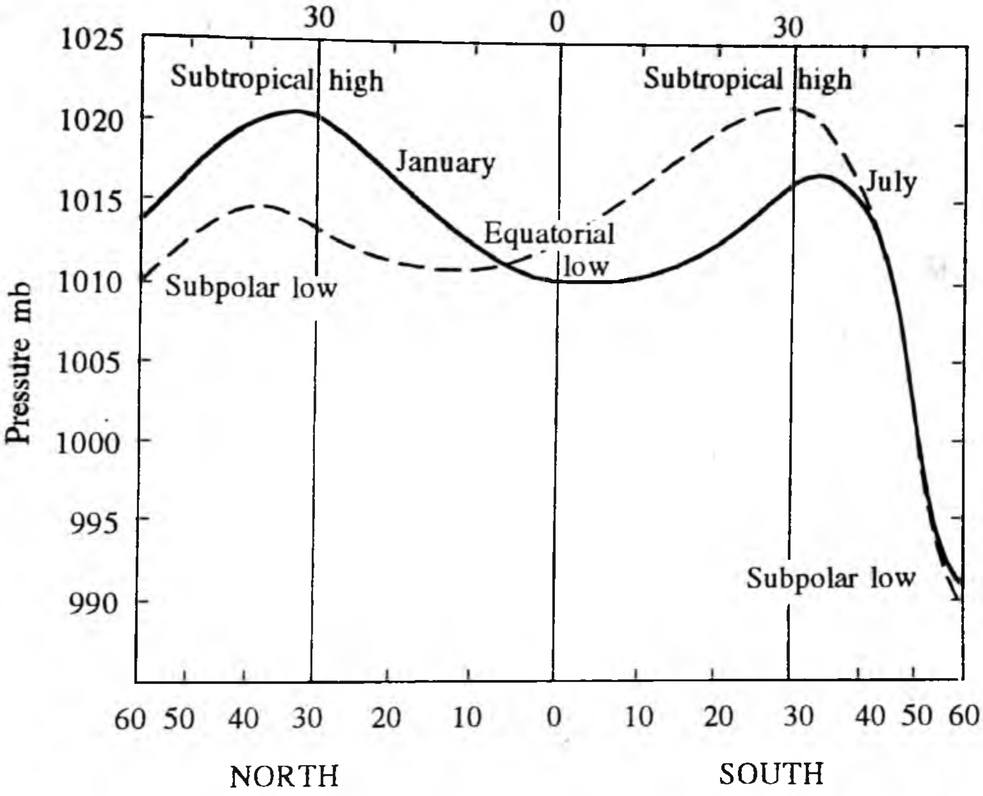


Fig. 5.8 : Meridional seasonal profiles of mean sea level pressure (in millibar, mb) over land areas, based on Mintz and Dean; and G.T. Trewartha, 1954.

is very low (about 990 mb) and is more or less stable during summer and winter seasons but the northern hemispheric subpolar low pressure ranges between 1008 mb and 1015 mb, (4) pressure gradients are more pronounced (steeper) during January and July in the northern and southern hemispheres respectively (i.e. in the winter hemisphere) than in the summer hemisphere (July in the northern hemisphere and January in the southern hemisphere), (5) 'there is an enormous mass transfer of atmosphere (air circulation) from the warmer summer hemisphere to the colder winter hemisphere. It has been calculated that the July to January net flow of mass across the equator amounts to approximately 2 trillion tons, but this is only 1/2,500 of the mass of the earth's atmosphere' (G. T. Trewartha, 1954) etc.

5.6 SHIFTING OF PRESSURE BELTS

The surface pattern of air pressure as discussed above and represented through figs. 5.1 and 5.2, seldom remains stationary in its latitudinal zone. There are daily, seasonal and annual changes in air pressure because of northward and southward movement of the overhead sun (summer and winter solstices), contrasting nature of the heating and cooling of land and water etc. The lowest pressure is developed between 2 to 4 p.m. during the day due to maximum temperature while highest pressure is recorded between 4-6 a.m. due to minimum temperature during night. It may be mentioned that there are two pressure minima 4 a m. and 4 p.m. and two pressure maxima at 10 a.m. and 10 p.m. Coastal land records low pressure while adjoining oceanic area has high pressure during the day. This situation is reversed during night. Except polar high pressure belt all the pressure belts move northward with the northward movement of the sun during summer solstice. On the other hand, except the polar high pressure belt, all the belts move southward due to southward movement of the sun during winter solstice when the sun is vertical at the tropic of Capricorn. The pressure belts occupy their normal ideal position at the time of vernal equinox (21 March) and autumnal equinox (23 September) when the sun is vertical at the equator. Seasonal shifting of pressure belts has been shown in fig. 6.9 (chapter 6).

5.7 ATMOSPHERIC MOTION

The atmosphere is a turbulent fluid because gases and liquids (water vapour in the case of the atmosphere) are fluids and these are principal constituents of the atmospheric composition. It, thus, becomes obvious that the laws of gases and fluids in terms of motions will also be applicable in the case of atmospheric motion (air circulation). Fluids are characterized by basically two types of motion (flow), namely **laminar flow** and **turbulent flow** where in a laminar flow particles move in only one direction i.e. in forward direction while particles move almost in all directions in turbulent flow which may assume the form of either convection currents or eddies. Turbulent flow is generated because of inequality of forces. In the case of the atmosphere inequality of forces is caused due to variation in temperature and pressure. According to **Newton's Law of Motions** the change in velocity of a body, which is in motion, is effected when the acting force changes and becomes unbalanced. The velocity and direction of motion of a body (here the atmosphere) remain constant so long as the forces of acceleration remain constant and in balance. In the case of the earth's atmosphere air seldom moves continuously in same direction with same velocity in straight line rather its velocity and direction frequently change because of frequent changes in temperature and pressure conditions. In fact, the acceleration of air motion is the function of the sum of all forces acting on it. These forces include (1) **pressure gradient force**, (2) **Coriolis force** or the **earth's deflective force**, (3) **frictional force**, and (4) **rotational force**. Newton's **second law of motion** states 'that the acceleration of any body-in this case, the parcel of air-is directly proportional to the magnitude of the net forces acting on it and inversely proportional to its mass' (Oliver and Hidore, 2003).

1. Pressure Gradient and Air Circulation

The difference of pressure between two places is called **pressure gradient**. Since pressure is inversely related to temperature, differences in pressure are, thus, the result of differences in the heating and cooling of land and water surfaces. Low temperature generates high pressure and high temperature gives birth to low pressure. Steep pressure gradient is represented by closely spaced isobars while widely spaced isobars reveal low pressure gradient. Since pressure is the function of temperature, steep pressure gradient is generated by large temperature variation between two places and gentle (low) pressure gradient is the result of small temperature variation. The direction of pressure gradient is considered from high pressure to decreasing pressure and the pressure gradient is always perpendicular to isobars. Pressure gradient is also called **barometric slope**. There is very close relationship between pressure gradient and atmospheric motion (air circulation) in terms of speed and direction of air movement. As per rule air moves down the pressure gradient from high pressure to low pressure. In other words, air movement follows barometric slope. The rate of air movement (*i.e.* wind speed) depends on the steepness of gradient. As per rule there is direct positive relationship between steepness of pressure gradient and wind speed. The steeper the pressure gradient, the higher the rate of air movement (wind speed) and lower the pressure gradient, the slower the wind speed. The wind direction is also dependent on the direction of pressure gradient (which is always from high pressure to low pressure areas). As per rule the direction of air movement should be perpendicular to the isobars (fig. 5.9) because the direction of pressure gradient is perpendicular to the isobars but the direction is deviated from the expected theoretical direction due to Coriolis force caused by the rotational movement of the earth and hence the winds cross the isobars at acute angle instead of right angle. Centers of high pressure and low pressure cause horizontal divergence and convergence of air circulation on the ground surface but convergence and divergence aloft respectively.

It may be pointed out that the force generated by pressure gradient is called **pressure gradient force** which is accelerating force for air movement. Since pressure varies both horizontally and vertically, and hence pressure gradient force is divided into two types, namely (1) horizontal pressure gradient force (P_H), and (2) vertical pressure gradient force (P_V). The horizontal pressure gradient force generates horizontal movement of air at the ground surface from the center of high pressure to the low pressure center, while the

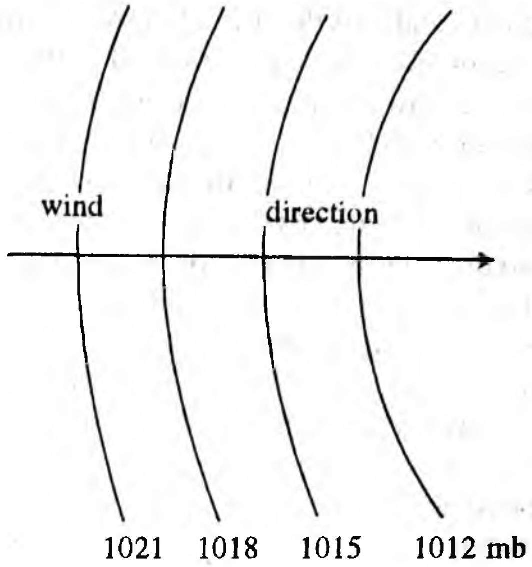


Fig. 5.9 : Pressure gradient and wind direction.

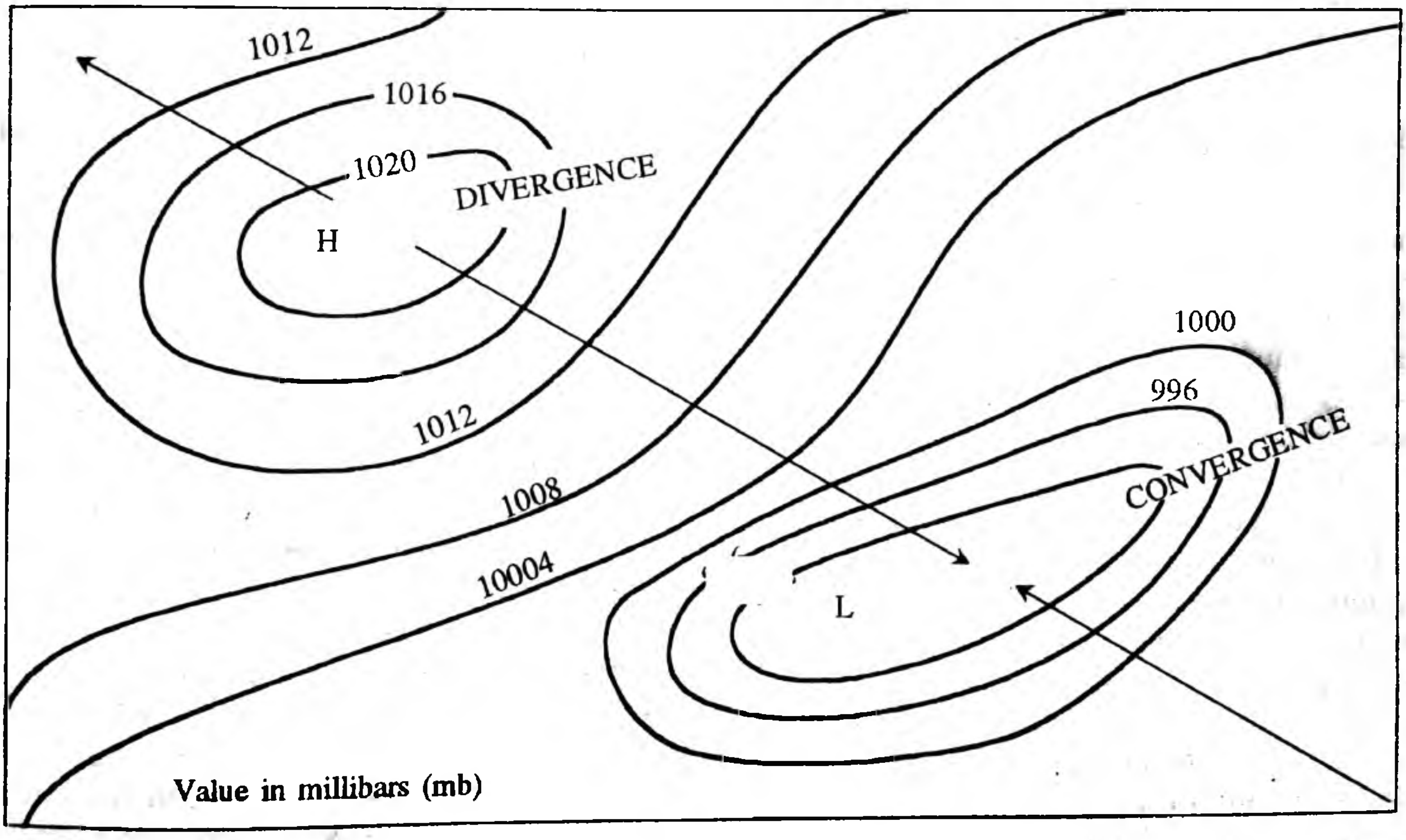


Fig. 5.10 : High and low pressure systems and wind direction. Pressure gradient is directed from the center of high pressure (H) towards the center of low pressure (L) and so is the wind direction i.e. from H to L.

vertical pressure gradient force generates upward and downward movement of air as convection currents and turbulent air circulation. The pressure decreases upward rapidly and hence pressure gradient is also steepened vertically. Since the wind speed depends on the steepeness of pressure gradient and resultant pressure gradient force, it is expected that the speed of upward movement of air should be high but the force of gravity (G) acts downward and hence it obstructs the upward movement of air and thus the speed is slowed down. When the upward pressure gradient force is balanced by downward acting gravity force, the vertical acceleration becomes zero. This situation of balance is called **hydrostatic equilibrium.** So long as this equilibrium exists, there is atmospheric stability and dry condition prevails, but whenever deviation from this ideal equilibrium condition is occasioned, vertical acceleration of air is activated, upward movement of air occurs, equilibrium condition is disturbed, atmospheric instability prevails resulting into cloud formation, precipitation and moist weather condition. It may also be mentioned that the horizontal pressure gradient force (P_H) is not balanced by any other force as is the case of vertical pressure gradient force and the gravity force, the acceleration continues, but the speed of horizontally moving wind is slowed down due to frictional force generated by the friction of ground and water surfaces over which blows the wind.

2. Coriolis Force (Effect)

The direction of surface winds is usually controlled by the pressure gradient and rotation of the earth. Because of rotation of the earth along its axis the winds are deflected. The force which deflects the direction of winds is called **deflection force.** This force is also called **coriolis force** on the basis of the name of famous scientist G.G. Coriolis (1792-1843) who observed and explained the process of deflection in wind direction for the first time. Because of coriolis force all the winds are deflected to the right in the northern hemisphere while they are deflected to the left in the southern hemisphere with respect to the rotating earth. This is why winds blow counter clockwise around the center of low pressure (to make a cyclonic circulation) in the northern hemisphere while they blow in clockwise direction in the southern hemisphere. It may be mentioned that coriolis force is not in itself a force in real sense rather it is an effect of the rotational movement of the earth and hence it is also called as **Coriolis Effect.** The characteristic features of Coriolis Effect may be summarized as follows :

(1) Coriolis force is not in itself a force rather is an effect of rotational movement of the earth.

(2) Coriolis force becomes effective on any object which is in motion (*i.e.* wind, flying birds, aircrafts, ballistic missiles, long-range artillery fire etc.).

(3) Coriolis force affects wind direction and not the wind speed as it deflects the wind (and other moving objects) direction from expected path.

(4) The magnitude of Coriolis force is determined by wind speed. The higher the wind speed, the greater is the deflection of wind direction due to resultant greater deflective (Coriolis) force.

(5) It becomes maximum at the poles due to minimum rotational speed of the earth while it becomes zero at the equator.

(6) It always acts at right angles to the horizontally moving air and other moving objects. The net effect is that the horizontal winds are deflected to the right in the northern hemisphere and to the left in the southern hemisphere.

(7) The magnitude of deflection (Coriolis effects) is directly proportional to (i) the sine of the latitude (sin $0^0 = 0$, sine $90^0 = 1$), (ii) the mass of the moving body, and (iii) horizontal velocity of the wind.

It may be remembered that the direction of pressure gradient is always from high pressure to low pressure. The earth rotates from west to east. Every latitude is a complete circle. Equatorial latitudinal circle is the largest one and the latitudinal circles decrease poleward wherein polar circle is the smallest one. The whole earth completes one rotation along its axis roughly in 24 hours. Thus, the rotational speed of the earth is highest at the equator and decreases poleward. When the wind moves either northward or southward following straight path in equatorial region it does not reach its destination because by that time the destination place moves ahead and the wind lags behind because of high rotational speed of the earth (fig. 5.11). Contrary to this the wind moving either northward or southward in high latitudes reaches ahead of its destination because of decreasing rotational speed of the earth.

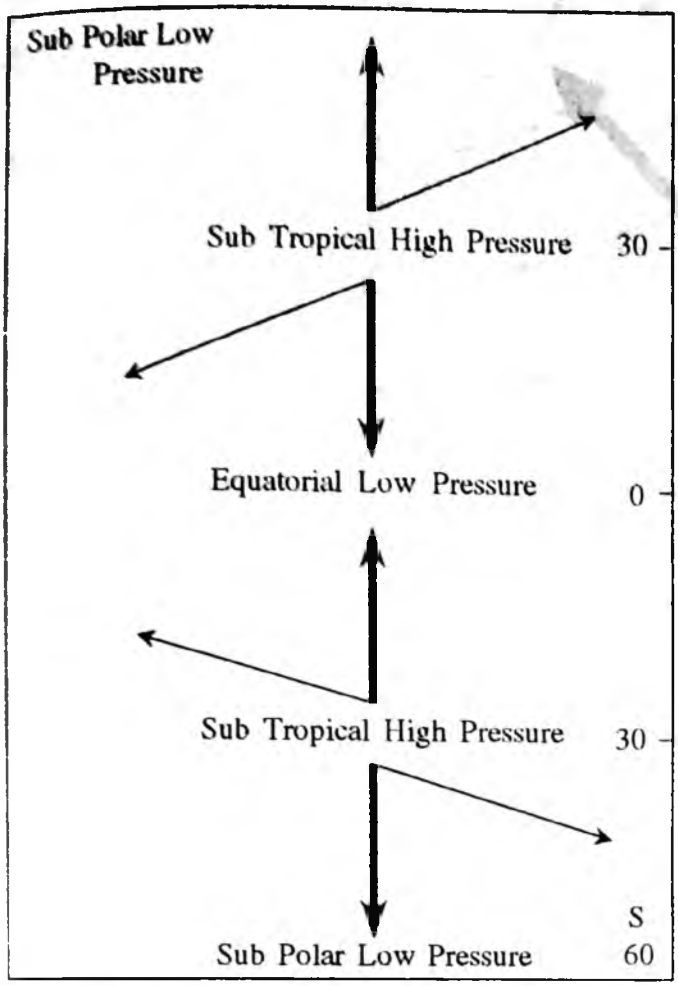


Fig. 5.11 : Deflective force and wind direction.

Wind Direction and Related Laws

Based on the deflective force (Coriolis force) of the earth and deflection of winds Ferrel has propounded his law which is popularly known as **Ferrel's Law**. This law states that '*if one stands with one's back towards the direction from where winds are coming they (winds) are deflected to the right in the northern hemisphere and to the left in the southern hemisphere.*' Buys Ballot, a Dutch meteorologist, formulated his law of wind direction in 1857 on the basis of relationship between wind direction and pressure. According to his law '*In the northern hemisphere if you stand with your back to the wind there will be low pressure to your left and high pressure to your right. In the southern hemisphere the coriolis deflection being to the left the situation is reversed.*'

3. Frictional Force

The force generated by the resistance of the surface of an object against a moving object is called **frictional force.** In the case of atmospheric motion the frictional force is generated by the resistance of ground or water surfaces over which blows the wind. Thus, frictional force works in opposition to the pressure gradient force and reduces the wind speed and Coriolis force. It may be mentioned that frictional force like Coriolis force becomes operative and effective only when the object (here, wind) is in motion. The following are the characteristics of frictional force.

(1) The magnitude of frictional force depends upon the degree of roughness of the surface over which winds blow following the pressure gradient (high pressure to low pressure). The surfaces are of two types, namely ground surface and water surface. The ground surface is characterized by high degree of roughness because of hill ranges, stony surface, vegetation cover (ranging from grasses to forests), buildings while the water surface is smooth. Thus, ground surface offers maximum degree of resistance and hence friction due to higher degree of roughness while water surface offers minimum resistance. It may be summarized that the greater the roughness of the surface, the higher the degree of resistance and resultant friction and vice versa.

(2) The frictional force works in opposition to the pressure gradient force and hence against the horizontal movement of air. Thus, the frictional force hinders the free movement of air down the pressure gradient and reduces the wind speed (velocity) and Coriolis effects.

(3) The zone of lower atmosphere where frictional force becomes effective is called **friction layer**. The frictional force is maximum at the surface and decreases upward in the lower atmosphere. It may be mentioned that the frictional effect is transported upward due to turbulence upto the height of about 1000 meters. It may also be pointed out that the effect of frictional force diminishes rapidly upward in the lower atmosphere and thus the winds characteristics become equal to geostrophic winds aloft. The altitudinal variations of winds are shown by spirals wherein each spiral of winds represents equal angle. Such equi-angle spirals are called **Ekman Spirals.**

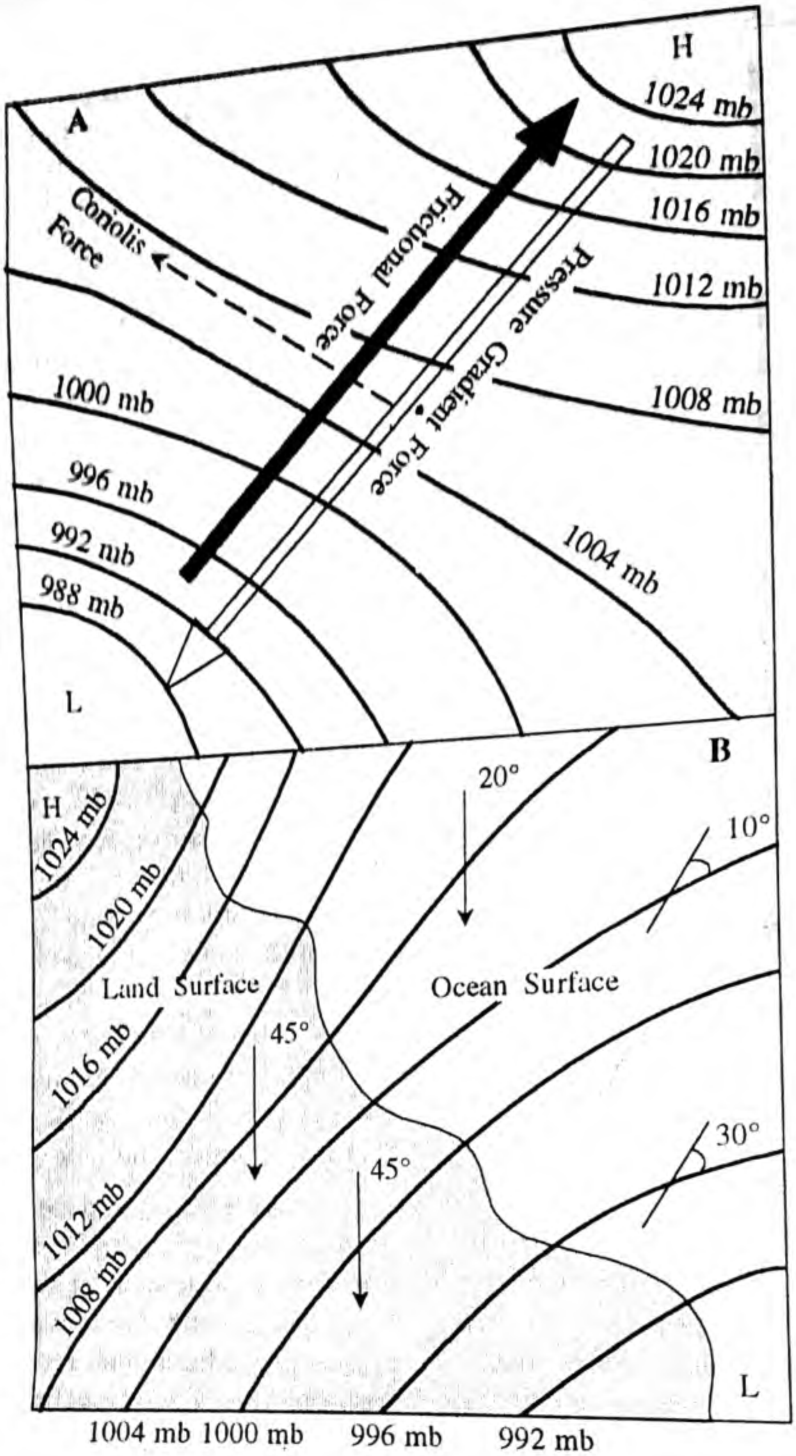


Fig. 5.12 : (A) Pressure gradient force (P_F), frictional force and Coriolis force (effect), (B) angle of horizontal wind direction over ocean and land surfaces. Isobars are in millbars.

(4) As stated above the ground and water surfaces having contrasting behaviours due to varying degree of roughness reduce the Coriolis effect differently. Over the water surfaces of the seas and oceans the horizontal winds cross the isobars at the angle of 10^0-20^0 due to least frictional force while they cross the isobars at the ground surface at the angle of 45 degree. The net result of the frictional force working in opposition to the horizontal winds is that the velocity of wind is reduced by 35 per cent and hence winds blow with only 65 per cent of the velocity generated by pressure gradient force (i.e. gradient velocity) over oceanic surfaces. On the other hand, wind velocity is reduced by 60 per cent over ground surface and hence winds below with only 40 per cent of the gradient velocity (velocity produced by the horizontal pressure gradient force) (fig. 5.12).

The relative directions of pressure gradient force, frictional force and Coriolis force have been shown in figs. 5.14 & 15.

5.8 RESULTANT AIR CIRCULATION

As stated above the pressure gradient force, Coriolis force or effect (diffective force), frictional force, rotational force etc. control the speed and direction of air circulation at the surface and above the surface. Pressure gradient force is, in fact, acceleration force which is responsible for the air circulation down the pressure gradient (from high pressure to low pressure centers) while frictional force obstructs the free circulation, of air and reduces the wind speed. The Coriolis force (effect) deflects the wind. Thus, the interaction of these controlling forces generates a few significant patterns of air circulation, namely **geostrophic wind** and **gradient wind.**

1. Geostrophic Wind

The air blowing above the ground or water surfaces, generally between the altitudes of 500-1000 meters, parallel to the isobars and at the right angle to the pressure gradient, is called geostrophic wind. It may be mentioned that above the friction layer, the air circulation becomes free of frictional force and it is controlled by only two forces e.g. pressure gradient force (PGF) and Coriolis force (CF). As stated earlier winds blow down the pressure gradient (from high pressure to low pressure) but they are deflected to the right in the northern and to the left in the southern hemispheres by the Coriolis force. When these two forces are balanced (PGF= CF), the resultant winds blow parallel to the isobars and are called geostrophic winds, and the zone of geostrophic winds is called **geostrophic layer** which is usually between the altitudes of 500-1000 meters (fig. 5.13).

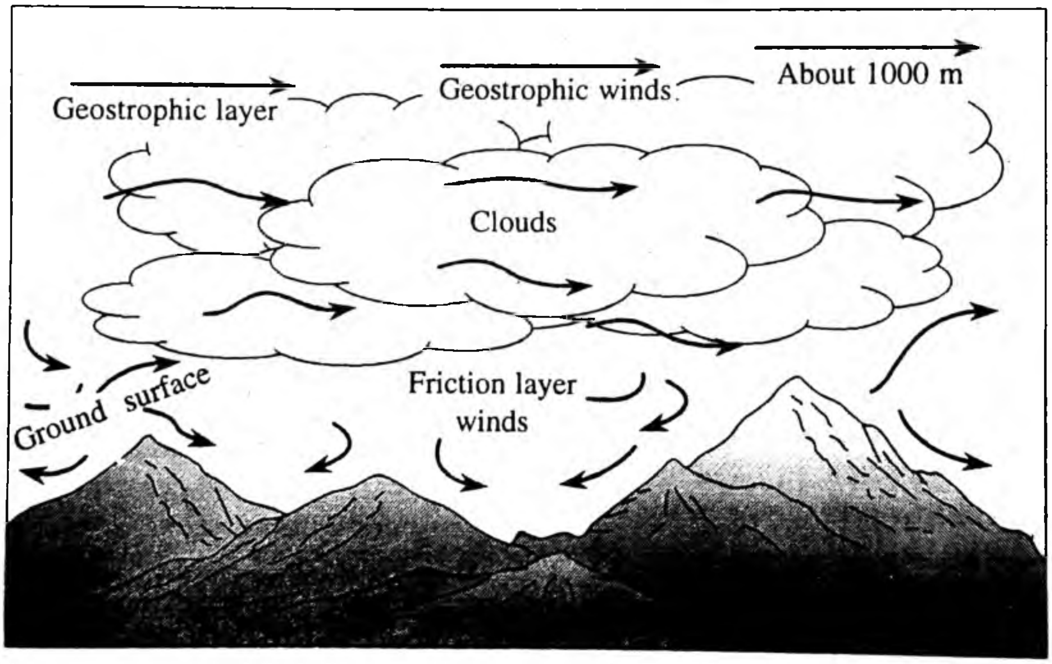


Fig. 5.13 : Presentation of friction and geostrophic layers and friction layer winds and geostrophic winds. Based on Oliver and Hidore, 2003.

The pressure gradient force (PGF) is directed from high pressure to low pressure centers while Coriolis force (effect) in directed from low pressure to high pressure centers. Thus, the Coriolis force works in opposition to pressure gradient force (*i.e.* in opposition to wind direction). As the wind begins to blow down the pressure gradient (towards low pressure center), the Coriolis force becomes active and deflects the wind to the right in the northern hemisphere. It is also significant to note that the Coriolis force (effect) is proportional to wind speed. As the wind speed

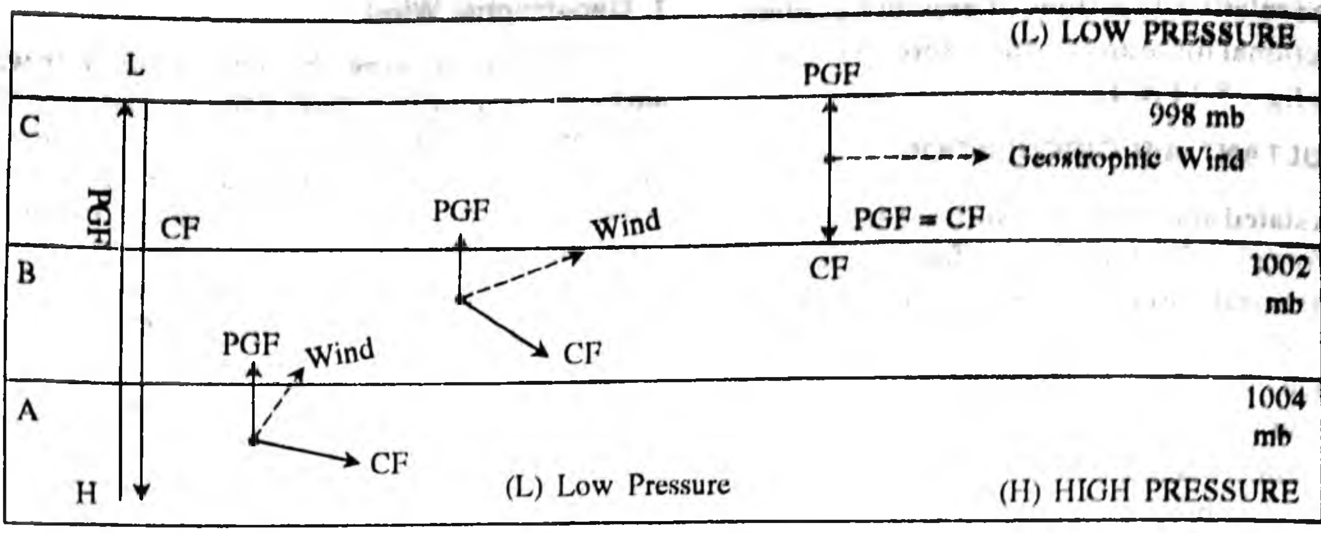


Fig. 5.14 : (A) Direction of pressure gradient force (PGF) and Coriolis force (CF) and relation between wind direction and Coriolis force, (B) with increase in wind speed Coriolis force increases and deflection of wind direction also increases ; (C) pressure gradient force is balanced by Coriolis force and resultant wind (geostrophic) blows parallel to the isobars (in millibars).

increases, the Coriolis effect also increases. Consequently, winds are deflected more and more to the right (fig. 5.14B). When the Coriolis force (effect) works diametrically opposite to pressure gradient force (PGF) or the pressure gradient force and Coriolis force (CF) are balanced, the winds begin to blow parallel to the isobars and become geostrophic winds (fig. 5.14C). It may be mentioned that when PGF is balanced by the CF, the net force becomes zero and hence winds blow in straight path parallel to isobars. This state is called **geostrophic balance.** Buys Ballot, a Dutch meteorologist, postulated a principle in 1857 that in the northern hemisphere low pressure is to the left of geostrophic wind while high pressure is to its right. In the southern hemisphere, the position is reversed (fig. 5.14). In the case of planetary surface winds, in the northern hemisphere if you stand with your back to the wind, there will be low pressure to your left and high pressure to your right (Buys Ballot, 1857).

It may be pointed out that the above mentioned geostrophic wind position is in fact theoretical approximation and is far from reality in the actual atmospheric condition because there are a set of other geographical factors (namely altitude, frictional force, topographic features, thermal conditions etc.) which make the upper atmospheric circulation very complex and hence winds in geostrophic layer never adopts straight paths, rather they blow along curved path.

2. Gradient Wind

Gradient wind is, in fact, a variant of geostrophic wind and blows along a curved or circular path parallel to the curved or circular isobars. If the geostrophic winds are the result of balance between pressure gradient force (PGF) and Coriolis force (CF), the gradient winds are the result of pressure gradient force, Coriolis force, and centrifugal and centripetal forces (fig 5.15). Gradient winds follow circular path around a low pressure center or high pressure center. In the northern hemisphere gradient winds blow parallel to isobars in clockwise direction around a high pressure center (the case of anticylonic circulation) while they blow in anti-clockwise direction around a low pressure center (the case of cyclonic circulation).

In a low pressure system (fig. 5.15B) characterized by circular isobars with lowest pressure in the center, the outward directed Coriolis force is slightly less than inward directed pressure gradient force and hence the net force (difference between outward directed Coriolis force and inward directed pressure gradient force)

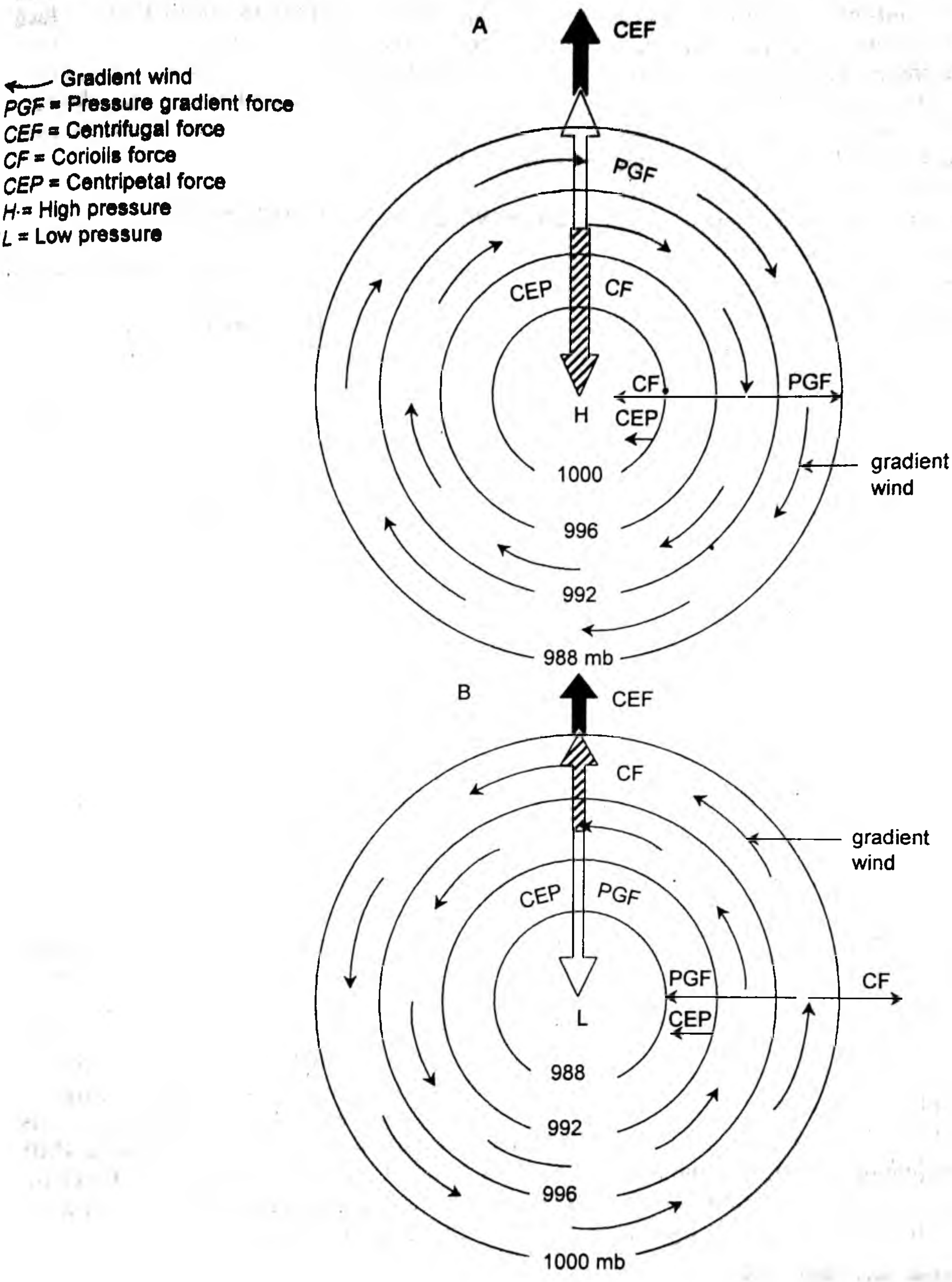


Fig. 5.15 : *Illustration of gradient winds : (A) gradient winds blowing parallel to circular isobars around high pressure center in clockwise direction in the northern hemisphere, and (B) gradient winds blowing parallel to circular isobars in anti-clockwise direction around low pressure center in the northern hemisphere. Isobars are in millibars.*

is equal to net inward directed centripetal force. As a result the gradient winds blow in anti clockwise direction parallel to the curved or circular isobars in the northern hemisphere where the Coriolis force deflects the wind to its right. It should be kept in mind that in a cyclonic system outer margin has high pressure while center has low pressure, with the result right hand deflection of wind by Coriolis force causes anticlockwise circulation of gradient wind. In the southern hemisphere the situation is reversed.

In a high pressure system (anticyclonic system) in the northern hemisphere, the inward directed Coriolis force is slightly greater than the outward directed pressure gradient force (fig. 5.15A). The difference of these two forces is equal to net inward directed centripetal force. The winds are deflected to the right and thus the winds blow in clockwise direction parallel to the curved or circular isobars in the northern hemisphere.

It may be further clarified that in a low pressure system (cyclonic system) pressure decreases from outer margin towards the center and hence pressure gradient force (PGF) is directed towards the center and Coriolis force works outward. The right hand deflection of wind should be perceived from high pressure to low pressure direction (fig 5.15 B). This is why winds blow in anticlockwise in the cyclonic circulation in the northern hemisphere while they blow in clockwise direction in the southern hemisphere where Coriolis force deflects the winds to the left. The situation is opposite in anticyclonic system wherein pressure decreases from the center outward and hence pressure gradient force works outward while Coriolis force (CF) works inward (towards the center). Consequently, winds are deflected to the right with reference to the direction from high pressure to low pressure and winds blow clockwise in the northern hemisphere and anticlockwise in the southern hemisphere (fig. 5.15 A).

Like geostrophic winds gradient winds are also approximations of real situation of air circulation above friction layer. It is also significant to point out that the geostrophic and gradient winds are much stronger in speed than surface winds in the friction layer over ground and sea surfaces because they are free from friction of the surface while surface winds have to face obstruction through resistance from the surfaces over which they blow.

5.9 WIND DIRECTION AND SPEED

The direction from which a wind blows down the horizontal pressure gradient is called direction of that wind. For example, if a wind blows from north to south, the wind becomes northerly wind. It means that the direction of a high pressure center with respect to low pressure center becomes wind direction. A south-east wind means the wind is blowing from south-east direction which is also called **upwind** side while **downwind** side indicates the direction towards which the wind blows. The hillslope or groundslope facing the wind is called **windward slope** while the opposite slope through which the wind descends is called **leeward slope. Wind vane** is used to determine wind direction while **wind roses** are used to depict direction and speed of prevailing winds on the map. Sir Francis Beaufort, a British admiral, first devised a method to estimate wind force in the year 1805 wherein he used a scale of 0-12 for the purpose. This is known as **Beaufort scale** which was subsequently modified to wind velocity (table 5.3). **Anemometer** is commonly used to measure wind speed. The **propeller-type anemometer** measures both wind speed and wind direction. **Meteorograph or tripple register** instrument records wind speed, wind direction, sunshine and precipitation. This is an automatic self recording instrument which not only records the above attributes but also provides graphic presentation. The substantial change in wind direction is called **wind shift which** falls under two types, namely (1) **veering wind shift** wherein wind direction changes in clockwise pattern, and (2) **backing wind shift** wherein wind direction changes anticlockwise.

Table 5.3 : Beaufort scale and wind speed

Beaufort Number	Kmph	Knot	Wind description	Observed effects at sea surface	Observed effects at ground surface
0	<1	<1	calm	gusty calm, like a mirror	calm, no movement of leaves

1	1–5	1–3	light air	small ripples, wavelet scales, no foam on crest	slight leaf movement, smoke drifts, wind vanes still
2	6–11	4–6	light breeze	small wavelets	leaves rustling, wind felt on face, wind vanes move
3	12–19	7–10	gentle breeze	large wavelets	leaves and twigs move, small flags and banner extend
4	20–29	11–16	moderate breeze	small longer waves	small branches moving, rising dust, paper, litter and dry leaves
5	30–38	17–21	fresh breeze	moderate, pronounced waves, some spray	small trees and branches swaying, wavelets forming on inland water bodies
6	39–49	22–27	strong breeze	large waves, white foam crests, some spray	large branches swaying, overheat wires whistling, difficult to control umbrella
7	50–61	28–33	moderate (near) gale	sea mounding up, foam and sea spray blown in streaks in wind direction	entire trees moving ,difficult to walk
8	62–74	34–40	fresh gale (or gale)	moderately high waves of greater length, breaking crests forming sea spray, well marked foam streaks	small branches breaking, difficult to walk, moving automobiles drifting and verring
9	75–87	41–47	strong gale	high waves, wave crests tumbling and sea beginning to roll, visibility reduced by blowing spray	roof shingles blown away, slight damage to structures, broken branches littering the ground
10	88–101	48–55	whole gale (or storm)	very high waves and heavy rolling seas, overhanging waves, visibility reduced	trees broken and uprooted, structural damage, considerable damage, seldom occuring
11	102–116	56–63	storm (or violent storm)	white foam covering a breaking sea of exceptionally high waves, small and medium-sized ships lost from view in wave troughs, wave crests frothy	widespread damage to structures and trees, a rare occurrence
12	>117	>64	hurricane	driving foam and spray filling the air, white sea, visibility poor to non-existent	severe to catastrophic damage, devastation to affected society

Source : Abriedged from R.W. Christopherson (in Oliver and Hidore, 2003).

5.10 CLASSIFICATION OF WINDS

The winds blowing almost in the same direction throughout the year are called prevailing or **permanent winds.** These are also called as **invariable** or **planetary winds** because they involve larger areas of the globe. On the other hand, winds with seasonal changes in their directions are called **seasonal winds** (*e.g.* monsoon winds). Winds blowing in a particular locality are called **local winds** (*e.g.* chinook, sirocco, harmattan, mistral, bora, blizzard, loo etc.). Winds blowing from hill tops to the valleys and from valley floor to the hill tops are called **mountain and valley breezes.** Winds blowing from land to sea and from sea to land are called **land and sea breezes.** Thus, the winds are classified into two broad categories *e.g.* (1) **permanent winds** or **invariable winds** or **prevailing winds** (*e.g.* trade winds, westerlies and polar winds), (2) and **variable winds,** which are further divided into (i) seasonal winds, (ii) local winds, (iii) mountain and valley breezes, (iv) land and sea breezes etc. Alternatively, atmospheric motion or wind movement is divided into 3 categories e.g. (1) **primary** or **general circulation** including planetary wind systems which are related to global pressure belts (*e.g.* trade winds, westerlies and polar winds), (2) **secondary circulation** consisting of cyclones, anticyclones, monsoons, and air masses, and (3) **tertiary circulation** which includes local winds as refered to above.

5.11 IMPORTANT DEFINITIONS

Buys Ballot Law : is related to wind direction and air pressure, and states that ' in the northern hemisphere if you stand with your back to the wind, there will be low pressure to your left and high pressure to your right. In the southern hemisphere the coriolis deflection being to the left the situation is reversed.

Coriolis force : is the force which deflects the direction of surface winds. Coriolis force or effect is not a force in itself in real sense rather it is an effect of the rotational movement of the earth (named after G.G. Coriolis).

Ekman spirals : denote altitudinal variations of winds shown by equi-angle spirals.

Ferrel's law : is related to deflection of winds. The law states that if one stands with one's back towards the direction from where winds are coming they (winds) are deflected to the right in the northern hemisphere and to the left in the southern hemisphere.

Frictional force : the force generated by the resistance of the surface of an object against a moving object is called frictional force.

Friction layer : The zone of lower atmosphere where frictional force becomes effective is called friction layer.

Geostrophic balance : when pressure gradient force (PGF) is balanced by Coriolis force (CF), the net force becomes zero and hence winds blow in straight paths parallel to isobars. This state is called geostrophic balance.

Gestrophic wind : The wind blowing parallel to the isobars and at right angle to the pressure gradient is called geostrophic wind.

Gradient wind : Gradient wind, a variant of geostrophic wind, blows along a curved path parallel to the curved circular isobars.

Hydrostatic equilibrium : When the upward pressure gradient force is balanced by downward acting gravity force, the vertical acceleration becomes zero. This situation of balance is called hydrostatic equilibrium.

Isobars : The lines joining the places of equal pressures reduced to sea level on the maps are called isobars.

Laminar flow : denotes the movement of particles in only one direction *i.e.* forward direction.

Pressure gradient : is defined as decrease of air pressure between two isobars of different values *i.e.* from high to low pressure. This is also called barometric slope.

Turbulent flow : denotes the movement of particles in all directions such as convection currents or eddies.

6

GENERAL ATMOSPHERIC CIRCULATION

6.1 ATMOSPHERIC CIRCULATION : MEANING AND TYPES

Atmospheric circulation means movement of air due to pressure gradient from local to global levels and from daily to seasonal and annual patterns over the earth's surface (including ground and oceanic surfaces) and above the earth's surface. It is, thus, apparent that the atmospheric circulation has spatial, temporal and altitudinal components. Temporally, atmospheric circulation may be divided into (1) **primary circulation** or **long-term circulation**, (2) **seasonal circulation** , and (3) **diurnal circulation** (example : land and sea breezes, mountain and valley breezes). Considering the spatial dimension and genesis atmospheric circulation is generally classified into (1) **primary** or **general circulation** including planetary wind systems which are related to global pressure belts (*e.g.* trade winds, westerly winds, and polar winds) and variants of general or **global atmospheric circulation** (*e.g.* jet stream circulation and Walker circulation and southern oscillation), (2) **secondary circulation** consisting of cyclones, anticyclones, seasonal circulation like monsoons and airmasses, and (3) **tertiary circulation** which includes local winds like Harmattan, Chinook, sirocco, norwester, buran etc. and diurnal winds like **land and see** breezes and mountain and valley breezes.

6.2 GENERAL CIRCULATION

The general circulation also called as primary circulation involves the wind patterns over the entire globe. In other words, the large-scale motion (circulation of air) of the atmosphere in both time and space involving the whole globe and its atmosphee is called general circulation of the atmosphere. It is primary circulation because it is of vital importance for the weather and climatic conditions at global scale and it also gives birth to secondary and tertiary atmospheric circulation. The significance of general or primary circulation may be outlined as follows:

(1) General circulation transports heat from the surplus heat areas (where insolation received at the earth's surface exceeds the heat loss by outgoing terrestrial radiation-tropical zone) to deficit heat areas (where heat lost by outgoing terrestrial radiation exceeds the gain of heat by incoming solar radiation-polar and high latitude zones). In other words, the general horizontal atmospheric planetary circulation transfers surplus

heat energy from tropical zones extending between 35^0N and S latitudes to high latitude deficit heat zone extending over polar regions.

(2) General circulation is, thus, a mechanism of transfer of energy which attempts to equalize the distribution of heat energy over the earth's surface including both land and ocean surfaces.

(3) General atmospheric circulation also transports moisture from the oceans to the continents and thus helps in the formation of clouds and precipitation mechanism. Thus, general circulation also helps in maintaining hydrological cycle at global scale. It also moves moisture from low latitudes to high latitudes.

(4) General circulation if considered at large temporal scale is not static rather it changes due to a host of factors and causes which result in climatic changes.

(5) General circulation of the atmosphere also helps in maintaining balance of atmospheric moisture through the processes of evaporation and precipitation and transfer of moisture from surplus moisture areas (equatorial zone) to deficit moisture areas (deserts).

6.3 MECHANISM OF GENERAL CIRCULATION

The primary cause of atmospheric motions and general circulation is spatial imbalance of heat energy. As already stated earlier the primary source of heat energy of the earth is the solar radiation which is unequally received at the earth's surface (causes already discussed in the 3rd Chapter of this book) resulting into the development of heat energy surplus zone (tropical zone) and heat energy deficit zone(polar zone). This energy imbalance causes variations in pressure and thus the resultant pressure gradient, both at the earth's surface and aloft, causes atmospheric motions at large and small scales. Several models have been suggested (to be discussed in the foregoing sections) for the horizontal and vertical transfer of heat energy and for the general atmospheric circulation.

The second controlling factor of the general circulation of the atmosphere is the angular momentum of the earth and its atmosphere which is gravitationally attached to the earth, and hence it also rotates with the earth. The absolute angular momentum is the highest at the equator (465 ms^{-1}) and decreases poleward and it becomes zero at the poles because the entire earth completes its one rotation in about 24 hours (rounded figure) and hence the rotation of speed becomes maximum at the equator and becomes zero at the poles. Because of decreasing poleward angular momentum the poleward blowing winds acquire progressively higher eastward velocity due to conservation of angular momentum. It may be mentioned that in order to maintain atmospheric motion and general circulation, like heat transport from tropical to polar areas, there is also transport of angular momentum from equator towards the poles.

On an average, heat and angular momentum are transported in two ways, namely (1) by vertical circulation, and (2) by horizontal circulation. The vertical transport of heat is accomplished through tri-cellular meridional circulation (Hadley cell, Ferrel cell and Polar cell) of the atmosphere (this mechanism will be discussed in much detail later in this chapter). The horizontal transport of heat is carried through horizontal circulation (tropical and polar circulation). The traditonal model of horizontal transport of heat and angular momentum was modified by A. Defant and H. Jeffreys in 1920s and their result was tested by V.P. Starr and R.M. White on the basis of upper air data and the result revealed the fact that 'in middle latitudes horizontal cells transport most of the required heat and momentum poleward. This operates through the mechanism of the quasi-stationary highs and the travelling highs (anti-cyclones) and lows (cyclones) near the surface acting in conjuntion with their related wave patterns aloft' (R.G. Barry and R.J. Chorley, 2002). It may be mentioned that the modern view regarding the mechanism of general circulation of the atmosphere through energy transport states that ' the energy of the zonal winds is being derived from travelling waves, not from meridional circulation' (Barry and Chorley, 2002). In other wards, the required energy and angular momentum are not transported through cellular meridional circulation but are transported through moving cyclonic and anticyclonic circulation and eddies.

The following are a few important models of the mechanism of general circulation of the atmosphere :

(1) Uni-cellular model or thermal circulation model (on a non-rotating earth),

(2) Uni-cellular model or thermal circulation model (on a rotating earth),

(3) Tri-cellular meridional circulation model,

(4) Wave theory model,

(5) Global computer models (GCMs) etc.

The general circulation of atmosphere, for convenience, is generally described following two approaches as given below :

(1) Zonal circulation of the atmosphere.

(2) Meridional circulation of the atmosphere.

1. Unicellular Circulation Model

(thermal circulation model on a non rotating earth)

This model of general circulation of the atmosphere is based on hypothetically conceived homogeneous earth's surface consisting of only land surfaces having level topography (*i.e.* near absence of contrasting reliefs of mountains and valleys). Thus, in the absence of land and sea contrasts and relief variations, the earth's surface would not be affected by contrasting heating and cooling as is the case of the real earth's surface. Consequently, the tropical areas would be intensely heated and would become warm while the polar areas would be excessively cooled and would become cold. The air coming in contact with heated tropical land surface would also be heated, would become light and rise upward and after reaching upper troposphere would move poleward where being cooled above would descend at the poles. The polar areas being excessively cool would become areas of high pressure. Thus, there would be horizontal pressure gradient from polar high pressure area towards equatorial low pressure area and the winds would move horizontally from polar high pressure to the equatorial low pressure area. Thus, there would be a complete convective cell in each hemisphere wherein winds would blow from colder pole areas (high pressure) following equatorward directed pressure gradient towards warmer tropical zone as surface air currents and above in the upper troposphere the winds would blow following poleward directed pressure gradient towards the poles and ultimately would descend at the poles (fig. 6.1). This model cannot be accepted because this is an idealised and hypothetical model. The general circulation becomes more complex than this generalized circulation because the earth rotates on its axis and hence Coriolis force is bound to have its effect on the circulation pattern. Secondly, the real earth consists of both land and water and the land surface (lithosphere) has contrasting relief features resulting into differential heating and cooling of the continents and oceans and varying degrees of frictional force over land and sea surfaces.

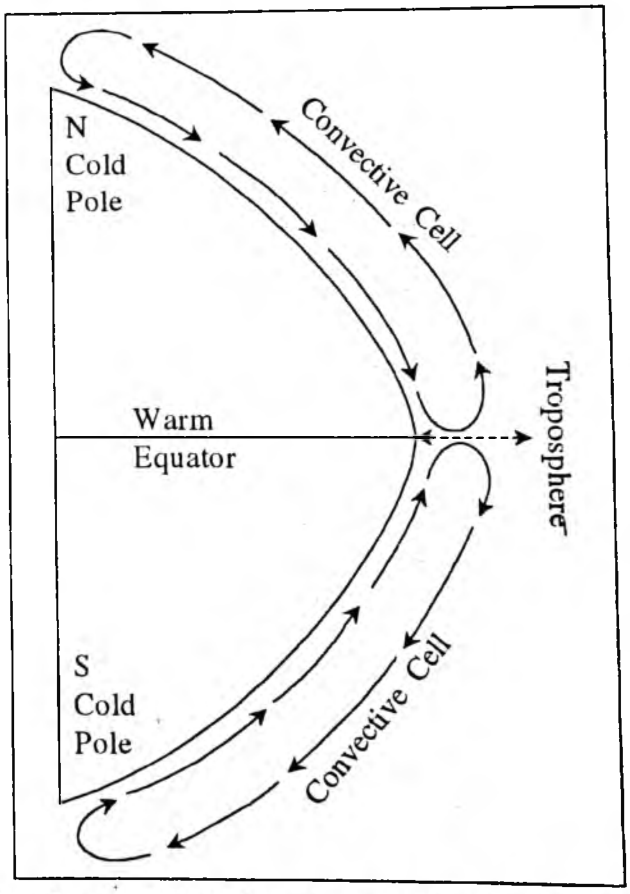


Fig. 6.1 : Unicellular atmospheric circulation on a non-rotating earth.

2. Unicellular Circulation Model of Hadley

George Hadley for the first time proposed a cellular model of atmospheric general circulation on a rotating earth in 1735. The unicellular model of atmospheric circulation on non-rotating earth as discussed above was modified by Hadely as he included the effects of rotation of the earth and resultant Coriolis effect which deflects the winds to the right in the northern hemisphere and to the left in the southern hemisphere. His model is based on a single convective cell as referred to above and shown in fig. 6.1 but direction of winds will not be true meridional *i.e.* north-south and south-north as is the case in unicellular model of atmospheric circulation on a non-rotating earth. The convective cell, one each in the northern and the southern hemispheres, is called **Hadley cell.** In the northern hemisphere wind blowing from north polar high pressure area towards equatorial low pressure area as directed by equatorward pressure gradient turns to its right and becomes north-easterly surface wind due to Coriolis force while in the southern hemisphere the equatorward moving south wind (from south pole to the equator) turns to its left due to Coriolis force and becomes south-easterly surface wind. In order to counter the surface winds there is south-westerly air circulation in the northern hemisphere and north-westerly air circulation in the northern hemisphere in the upper troposphere. It may be remembered that Hadley's model of general atmospheric circulation was based on a single **thermally direct cell** (thermally induced convective cell), as equatorial low pressure develops due to intense heating of earth's surface due to highest amount of solar radiation received in the equatorial areas (low latitudes) while polar high pressure develops due to intense cooling of earth's surface due to lowest amount of solar radiation received in high latitudes-polar areas-and excessive loss of heat energy through outgoing longwave earth radiation. It is, thus, evident that Hadley's concept of basic factor for the pressure differences over the earth's surface was uneven heating of the earth's surface consequent upon uneven distribution of insolation. The single cell model of Hadley was subsequently modified to accommodate mid-latitudes conditions of pressure and air circulation and non-thermal origin of subtropical high pressure and subpolar low pressure belts as they are considered to be dynamically induced and **thermally indirect pressure belts** while equatorial (heating) and polar (cooling) high pressure belts are thermally induced pressure belts.

3. Tricellular Meridional Circulation Model

Ferrel disagreed with the continuity of a single thermally direct cell of atmospheric circulation between the equator and the poles and thus improved upon Hadley's unicellular circulation model and suggested 3 interlocking cells of circulation to explain the wind systems of the whole globe. According to him between the tropical and polar cells there is an intermediate mid-latitudes thermally indirect cell of circulation which was later on named as **Ferrel Cell.** The first cell is known as **thermally direct Hadley cell** which operates between the equator and 30^0 latitude in both the hemispheres. The second is the **thermally indirect Ferrel cell** which operates between 30^0 and 60^0 latitudes in both the hemispheres. The **third thermally direct cell** operates between 60^0 and 90^0 (poles) in the northern and the southern hemispheres. The detailed description of tricellular meridional circulation of the atmosphere has been presented in section 6.5 but it may be emphasized here that cellular model of atmospheric circulation demands anti-horizontal circulation aloft *i.e.* in the upper troposphere. For example, if the trade winds blow from north-east to south-west direction in the northern hemisphere and from south-east to north-west direction in the southern hemisphere, there should be from south-west to north-east and from north-west to south-east movement of winds in the upper troposphere in the tropical Hadley cell. This situation is observed in real atmospheric circulation and hence the cellular meridional circulation is valid in the tropical Hadley cell but this model is not valid in the mid-latitude cell or Ferrel cell between the latitudes of 30^0-60^0 in both the hemispheres because there are westerlies on the surface, and upper air circulation has also westerly direction. The model is valid in the polar cell where there is opposite upper air circulation to surface air circulation. So the anomalous condition of west to east zonal circulation of winds in the upper troposphere in the Ferrel cell (30^0-60^0 latitudes) cannot be explained by unicellular model. The upper air west-east flow of winds in the Ferrel cell actually determines the position and location of moving and semi-stationary high (anticyclonic) and low (cyclonic) pressure systems which are responsible for the transport and transfer of heat energy in the mid-latitudinal (30^0-60^0 latitudes) and subpolar zones.

4. Wave Theory Model of Atmospheric Circulation

The wave theory model is based on the concept of transfer of heat energy and angular momentum. It may be mentioned that this model retains the basic structure of tricellular model but views the roles and relative importance of three convective cells (namely, tropical Hadley thermally direct cell, mid-latitude Ferrel thermally indirect cell and polar thermally direct cell) in the global pattern of atmospheric circulation with different angles. This model emphasizes horizontal transfer of energy and angular momentum rather than meridional transfer in vertical plane. Thus, the wave theory model is based on the mechanism of the conservation of angular momentum and poleward transfer of energy and angular momentum in order to maintain the planetary wind systems. This can be achieved only if the air progressively increases its velocities poleward and this requires poleward transfer of angular momentum. It is important to note that the atmosphere also rotates with the earth from west to east. Since the latitudinal circumferences decrease poleward and hence the rotational speed of the earth also decreases poleward. The angular momentum also decreases from the equator towards the pole and therefore there is need for the conservation of angular momentum and its transfer poleward in order to maintain the planetary wind systems and their circulation. This cannot be achieved, as modern views on atmospheric general circulation state, through three-cell model but can be achieved by surface waves of moving and quasi-stationary high (anticyclonic) and low (cyclonic) pressure systems on the surface and related wave patterns (e.g. **Rossby waves**) in the upper troposphere and thus the mid-latitude Ferrel thermally indirect cell is replaced by the mechanism of moving cyclonic and anticyclonic waves on the surface to the north and south in the northern and the southern hemispheres respectively and meandering **Rossby waves** in the corridor of jetstreams in the upper troposphere.

5. Global Computer Models (GCMs)

Global computer models are basically tools for weather forecasting on the basis of simulation of real weather phenomena and involving laws of physics and mathematical principles such as laws of motion, principles of thermodynamics, basic equations related to atmospheric motion and air flow, and hydrostatic equation. In fact, the GCMs are sets of computer-generated maps of weather conditions of real atmosphere and these maps are used to predict the future weather conditions. This technique is based on the basic tenet that the present weather condition of a specific place of a region at specific time depends on initial condition (preceding the present one) and may have its impact on future condition. It may be mentioned that ample data of temperature, pressure and humidity at numerous centers at the earth's surface and up in the atmosphere with short distances are required for weather forecasting and predicting atmospheric circulation but GCMs use sample data of sample points whether at the earth's surface (in a horizontal plane) or at different altitudes in the atmosphere, mainly in the troposphere (in a vertical plane) and hence the result may not be accurate. In order 'to predict the (atmospheric) circulation accurately, we need to sample pressure, temperature, and moisture at every point in the atmosphere. Since the atmosphere contains an infinite number of points, the task becomes impossible' (Oliver and Hidore, 2003).

6.4 ZONAL CIRCULATION OF ATMOSPHERE (GLOBAL WIND BELTS)

Zonal circulation of the atmosphere involves the consideration of the distribution and flow patterns of permanent wind systems in latitudinal zones from the equator towards the poles wherein characteristic features of air circulation on the earth's surface as well as at different heights in the troposphere are considered. Such zonal circulation is related to global pressure and wind belts which also register seasonal variations.

On an average, the location of high and low pressure belts is considered to be stationary on the globe (though they are seldom stationary and continuous). Consequently, winds blow from high pressure belts to low pressure belts. The direction of such winds remains more or less the same throughout the year though their areas change seasonally. Thus, such winds are called permanent winds. Since these winds are distributed all over the globe and these are related to thermally and dynamically induced pressure belts and rotation of the earth and hence they are called **planetary winds**. These winds include trade winds, westerlies and polar winds (fig. 6.3).

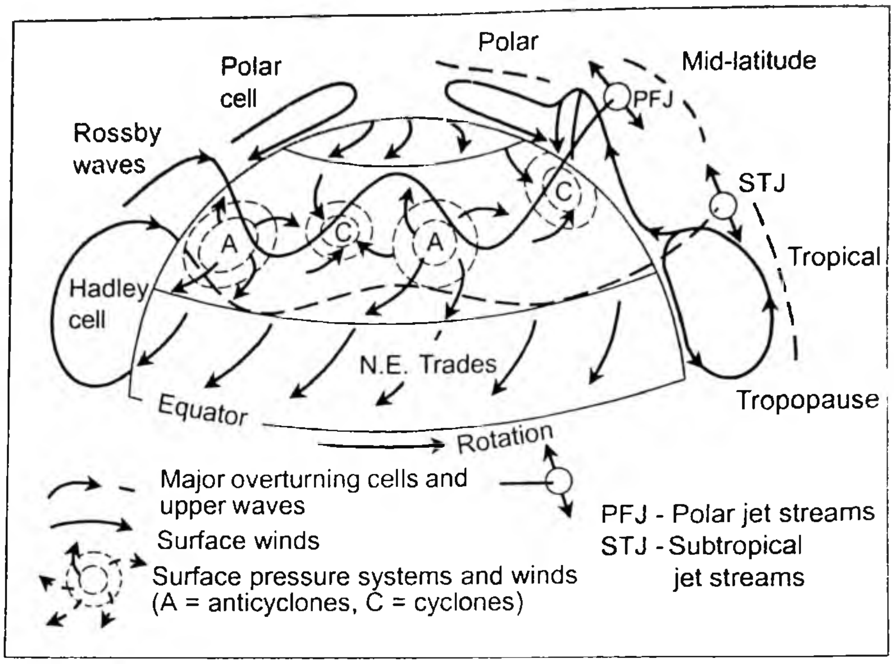


Fig. 6.2 : Zonal circulation of the atmosphere in the northern hemisphere. After J. Hanwell, 1980, in Oliver and Hidore, 2003.

It may be mentioned that both surface and upper air circulations are interrelated and control the weather conditions of the earth's surface at different spatial scales. The primary or planetary circulation of the globe is not as simple as referred to above. For example, the tropical zone is dominated by Hadley cell of surface easterly trade (north-east and south-east) winds and upper air antitrades or westerlies, the mid-latitudinal Ferrel's cell is characterized by surface westerlies associated with cyclones and anticyclones and upper air **Rossby waves** (named after Carl-Gustav Rossby) having west to east circulation and jet streams and the polar cell has the prevalence of surface polar winds (north-east and south-east in the northern and the southern hemispheres respectively) and upper air westerly polar jet streams. Figs. 6.2 and 6.3 depict zonal circulation of surface and upper air

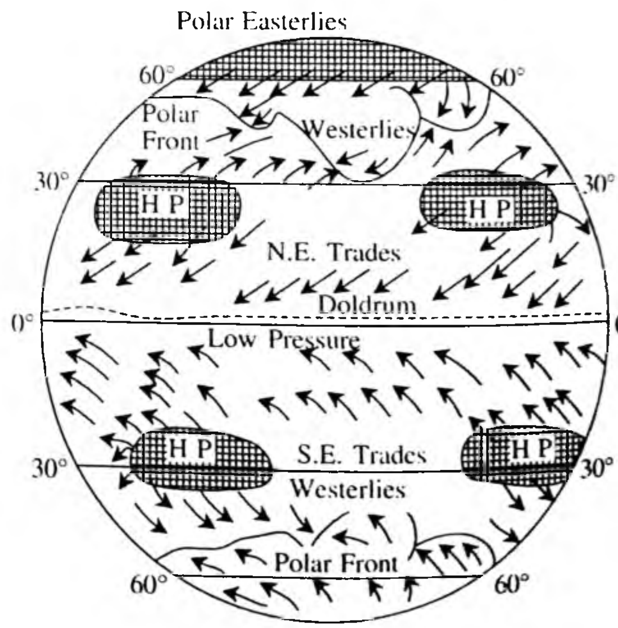


Fig. 6.3 : The generalized global pattern of planetary winds (zonal circulation of the atmosphere).

wind systems in the northern hemisphere and over the entire globe respectively.

The zonal circulation of surface winds is studied in the three-zone systems, namely 1. tropical circulation, 2. mid-latitudinal circulation, and 3. polar circulation. It may be mentioned that the belts of permanent or planetary surface winds as shown in fig. 6.3 are approximations as these wind belts are not continuous and regular in reality because of uneven distribution of land and sea, and their contrasting nature of heating and cooling.

TROPICAL CIRCULATION
(Winds in the Tropics)

The tropical circulation zone of planetary surface winds extends between equator and 25^0–30^0 latitudes in both the hemispheres and very closely corresponds to the Hadley cell of air circulation. The middle portion of this zone is dominated by thermally induced low pressure surrounding the equator and is popularly known as equatorial low pressure belt while the outer margin of this zone is characterized by dynamically induced (due to subsidence or sinking of air from above) high pressure surrounding the tropics of Cancer and Capricorn, known as subtropical high pressure belt. The air near the equator is heated due to solar radiation, rises upward and after reaching the upper troposphere, turns to the north (in the northern hemisphere) and south (in the southern hemisphere), gets cooled, becomes heavy and descends (sinks) near the tropics of Cancer and Capricorn to form high pressure. Thus, the pressure gradient is oriented towards the equator. This results in the circulation of winds from subtropical high pressure areas to equatorial low pressure and thus the equatorial zone becomes the zone of convergence of surface winds and the tropics become the zone of divergence. The convergence zone is characterized by higher amount of solar radiation, more evaporation and relative humidity, cloudy sky, and heavy precipitation while the divergence zone is dominated by highest amount of solar radiation, more sunshine, low or say least evaporation, clear sky, very low relative humidity, least precipitation or say almost dry conditions. This circulation zone is characterized by north and south blowing trade winds but their actual direction becomes north-east (in the northern hemisphere) and south-east (in the southern hemisphere) due to Coriolis force and angular momentum and anti-trades (westerlies) aloft. It is important to note that this primary tropical circulation of the atmosphere moves heat energy and moisture from low latitudes to high latitudes.

Formerly, it was believed that trade winds blow from the subtropical high pressure belts to the equatorial low pressure belt. The north-east and south-east trades converge along the equator and there are upper air anti—trades blowing in the opposite directions of the surface trade winds. The weather conditions throughout the tropical zone remain more or less uniform. There is a belt of calm or doldrum characterized by feeble air circulation. These views of weather conditions prevailing in the tropics are now considered as old concepts and have now been refuted on the basis of new information based on numerous observations made in the upper air and near the earth's surface during and after second world war. New discoveries have now put question marks against the views of zonal character and regularity of surface trade winds, uniformity of weather conditions in the tropics, and upper air antitrade winds. It has been discovered that trade winds blow with regularity only over some parts of the tropical oceans (mainly over the eastern parts). Upper air anti-trades, contrary to earlier beliefs, are not found every where but are confined to certain areas only. The weather conditions in the tropics are not calm and uniform but they are frequently interrupted by atmospheric disturbances (cyclones, hurricanes, typhoons, sea waves etc.) Thus, the tropical zone is characterized by **doldrum, equatorial westerlies,** and **trade winds.**

1. Doldrum : A belt of low pressure, popularly known as equatorial trough of low pressure, extends along the equator within a zone of 5^0N and 5^0S latitudes. This belt is called the **belt of calm** or **doldrum** because of light and variable winds. It was believed that doldrum is a regular feature all along the equator and is characterized by strong convective instability leading to the formation of cumulonimbus clouds and copious rainfall daily but the recent observations have now shown that the belt of doldrum is not continuous but is confined to certain localities only. This belt is subjected to seasonal and spatial variations due to northward and southward movement of the overhead sun (summer and winter solstices). In fact, the belt of doldrum shifts northward during summer solstice (when the sun is vertical over the tropic of Cancer (21 June) and comes back to its normal position at the time of winter solstice (when the sun is vertical over the tropic of Capricorn, 23 December). According to Flohn the doldrums extend upto 200 longitudes in discontinuous manner. Crowe has identified 3 zones of doldrums e.g. Indo-Pacific Doldrum extending from the eastern coast of Africa to 180° longitude for a distance of 16,000 km and covering an area of 25,800,000 km^2, thus, covers about one third of the total length of the equator, (2) Equatorial Western Coastal Region of Africa, and (3) Western Coastal Margin of Central America.

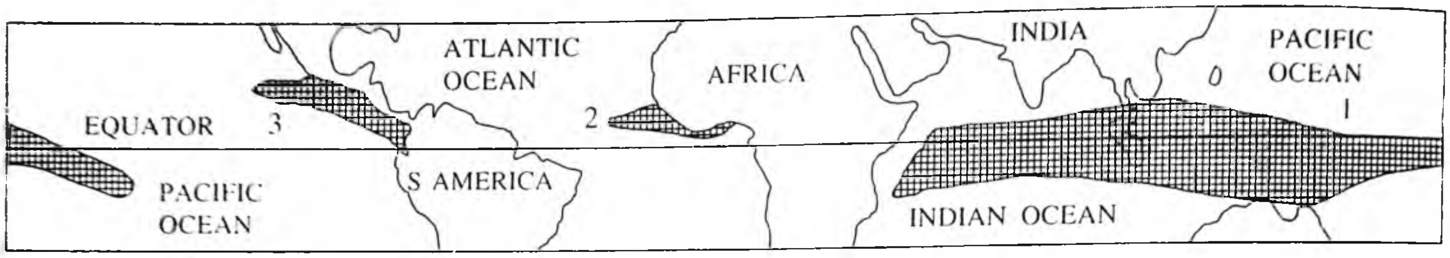


Fig. 6.4: Position of doldrums - (1) Indo-Pacific Doldrum, (2) equatorial western coastal region of Africa, and (3) western coastal region of Central America.

2. Inter-Tropical Convergence Zone : A few meteorologists and climatologists believe in the existence of cyclonic fronts in the equatorial regions while some refute this concept on the ground that fronts are formed only when two air masses of contrasting temperatures converge but such conditions are not found in the equatorial region. The equatorial or tropical fronts are called **intertropical fronts (ITF)** or **intertropical convergence (ITC)**. These fronts represent the meeting ground of north-east and south-east trade winds. The northern and southern boundaries of intertropical

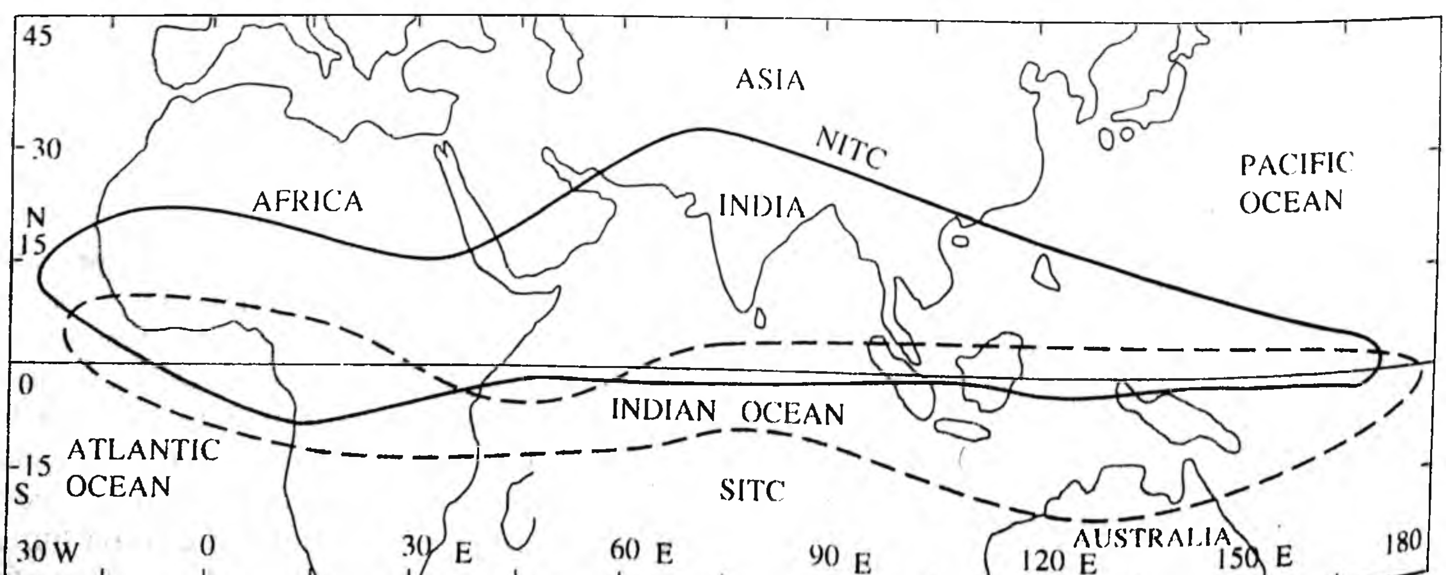


Fig. 6.5 : Intertropical convergence (NITC and SITC).

convergence are called north intertropical convergence (NITC) and south intertropical convergence (SITC) respectively (fig. 6.5). There is seasonal shifting in the NITC and SITC with the northward (summer solstice) and southward migration (winter solstice) of the sun.

3. Equatorial Westerlies : On an average, there is westerly air circulation (from west to east) in the doldrums or say in the intertropical convergence. These westerly winds have been called by Flohn as **equatorial westerlies** (fig. 6.6) which cover 200^0 longitudes. According to Flohn the equatorial westerlies cover the areas extending from the western parts of Africa across the Indian Ocean to the western Pacific Ocean. The equatorial westerlies are associated with strong atmospheric disturbances (cyclonic storms). Flohn has further maintained that south-western monsoons of South Asia are, infact, equatorial westerlies because these winds are extended upto 30-35^{0}N latitudes over Indian subcontinent due to northward shifting of NITC at the time of summer solstice (fig. 6.7).

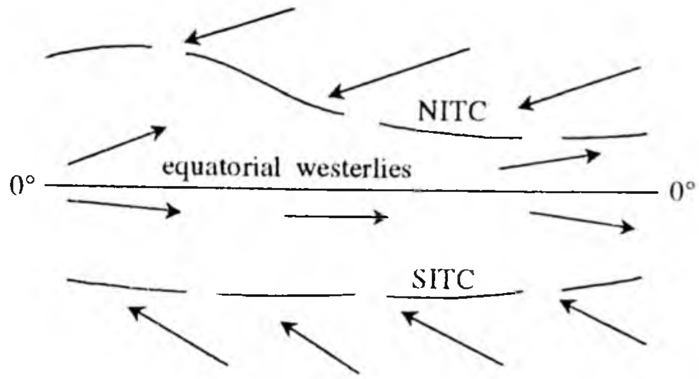


Fig 6.6. : NITC and SITC and equatorial westerilies.

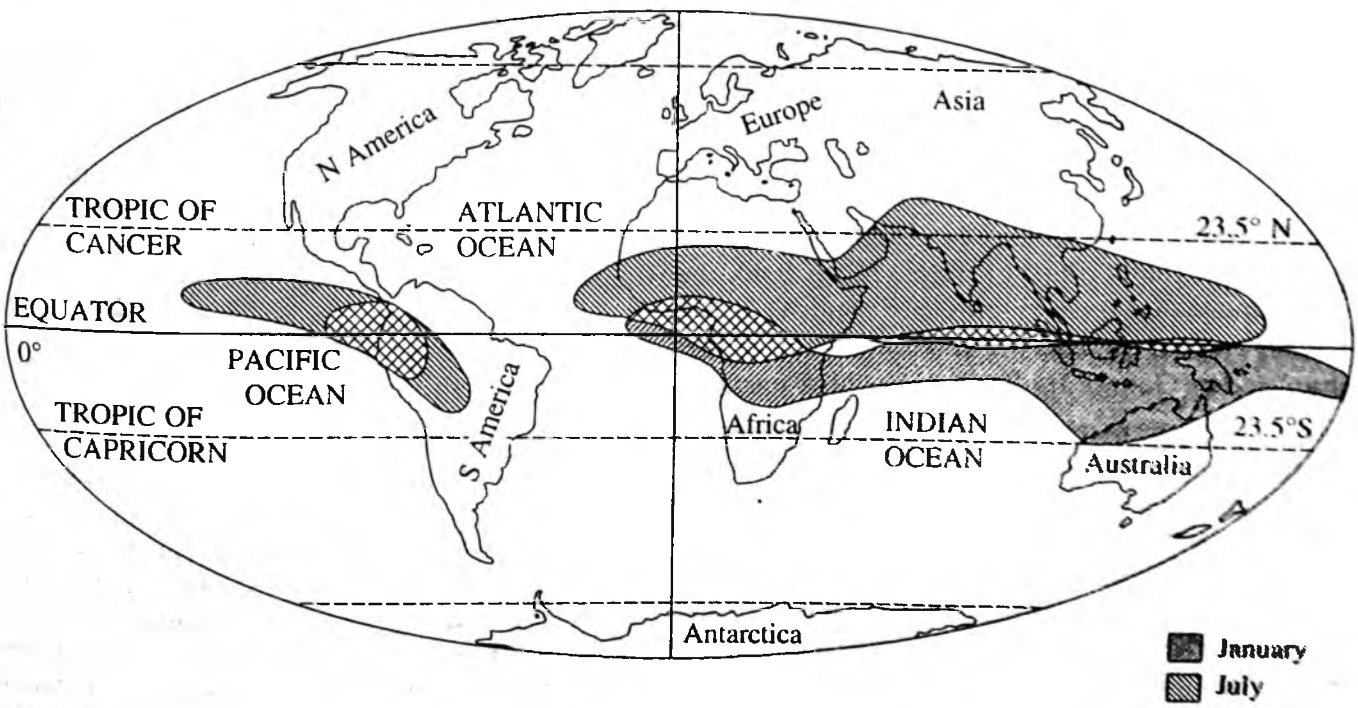


Fig. 6.7 : Seasonal (July and January) shifting of equatorial westerlies. After H. Flohn, 1960, in Barry and Chorley, 2002.

4. Trade Winds : There is more or less regular inflow of winds from subtropical high pressure belts to equatorial low pressure belt. These tropical winds have north-easterly direction in the northern hemisphere while they are south-easterly in the southern hemisphere. These winds are called trade winds because of the fact that they helped the sea merchants in sailing their ships as their (of trade winds) direction remains more or less constant and regular. According to Ferrel's law (based on Coriolis force generated by the rotation of the earth) trade winds are deflected to the right in the northern hemisphere and to the left in the southern hemisphere. There are much variations in the weather conditions in the different parts of trade winds.

The poleward parts of the trade winds or eastern sides of the subtropical anticyclones are dry because of strong subsidence of air currents from above. Because of the dominance of anticyclonic conditions there is strong atmospheric stability, strong inversion of temperature and clear sky. On the other hand, the equatorward parts of the trade winds are humid because they are characterized by atmospheric instability and much precipitation as the trade winds while blowing over the oceans pick up moisture. It may be stated that the trade winds are more regular and constant over the oceans than over the lands. At some places on the lands (e.g. S.E. Asia and southern USA) the trade winds disappear during summer season due to formation of low pressure cells because of high temperature but the trade winds are more constant and regular over the continents during winter season. It may be pointed out that the zone of trade winds is called **Hadley Cell** on the basis of the convective model prepared by George Hadley for the entire earth.

It may be mentioned that of all the planetary surface winds (westerlies and polar winds) trades are most persistent and regular wind systems. Vertically, trade winds have two layers e.g. (1) surface layer of moist and unstable air, and (2) upper layer of dry and stable air. The surface layer is characterized by high lapse rate of temperature over the oceans upto the height of 600 meters. The surface trades are also characterized by much convective and turbulent activities over western parts of the oceans and eastern parts of the continents. The equatorward part of the trade winds is more humid than their poleward parts. The vertical depth of trade winds varies seasonally but the average depth varies between 1.5 to 3.0 kilometers. There is anti-trade circulation in the upper troposphere. In other words, in opposition to north-easterly and south-easterly trade winds on the surface, there are westerly winds aloft (in the upper troposphere).

MID-LATITUDE CIRCULATION

Mid-latitude zonal circulation extends between 30^0-60^0 latitudes in the northern and the southern hemispheres and is represented by subpolar or Ferrel thermally indirect cell of air circulation wherein winds blow from subtropical semipermanent high pressure belt (30^0-35^0 latitudes) to subpolar thermally indirect semipermanent low pressure belt in both the hemispheres. The Ferrel cell of atmospheric circulation is not as much effective in this zone as is the Hadley cell in the tropical zone. The general surface air circulation is westerly which becomes south-westerly and north-westerly in the northern and the southern hemispheres respectively due to Coriolis force. The following are the characteristic features of this zonal atmospheric circulation.

(1) The actual wind systems in the mid-latitude zone is quite different from the three-cell model of atmospheric circulation because the local conditions at the surface and aloft complicate the general circulation pattern. As per three-cell model of meridional circulation there should be active meridional flow between subtropical high pressure and subpolar low pressure belts but the real meridional circulation is weak and is interrupted by frequent high (anticyclones) and low (cyclones) pressure systems.

(2) The general surface zonal circulation is from west to east but there are a lot of variations in both directions and velocities. It is interesting to note that unlike Hadley cell, the upper air winds also have westerly component. The surface westerlies are stronger in the southern hemisphere than in the northern hemisphere because of comparatively less friction due to overdominance of oceans in the southern hemisphere than in the northern hemisphere where land surface is predominant.

(3) The maximum transfer of energy and angular momentum takes place between the latitudes 38^0–40^0 in both the hemispheres, and hence the westerlies become strongest. It may be mentioned that such an active energy transfer is accomplished not only by weak meridional circulation but also by anticyclonic and cyclonic waves.

(4) The poleward part of this zone is infact a mixing zone of warm tropical and subtropical winds (westerlies) and cold polar winds along polar fronts.

(5) The upper air circulation is also characterized by westerly Rossby waves in the upper troposphere and lower stratosphere. The **Rossby waves** are meandering loops of flow patterns of upper air westerlies and are embedded with jet streams. The Rossby waves have westerly component of air flow which is directed from west to east but due to seasonal shifting the meandering loops of Rossby waves are intensified and are directed north-south and hence there begins meridional circulation aloft instead of horizontal flow (west to east). This meridional circulation also modifies surface zonal flow and hence there begins transfer of energy and angular momentum poleward more vigorously.

(6) The surface circulation is also characterized by the development of rotational eddies (or vortices) representing anticyclones and cyclones with a diameter runging between 1000-2000 km and a life span of several days. These are the cyclonic and anticyclonic waves of surface eddies which effectively transfer energy poleward. These eddies are rotational in the sense that they transport polar cold air to the tropical areas and tropical warm air to the high latitudes. It is also important to note that the subpolar zone of convergence is quite different from the tropical (equatorial) convergence zone because the former represents convergence of two dissimilar and contrasting air masses (polar cold air mass and tropical warm air masses) while the latter is formed due to convergence of two similar air masses (tropical air mass). The subpolar convergence generates polar front which becomes the source of the origin of temperate cyclones.

The subtropical high pressure zone, also called as **horse latitudes,** is associated with subsidence of air from above and divergent surface air circulation, and **westerlies** (both surface westerlies and upper air westerlies) are significant components of mid-latitude zonal atmospheric circulation and hence needs separate discussion.

(i) **Horse Latitudes**—The dynamically induced (due to subsidence of air currents) subtropical high pressure belt extends between 30^0–35^0 (25^0-35^0) latitudes in both the hemispheres. Thus, this belt separates two wind systems viz. trade winds and westerlies. It is also apparent that the subtropical high pressure belt is the source for the origin of trade winds (blowing towards equatorial low pressure belt) and westerlies (blowing towards subpolar low pressure belt) because winds always blow from high pressure to low pressure. The air after being heated near the equator ascends and after blowing in opposite direction to the surface trade winds descends in the latitudinal zone of 30^0-35^0. Thus, the descent of winds from above causes high pressure on the surface which in turn causes anticyclonic conditions. This is why the anticyclonic conditions cause atmospheric stability, dry conditions and very weak air circulation. Thus, this zone (30^0-35^0) is characterized by weak and variable winds and calm. This belt of calm is very popularly known as **horse latitudes** because of the fact that in ancient times the merchants had to throw away some of the horses being carried in the ships in order to lessen the weight so that the ships could be sailed through the calm conditions of these latitudes.

Anticyclones are produced due to subsidence of air currents in the horse latitudes. These anticyclones are known as '**subtropical highs**' or subtropical anticyclones, the eastern and western parts of which are characterized by contrasting weather conditions. The eastern parts (spreading over the western parts of the continents) are marked by descent of air currents, inversion of temperature and consequent atmospheric stability and dry conditions. This is why hot and dry tropical deserts are found in the western parts of the continents within the latitudinal zones of 20^0-30^0 in both the hemispheres (*e.g.* Sahara and Kalahari in Africa, Chile-Peru desert or Acatama in South America, Arabian and Thar deserts in Asia, deserts of S.W. USA, and Australian deserts). The western parts of subtropical anticyclones (covering the eastern parts of the continents and western parts of the oceans) are humid because some sort of atmospheric instability is caused due to weakening of air descent (*e.g.* in the areas of Caribbean Sea, Mexican Gulf and adjoining areas, eastern China, southern Japan, south-east Brazil and eastern Australia).

(ii) **Westerlies** —The permanent winds blowing from the subtropical high pressure belts (30^0-35^0) to the subpolar low pressure belts (60^0-65^0) in both the hemispheres are called westerlies (fig. 6.3). The general direction of the westerlies is S.W. to N.E. in the northern hemisphere and N.W. to S.E. in the southern hemisphere. There is much variation in the weather conditions in their poleward parts where there is convergence of cold and denser polar winds and warm and lighter westerlies. In fact, a cyclonic front, called as **polar front**, is formed due to convergence of two contrasting air masses as referred to above and thus temperate cyclones are originated. These cyclones move along with the westerlies in easterly direction. Thus, the general characteristic features of the westerlies are largely modified due to cyclones and anticyclones associated with them. Because of the dominance of land in the northern hemisphere the westerlies become more complex and complicated and become less effective during summer seasons and more vigorous during winter season. These westerlies bring much precipitation in the western parts of the continents (*e.g.* north-west European coasts) because they pick up much moisture while passing over the vast stretches of the oceans. The westerlies become more vigorous in the southern hemisphere because of lack of land and dominance of oceans. Their velocity increases southward and they become stormy. They are also associated with biosterous gales. The velocity of the westerlies becomes so great that they are called **roaring forties** between the latitudes of 40^0-50^0S, **furions fifties** at 50^0S latitude and **shriecking sixties** at 60^0S latitude.

The upper air circulation in the mid-latitude zone is also westerly and is called **upper air westerlies**, which are associated with westerly **Rossby waves** embedded with the corridors of high speed winds called as **jet streams** (subtropical jet stream, fig. 6.2). These subtropical jet streams control Indian monsoon (chapter 7). Due to summer warming of north polar areas the equatorward pressure gradient is lessened, the surface westerlies are weakened and hence upper air jet streams shrink and migrate towards the north pole but during northern winter (winter solstice) the polar areas are cooled and high pressure is intensified with the result the equatorward pressure gradient is steepened, the surface westerly circulation becomes strong and the jet streams migrate as far south as the tropic of Cancer and thus affect Indian monsoon. The surface polar front also migrates southward with the result cold polar airmasses invade tropical areas and cold waves are generated in those countries where there is absence of east-west mountain barriers. For example, during winter season cold powdery polar winds reach as far south as New Orleanse, Galveston and Houston located near the Mexican Gulf coast and lower the temperature to frost level due to absence of any mountain barrier stretching in east-west direction. On the other hand, the Himalayan ranges protect India from the invasion of cold waves coming from over Siberian arctic region.

POLAR CIRCULATION

Polar circulation is represented by **polar cell** of the atmospheric circulation which, on an average, is confined between 60^0–90^0 latitudes in both the hemispheres and is characterized by surface polar easterly winds, upper air polar whirl and westerly winds, eastward flowing jet streams, upper air divergence and temperature inversion, surface divergent circulation over polar areas mainly over north American and Eurasian cold poles etc. It may be mentioned that cold pole representing lowest temperature does not coincide with the geographical pole, this is why there are two cold poles in the northern hemisphere as mentioned above. Since temperature remains below freezing point during most part of the year, the high pressure systems and resultant divergent air flow from the polar areas are more persistent and become annual feature. The influence zone of cold poles expands during winter season and shrinks during summer season. The pressure gradient between polar high pressure and subpolar low pressure generates easterly air circulation known as polar circulation dominated by weak polar easterly winds which are elaborated below.

A low pressure belt, produced due to dynamic factor, lies within the latitudinal belt of 60^0–65^0 in both the hemispheres. This belt of low pressure is more persistent in summer season but generally disappears in winter season. The Icelandic and Aleutian low pressure cells persist throughout the year. There is very high pressure over the poles because of exceedingly low pressure. Thus, winds blow from the polar high pressure to subpolar low pressure cells. These are called polar winds which are northeasterly in the northern hemisphere and south-easterly in the southern hemisphere. The zone of polar winds shrinks due to northward shifting of pressure belts at the time of northern summer (summer solstice) in the northern hemisphere but it is extended upto 60^0N latitude during northern winter (winter solstice). As mentioned earlier polar easterly winds are weak but become stronger and more effective during northern summer i.e. summer season in the northern hemisphere. Tundra region is characterized by weak pressure gradient resulting into weak easterly circulation which makes tundra region the least stormy region of the planet earth. The polar easterly wind system is complicated in the southern hemisphere, by the presence of ice-capped continent of Antarctica where anticyclonic circulation is predominant feature mainly in the eastern part of the continent.

6.5 TRICELLULAR MERIDIONAL CIRCULATION OF THE ATMOSPHERE

According to the old concept of the mechanism of general circulation of the atmosphere the movement of air is temperature dependent. In other words, temperature gradient causes air circulation on the earth's surface. According to the advocates of thermal school of the mechanism of general circulation of the atmosphere the tropical areas receive maximum amount of solar energy which substantially decreases poleward. Thus, there is latitudinal imbalance of solar radiation from lower to higher latitude. Consequently, there is transfer of heat through horizontal air circulation from the areas of high solar radiation (low latitudes) to the areas of low solar radiation (high latitudes) in order to balance the heat energy so that there does not exist too much heat energy in the low latitudes and too low heat energy in the high latitudes. This old school considers only the horizontal component of the atmospheric circulation and does not consider the potential energy generated by unequal heating of the earth and its atmosphere and its continuous transformation into kinetic energy. It may be pointed out that the potential heat energy is continuously transformed into kinetic energy by the upward movement (ascent) and downward movement (descent) of heated and cold air respectively. It may be remembered that the kinetic energy is also dissipated due to friction and small-scale atmospheric disturbances upward. Thus, it is necessary that there must exist balance between the rate of generation of kinetic energy and the rate of its dissipation due to friction. The modern concept of the mechanism of general circulation of the atmosphere, thus, includes both, the horizontal and vertical components of atmospheric circulation.

The modern school envisages a **three-cell model** of meridional circulation of the atmosphere, popularly known as **tricellular meridional circulation** of the atmosphere, wherein it is believed that there is cellular circulation of air at each meridian (longitude). Surface winds blow from high pressure areas to low pressure areas but in the upper atmosphere the general direction of air circulation is opposite to the direction of surface winds. Thus, each meridian has three cells of air circulation in the northern hemisphere *e.g.* (1) **tropical cell** or **Hadley cell**, (2) **polar front cell** or **midlatitude cell** or **Ferrel cell**, and (3) **polar** or **subpolar cell** (figs. 6.2 and 6.8).

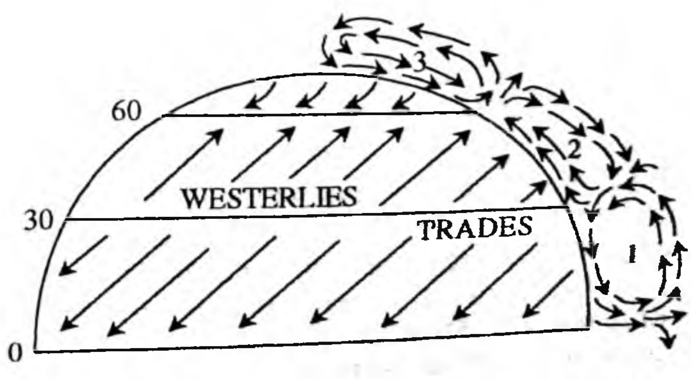


Fig. 6.8 : Tricellular meridional circulation of the atmosphere : (1) tropical Hadley cell, (2) Midlatitude (Ferrel) cell, and (3) Polar cell.

1. Hadley Cell (Tropical Cell)

Tropical cell is also called as Hadley cell because G. Hadley first identified this thermally induced cell in both the hemispheres in the year 1735. The winds after being heated due to very high temperature at the equator ascend upward. These ascending warm and moist winds release latent heat after condensation which causes further ascent of the winds which after reaching the height of 8 to 12 kilometers in the troposphere over the equator diverge northward and southward or say poleward. The surface winds in the name of trade winds blow from subtropical high pressure belts to equatorial low pressure belt in order to replace the ascending air at the equator. The upper air moving in opposite direction to surface winds (trade winds) is called antitrade. These upper air antitrades descend near 30^0-35^0 latitudes to cause subtropical high pressure belt. These antitrades after descending near 30^0-35^0 latitudes, again blow towards the equator where they are again heated and ascend. Thus, one complete meridional cell of air circulation is formed. This is called **tropical meridional cell** which is located between the equator and 30^0 latitudes. It may be pointed out that the regularity and continuity of the antitrade wind systems in the upper air has been refuted by a host of meteorologists on the basis of more upper air data being available during and after Second World War.

2. Ferrel Cell

The mid-latitude cell is called as Ferrel cell or polar front cell. According to old concept surface winds, known as westerly winds or simply westerlies, blow from the subtropical semi-permanent high pressure cells to subpolar semi-permanent low pressure cells (60^0–65^0). The winds ascend near 60^0–65^0 latitudes because of the rotation of the earth and after reaching the upper troposphere diverge in opposite directions (poleward and equatorward). These winds (which diverge equatorward) again descend near horse latitudes (30^0-35^0 latitudes) to reinforce subtropical high pressure belt. After descending these winds again blow poleward as surface westerlies and thus a complete cell is formed.

According to new concept of air circulation the pattern between 30^0–60^0 latitudes consists of surface westerlies. In fact, winds blow from subtropical high pressure belt to subpolar low pressure belt but the winds become almost westerly due to Coriolis force. It may be mentioned that the regularity and continuity of westerlies are frequently disturbed by temperate cyclones, migratory extratropical cyclones and anticyclones. Contrary to the existing view of upper air tropospheric easterly winds in the zones extending between 30^0–60^0 latitudes Rossby observed the existence of upper air westerlies in the middle latitudes due to poleward decrease of air temperature. According to G.T. Trewartha the middle and upper tropospheric westerlies are associated with long waves and jet streams. Warm air ascends along the polar front which is more regular and continuous in the middle troposphere. It may be pointed out that this new concept does not explain the cellular meridional circulation in the middle latitudes.

(3) Polar Cell

Polar cell involves the atmospheric circulation prevailing between 60^0 and poles. Cold winds, known as polar easterlies, blow from polar high pressure areas to sub-polar or mid- latitude low pressure belt. The general direction of surface polar winds becomes easterly (east to west) due to Coriolis force. These polar cold winds converge with warm westerlies near 60^0–65^0 latitudes and form polar front or mid-latitude front which becomes the centre for the origin of temperate cyclones. The winds ascend upward due to the rotation of the earth at the subpolar low pressure belt and after reaching middle troposphere they turn poleward and equatorward. The poleward upper air descends at the poles and reinforce the polar high pressure. Thus, a complete polar cell is formed.

Numerous objections have been raised against the concept of tricellular meridional circulation of the atmosphere. The temperature gradient should not be taken as the only basis for the origin and maintenance of cellular meridional circulation because not all the high and low pressure belts are thermally induced. For example, the subtropical high pressure and subpolar low pressure belts are dynamically induced due to subsidence and spreading of air caused by the rotation of the earth respectively. Upper air anti-trades are not uniformly found over all the meridians. If the trade winds are exclusively of thermal origin, then the thermal gradient must be present boldly throughout the tropics but this is not true. At the height of 500 to 1000 m in the atmosphere the winds become almost parallel to the isobars which are generally parallel to the latitude. If this is so, the meridional cell of air circulation may not be possible. The pressure and winds in most parts of lower atmosphere are found in cellular form rather than in zonal pattern. These pressure and wind cells are elliptical, circular or semicircular in shape. These evidences (cellular form of air circulation) no doubt contradict the old concept of general pattern of atmospheric circulation but the cellular meridional circulation has not been fully validated.

6.6 SEASONAL SHIFTING OF PRESSURE AND WIND BELTS AND THEIR CLIMATIC SIGNIFICANCE

The zonal circulation of the atmosphere and global wind belts as discussed in section 6.4 undergo spatio-temporal changes with seasonal changes caused by the revolution of the earth around the sun. A generalized pattern of seasonal shifting of the location of global wind belts with seasonal migration of overhead sun is discussed below :

In the absence of the revolution of the earth around the sun in about 365 days the global pressure belts would have been permanent and stationary at their places but the relative position of the earth with the sun changes within a year due to earth's revolution and thus the position of all the pressure belts except the polar high pressure belt changes with the northward and southward migration of the sun. At the time of summer solstice the sun is vertical over the tropic of Cancer (June 21) and therefore all the pressure belts except the northern polar high pressure belt shift northward (fig.6.9). The equatorial low pressure belt prevails between 0° latitude (equator) and 10°N latitude, subtropical high pressure belt extends between 30°-40°N latitudes. Thus, all the wind belts associated with the said pressure belts also shift northward. The sun becomes vertical over the equator at the time of autumnal equinox (23 September) and hence all the pressure belts which shifted to the north occupy their normal positions (fig. 6.9). After this there is southward migration of the sun which becomes vertical over the tropic of Capricorn at the time of winter solstice (23 December) and hence the pressure and wind belts shift southward except the southern polar high pressure belt. Thereafter the sun again becomes vertical over the equator at the time of vernal equinox (21 March) and hence all the pressure and wind belts occupy their normal positions (fig. 6.9), thus, there is shifting in the positions of the pressure and wind belts due to seasonal changes of the position of the earth in relation to the sun.

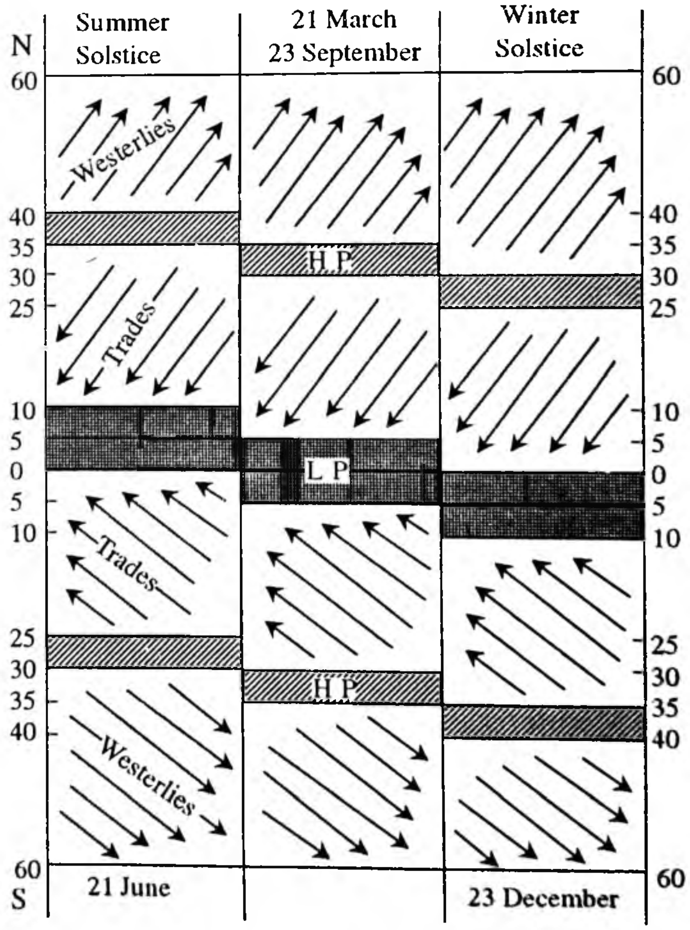


Fig. 6.9 : Shifting of pressure and wind belts.

The seasonal changes in the location of tropical Hadley cell during summer and winter solstices are of vital importance. The locational change of Hadley cell is more effective over the continents than over the oceans because of contrasting nature of heating and cooling of the continents (quick heating and cooling) than the oceans (delayed heating and cooling). The seasonal locational shifting of Hadley cell causes seasonal changes in the direction of tropical easterlies (trade winds) and amount of precipitation. The seasonal shifting of location of global pressure and wind belts also introduces changes in the weather conditions of the transitional zones and give birth to certain typical climates, namely monsoon climate, mediterranean climate, west European climate etc. as follows :

(i) The Mediterranean climatic regions are found in the western parts of the continents within the latitudinal zone of 30^0–40^0 in both the hemispheres. The subtropical high pressure belts extending between 30^0–35^0 latitudes are characterized by dry trade winds during summer season because mostly they come from over the land. Moreover, this zone is characterized by anticyclonic conditions due to descent of air currents. This belt extends upto 40^0 latitudes in the northern hemisphere at the time of summer solstice and in the southern hemisphere at the time of winter solstice. Thus, the western parts of the continents within the zone of 30^0–40^0 latitudes do not receive rainfall during summer season. On the other hand, the subtropical belt shifts towards the equator at the time of winter solstice in the northern hemisphere and at the time of summer solstice in the southern hemisphere, consequently the zone between 30^0–40^0 latitudes is characterized by westerlies which give much precipitation during winter season because they come from over the oceans. This is why the Mediterranean regions are characterized by dry summers and wet winters and a typical Mediterranean type of climate is produced.

(ii) The regions lying between 60^0–70^0 latitudes are characterized by two types of winds in a year because of shifting of pressure and wind belts. With the northward migration of the sun at the time of summer solstice the polar easterlies are weakened during northern summer because the westerlies extend over these areas due to northward (poleward) shifting of subpolar low pressure belt while the situation is quite opposite in the southern hemisphere because the polar easterlies extend over much of the areas of the westerlies due to equatorward shifting of subpolar low pressure belt. This situation is reversed at the time of winter solstice when there is southward migration of the sun. Thus, the polar easterlies are re-established over the areas lying between 60^0-70^0 latitudes in the northern hemisphere because of the shifting of the belt of westerlies southward. Consequently, a typical climate characterized by wet summers through westerlies and associated cyclone and dry winters due to polar easterlies is produced.

(iii) Monsoon climate is the result of the shifting of pressure and wind belts. Due to northward migration of the sun in the northern hemisphere at the time of summer solstice the north intertropical convergence (NITC) is extended upto 30^0N latitude over Indian subcontinent, south-east Asia and parts of Africa. Thus, the equatorial westerlies are also extended over the aforesaid regions. These equatorial westerlies, in fact, become the south-west or summer monsoons. These south-west monsoon winds bring much rains because they come from over the ocean and are associated with tropical atmospheric storms (cyclones). The NITC is withdrawn from over the Indian subcontinent and south-east Asia because of southward shifting of pressure and wind belts due to southward migration of the sun at the time of winter solstice. Thus, north-east trades are re-established over the aforesaid areas. These north-east trades, in fact, are north-east or winter monsoons. Since they come from over the lands, and hence they are dry.

The Indian monsoon is more specifically affected by changes in the location of upper air tropospheric westerlies or jet streams during summer and winter seasons. The summer warming of north polar areas (during summer solstice) the polar high pressure is weakened, the north polar upper air whirl shrinks and retreats towards the north pole, the surface westerly winds and north intertropical convergence (NITC) also extend northward. With poleward shifting of north polar whirl the upper air westerly jet stream is withdrawn from over India by middle of June.

It may be remembered that during northern summer there is winter season in the southern hemisphere, with the result southern polar whirl is more developed and is extended upto the equator.

Consequently, the intertropical convergence (ITC) is pushed to the north of equator. Because of the push factor of the southern polar whirl the south-east trade winds are forced equatorward and while crossing over the equator they become south-westerly due to Coriolis force (deflective force caused due to the rotation of the earth) and rush towards India. It may be pointed out that rapid advance of inter-tropical convergence northward is because of the push factor of the southern circum polar whirl and not because of sucking by the thermally induced surface low pressure over north-west India. No doubt, this surface low pressure accelerates the advance of intertropical convergence northward. Intertropical convergence is characterized by dynamically induced waves and not by frontal cyclones. These dynamically induced waves after coming over India become cyclone vortices. The summer monsoon rains of India result from these cyclonic vortices. In other words, the development of cyclonic vortices is followed by wet weather while their occlusion causes dry weather which continues till new cyclonic vortex is formed.

With the southward migration of the sun and its location at the tropic of Capricorn(23 December) the northern circumpolar whirl again expands and hence the westerly jet streams again establish themselves to the south of the Himalayas, the NITC is withdrawn from over India due to southern summer (winter solstice) and poleward shifting of the southern circumpolar whirl, the summer monsoons are terminated and N. E. trades are re-established over south Asia during winter season.

6.7 JET STREAM

1. Meaning

The strong and rapidly moving circumpolar upper westerly air circulation in a narrow belt of a few hundred kilometers width in the upper limit of troposphere is called jet stream. The circulation of westerly jet stream is confined between poles and 20^0 latitudes in both the hemispheres at the height of 7.5-14 km. According to World Health Organization (WHO), 'a strong narrow current concentrated along a quasi-horizontal axis in the upper troposphere or in the stratosphere characterized by strong vertical and lateral wind shear and featuring one or more velocity maxima is called jet stream'. In fact, jet stream was discovered during second world war when American jet bomber fighter planes while flying towards Japan (from east to west) found obstructions of an air circulation which was moving in opposite direction (west to east) resulting into marked reduction in the velocity of jet fighter planes, while these planes registered marked increase in their velocity while they used to return to their bases (west to east). After careful study of this phenomenon, it was found that there was a strong upper air circulation from west to east in the upper portion of troposphere which presented obstruction in the free movement of jet fighter planes. Based on this fact, westerly strong meandering upper air circulation was called as **jet stream.**

2. Properties

The jet streams are characterized by the following properties.

(1) The circulation of jet streams is from west to east in a narrow belt of a few hundred kilometers width at the height of 7.5 -14 km in the upper troposphere.

(2) On an average, jet streams measure thousands of kilometers in length, a few hundred kilometers in width and a few kilometers (2-4 km) depth.

(3) Generally, their circulation is observed between poles and 20^0 latitudes in both the hemispheres. These are also called circum-polar whirl because these move around the poles in both the hemispheres.

(4) The vertical wind shear of jet streams is 5-10m/second (18-36 km/hour), meaning thereby the wind velocity above or below jet stream decreases by 18-36 km/hour. Lateral wind shear is 5m/second (18km/hour). The minimum velocity of jet stream is 30m/second (108 km/hour).

(5) Their circulation path (trajectory) is wavy and meandering (fig. 6.10).

(6) There is seasonal change in the wind velocity in jet streams wherein these become strong during winter season and the wind velocity becomes twice the velocity during summer season. Maximum wind velocity is 480 km (per hour).

(7) The extent of jet streams narrows down during summer season because of their northward shifting while these extend upto 20^0 latitudes during winter season.

3. Types of Jet Streams

On the basis of locational aspect, jet streams are divided into 5 types:

(1) **Polar front jet streams** are formed above the convergence zone (40-60 latitudes) of the surface polar cold air mass and tropical warm air mass. The thermal gradient is steepened because of convergence of two contrasting air masses. These move in easterly direction but are irregular.

(2) **Subtropical westerly jet streams** move in the upper troposphere to the north of subtropical surface high pressure belt (at the poleward limit of the Hadley cell in both the hemispheres) *i.e.* above 30^0-35^0 latitudes. Their circulation is from west to east in more regular manner than the polar front jet streams.

(3) **Tropical easterly jet streams** develop in the upper troposphere above surface easterly trade winds over India and Africa during summer season due to intense heating of Tibetan plateau and play important role in the mechanism of Indian monsoon.

(4) **Polar night jet streams,** also known as stratospheric subpolar jet streams, develop in winter season due to steep temperature gradient in the stratosphere around the poles at the height of 30 km. These jet streams become very strong westerly circulation with high wind velocity during winters but their velocity decreases during summer and the direction becomes easterly.

(5) **Local jet streams** are formed locally due to local thermal and dynamic conditions and have limited local importance.

4. Index Cycles of Jet Streams

The genesis of jet streams is related to temperature gradient from equator towards the poles, surface high pressure at the poles and genesis of circumpolar whirl above the poles caused by tropospheric low pressure. It may be pointed out that surface high pressure is intensified over the surface of arctic region due to subsidence of cooled heavy air during winter season in the northern hemisphere. On the other hand, upper air low pressure develops in the upper troposphere above the high pressure of ground surface of the

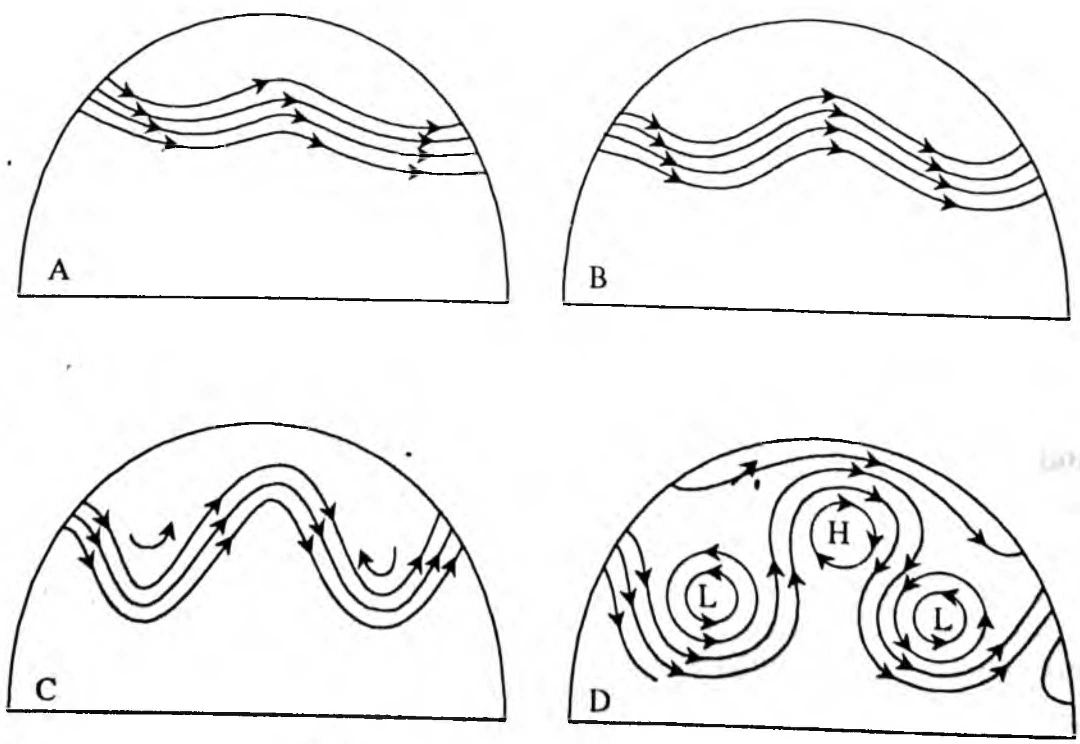


Fig. 6.10 : Index cycle of jet streams.

arctic region. Due to this phenomenon a cyclonic system (west to east) of air circulation in the form of a whirl develops around upper tropospheric low pressure. The general direction of this circulation is from west to east. The equatorward meandering part of this upper air circulation is called jet stream. The upper air arctic whirl becomes very strong during winter season in the northern hemisphere resulting into maximum southward extension of jet stream upto 20^0N latitude. There are changes in the position of extent of jet stream from the poles towards the equator. The wavy (meandering) jet stream is called **Rossby waves.** The period of transformation of straight path of jet stream to wavy or meandering path is called **index cycle** which is completed in four successive stages (fig 6.10).

First Stage : The position of jet streams is near the poles (6.10A) and is separated by polar cold air mass in the north and warm westerlies in the south (in the northern hemisphere). The circulation of jet stream is almost in straight path from west to east because Rossby wave is not developed by this time. There is steep pressure gradient across this strong upper air westerly circulation which generates high zonal index.

Second Stage : Gradually, the straight path of jet stream is transformed into wavy path with the march of time (fig 6.10B). This process initiates the beginning of the development of Rossby waves. With the march of time the amplitude of jet streams increases and gradually they extend towards the equator. The pressure gradient is north-south.

Third Stage is characterized by fully developed meandering course of jet stream (fig. 6.10C), with the result they are positioned near the equator (20^0 latitude). It may be noted that the pressure gradient in the first two stages is from north to south but in this stage it becomes east-west. There is displacement of polar cold air masses towards equator and of tropical warm air masses towards the poles.

Fourth Stage is characterized by cutting off meanders of jet stream from main path due to their more and more meridional circulation (*i.e.* from north to south) resulting into their circulation in independent circular pattern (fig. 6.10D) in the form of cyclonic and anticyclonic circulation. Thus, there develop several cellular circulation patterns which follow cyclonic pattern to the south (L in fig. 6. 10) and anticyclonic pattern in the north (H in fig. 6.10D). Such cut off low (cyclonic) or cut off high (anticyclonic) air circulation patterns obstruct west to east flow of jet streams.

5. Significance of Jet Streams

Though jet streams have not been properly studied as yet but they are supposed to have immense influence on local and regional weather conditions as follows :

(1) There is close relationship between the intensity of mid-latitude (temperate) cyclones and jet streams. These cyclones become very strong and stormy when the upper air tropospheric jet streams are positioned above temperate cyclones of ground surface and yield more precipitation than normal.

(2) There are fluctuations in the local weather conditions due to changes in the form and nature of ground surface cyclones and anticyclones caused by upper air jet streams.

(3) Jet streams cause horizontal convergence and divergence in the upper troposphere. The upper air convergence forms upper air anticyclones while upper air cyclones are developed due to upper air divergence.

(4) The vertical circulation of air in jet streams occurs in two ways *e.g.* cyclonic pattern is characterized by upward vertical air movement while there is downward vertical air movement in anticyclonic pattern of air circulation. This vertical air circulation causes rapid rate of mixing of air between troposphere and stratosphere, which helps in the transport of anthropogenic pollutants from troposphere to stratosphere. For example, the transport of ozone depleting chlorofluorocarbon substances into stratosphere causes global warming (see section 2.2 (2) of chapter 2 of this book).

(5) The monsoon of South Asia is largely affected and controlled by jet streams (see section 7.8 of chapter 7) of this book).

6.8 EL NINO-LA NINA PHENOMENON

El Nino is considered as a significant weather phenomenon or event which occurs off the west coast of S. America, mainly off the Peru

Coast. The El Nino event was first noticed in the year 1541. Since then more than a dozen events have occurred (e.g. 1. 1951-52, 53; 2. 1957-58; 3. 1963-64; 4. 1965-66; 5. 1969-70; 6. 1972-73; 7. 1976-77; 8. 1977-78; 9. 1979-80; 10. 1982-83; 11. 1986-88; 12. 1991-92, 93; 13. 1994-95; 14. 1997-98; etc.). La Nina event was identified and named as La Nina phenomenon in the year 1986 but its occurrence was recorded in 1950-51, 1954-56, 1964-65, 1970-72, 1973-74, 1974-76, 1984-85, 1988-89, 1995-96 etc. The occurrence of La Nina event strengthens Southern Oscillation and Walker Circulation, the eastern Pacific Ocean off the Peru Coast is characterized by relatively colder water and dry condition while the western equatorial Pacific Ocean has warm water and more humid weather, trade winds become more vigorous, the south and south-east Asia receives more precipitation etc.

A subsurface warm current, known as El Nino Current, flows from north to south between 3^0S and 36^0S latitudes at a distance of about 180 km from the Peruvian coast. The southward shifting of the counter equatorial warm current during southern winter gives birth to El Nino current. The temperature at Peruvian coast does not fall considerably because of this current. Though the amount of rainfall increases along the coasts due to this current but fishes die due to disappearance of planktons and occurrence of guano disease and pests caused by El Nino. It may be pointed out that El Nino also affects monsoons in the Indian Ocean. When El Nino is extended to the southern end of S. America warm water is pushed eastward to join the South Atlantic westerlies drift which brings warm water in the southern Indian Ocean during southern winters. Consequently, the high pressure in the Indian Ocean during southern winter is not intensified due to which the south-west summer monsoon is weakened.

Presently, El Nino is considered as a weather event or phenomenon. El Nino is considered as Christ child while La Nina as younger sister of El Nino. El Nino has been related to the increase of temperature of east Pacific Ocean off Peruvian coast while La Nina is related to the warming of the western Pacific Ocean. The strong El Nino brings heavy rainfall exceeding normal rainfall resulting into lush green otherwise dry coastal land of Peru. The cold water mass near Peruvian coast becomes warm due to strong El Nino event resulting into heavy rainfall in the first half of the year (January to March). Earlier the people of Peru in the event of dry conditions while looking towards the sky prayed 'Ye God, give us rain and keep drought away' but when they came to know that copious heavy rainfall causing mass destruction of marine life (mainly death of fishes due to disappearance of planktons) was associated with strong El Nino event, they began to pray, 'Ye God, give us rain and keep El Nino away.' The heavy rainfall associated with strong El Nino event makes coastal Peruvian deserts green and there is rich harvest of cotton, coconuts and bananas but there is oceanic biological disaster. It may be maintained that in the event of strong El Nino the tropical eastern Pacific receives four to six times more rainfall than normal amount but dry condition prevails in the tropical western Pacific resulting into severe drought in Indonesia, Bangladesh, India etc. The widespread fire in the forest of Indonesia in 1997-98 was related to drought resulting from strong El Nino event. La Nina is a counter ocean current which becomes effective in the tropical western Pacific when El Nino becomes ineffective in the tropical eastern Pacific. The dry condition in the western Pacific is terminated and wet condition is introduced in the tropical western Pacific by La Nina.

Effects of El Nino Events

The occurrence of El Nino events brings far reaching impacts on weather conditions in the northern hemisphere in general and tropical and subtropical regions in particular, marine life, vegetation, agriculture and human health and wealth. Two El Nino events of 1982-83 and 1997-98 have proved more disastrous. The 1982-83 El Nino event caused rise in normal temperature in the north-western parts of Canada and Alaska; rise in winter normal temperature in the eastern parts of the United states of America; severe drought conditions and failure of monsoon in S.E. and South Asia mainly in Indonesia and India; excessive rainfall and substantial fall in fish catch near the Peruvian coasts; coral bleaching in the Pacific Ocean; spread of encephalitis disease in the eastern United States of America; droughts in

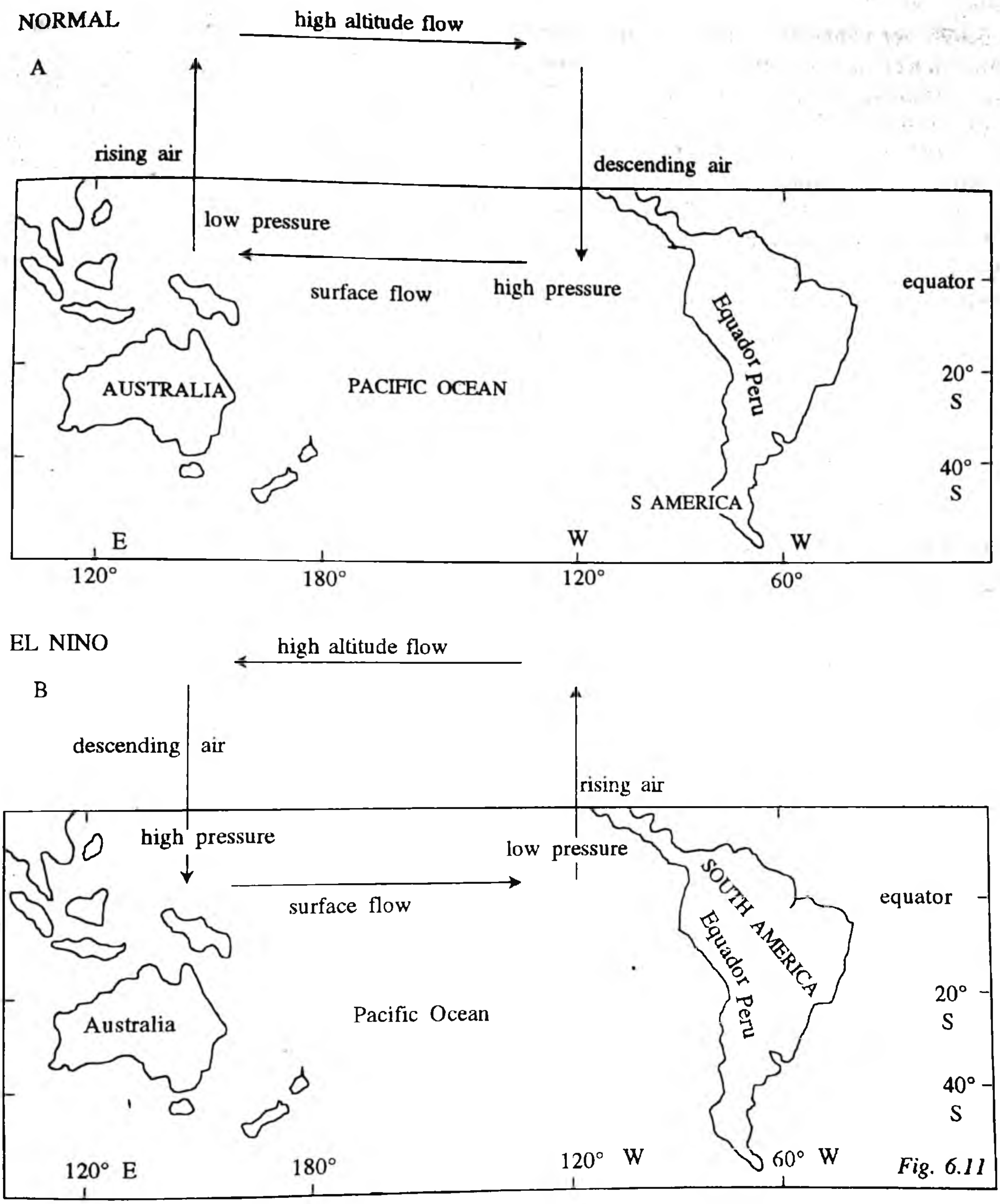


Fig. 6.11 : Southern oscillation, Walker circulation and EL Nino.

Mexico, S.E. Africa, Australia and New Zealand etc. The 1997-98 El Nino event caused rise in normal sea surface temperature by 5°C in the Pacific Ocean and Indian Ocean (2°C) which resulted in coral bleaching and mass destruction of corals. About 95 per cent of shallow water corals in Baharain, Maldives, Sri Lanka, Singapore and Tanjania were killed due to catastrophic bleaching while 50-70 per cent corals died due to severe bleaching in Kenya, Secheelles, Japan, Thailand, Vietnam, Andman and Nicobar Islands etc. The years of strong El Nino bring severe drought conditions in India, Indonesia, Australia, Mexico, South Africa, Philippines etc. which results in irreparable loss of agricultural production, devastating forest fire in Indonesia. Though strong El Nino brings copious rainfall in coastal deserts of Peru and Chile making the deserts lush green but it causes mass killing of fishes mainly anchovy species due to starvation because the presence of warm water stops the upwelling of cold water and nutrients from below and hence the supply of planktons is substantially reduced. The impact of El Nino on weather conditions is further elaborated in the following section.

6.9 WALKER CIRCULATION AND EL-NINO-SOUTHERN OSCILLATION (ENSO)

Certain variations are found from the atmospheric general circulation patterns *e.g.* surface trades, westerlies and polar winds circulation and tricellular meridional circulation. Circulation of local and seasonal (monsoon) winds may be cited example of such deviations. East- west zonal circulation of tropical winds is an important variant from general atmospheric circulation. This typical east-west circulation of tropical wind is called **Walker circulation** named after famous scientist G.T. Walkar in 1922-23. In fact, Walker circulation is a zonal convective cell of air circulation, which is formed due to the development of pressure gradient from east to west in the equatorial Pacific ocean. After two-three years this general condition of east-west pressure gradient is reversed *i.e.* pressure gradient becomes from west to east (fig. 6.11 B). Thus, there are oscillations in pressure gradient and air circulation after the intervals of 2-3 years. Walker called such oscillation as **southern oscillation**.

Walker circulation and southern oscillations are driven by the sea surface pressure gradient from the equatorial eastern Pacific ocean (near the western coastal areas of South America) to the equatorial western Pacific ocean (near S-E Asian coasts). In normal conditions high pressure develops on the sea surface of the equatorial east Pacific ocean and the western coastal lands of South America (fig. 6.11 A) due to subsidence of air from above and upwelling of cold oceanic water. On the other hand, low pressure is formed in the equatorial western Pacific ocean due to rise of air from the warm sea surface. This pressure gradient from east to west generates east-west circulation of trade winds on the surface while there is reverse upper air circulation *i.e.* from west to east (fig. 6.11A) which completes a convective cell. This east-west air circulation drives the ocean water mass from the western coast of South America towards the west. This phenomenon facilitates upwelling of cold sea water near the coasts of Peru and Equador resulting in further cooling of air, high air pressure, atmospheric stability and dry weather condition. Contrary to this, east-west air circulation becomes warm north-east trades in the equatorial west Pacific ocean where it, after being heated, rises upward, becomes unstable and causes precipitation. After rising to certain height it turns eastward and descends in the equatorial eastern Pacific ocean to complete the convective cell (fig. 6.11 A). This is now evident that tropical eastern and western Pacific is characterized by dry and wet weather conditions respectively.

By October-November the low air pressure of the tropical western Pacific is shifted to the tropical eastern Pacific causing weakening of trade winds. This reversal in pressure condition facilitates the return of warm sea water which was driven from the coasts of South America westward, towards the tropical east Pacific. Consequently, low air pressure is formed in the south-east Pacific mainly off the coasts of South America (Equador and Peru), upwelling of cold sea water is stopped, warm air rises upward and becomes unstable and ultimately yields rainfall after condensation. It is evident that the general normal condition (fig. 6.11 A) has got reversed (6.11B). This event is called **El Nino Phenomenon**. The rising air in the east Pacific cools above and turns westward in the troposphere and ultimately descends in the tropical west Pacific giving birth to high pressure which drives warm air towards the coasts of South America. Thus, again a complete convective cell is formed. Such condition is called **El Nino-Southern Oscillation Event** (ENSO Event). In fact, changes in the positions of air pressure in the tropical eastern and western Pacific are called **southern oscillations.** During El Nino event Walkar circulation is weakened due to the development of equatorial westerlies on sea surface (fig. 6.11 B) but Hadley circulation is activated. This phenomenon again activates trade winds which again drive sea-water of the tropical eastern Pacific westward resulting in the upwelling of cold water from below, weakening of El Nino event and re-establishment of normal condition (fig 6.11 A).

It may be mentioned that the phases and strengths of the Southern Oscillation (spatio-temporal shifting of pressure systems (high and low) between tropical eastern and western Pacific Ocean) are determined on the basis of differences of air pressure between these two areas, to be more specific, between Tahiti (eastern Pacific, 18^{0}S latitude and 150^{0}W longitude) and Darwin (Australia, western Pacific, 12^{0}S latitude and 130^{0}E longitude). The phases of the SO are termed as **Southern Oscillation Index (SOI)** wherein two phases are most significant, namely **high phase** and **low phase. High phase** of SO indicates normal condition or non-ENSO phase wherein tropical eastern and south-eastern Pacific is characterized by strong high pressure system whereas low pressure system develops in the tropical western Pacific (fig. 6.11A), strong easterly winds dominate over the surface, tropospheric subtropical westerly jet streams are weakened and shift poleward in both the hemispheres, La Nina effects set in, monsoon becomes strong and brings copious precipitation in the south and south-eastern Asian regions, tropical south America (i.e. Amazonia) and Africa (i.e. central Africa), and almost dry conditions in the tropical eastern Pacific (i.e. western coastal areas of S. America. mainly Peru and Chile)

The **low phase** of SO (fig. 6.11 B) is indicative of reversal of non-ENSO phase as described above and onset of El Nino phase characterized by the development of high pressure system over tropical western Pacific and low pressure system over tropical eastern Pacific, dominance of El Nino event off the Peruvian and Chilean coasts and accentuated rainfall but disappearance of La Nina phenomenon from the tropical western Pacific and decreased precipitation in India and Indonesia resulting into drought condition.

6.10 IMPORTANT DEFINITIONS

Doldrum : A belt of low pressure, popularly known as equatorial trough of low pressure extending discontinuously within a zone of 5^{0}N and 5^{0}S latitude is called the **belt of calm** or **doldrum.**

Equatorial westerlies : The westerly surface air circulation in the doldrum or in the intertropical convergence zone is called equatorial westerlies (named by Flohn).

Ferrel cell : An intermediate mid-latitude thermally indirect cell of air circulation between tropical Hadley cell and Polar cell is called Ferrel cell or Polar front cell.

Hadley cell : The tropical convective cell, one each in the northern and the southern hemispheres, is called Hadley cell (named after George Hadley, in 1735).

Index cycle : The period of transformation of straight path of jet streams is called index cycle which is completed in four successive stages.

Intertropical fronts : The equatorial or tropical fronts are called intertropical fronts (ITF) or intertropical convergence (ITC).

Jet streams : The strong and rapidly moving circumpolar upper air westerly air circulation in a narrow belt of a few hundred kilometers width in the upper limit of the tropospheres is called jet stream.

Rossby waves : The wavy jet stream is called Rossby wave (named after Carl-Gustav Rossby).

Southern oscillation : Spatio-temporal changes in the high and low pressure systems in the tropical eastern and western Pacific Ocean are called southern oscillation (SO).

Southern oscillation index : The phases of the Southern Oscillation (high and low phases) are termed Southern Oscillation Index (SOI).

Walker circulation : A typical east-west convective cell of circulation of tropical winds is called Walker circulation named after G.T. Walker in the year 1922.

7

LOCAL AND SEASONAL WINDS

7.1 LOCAL WINDS : MEANING AND CONCEPT

The winds confined to a limited spatial locality and caused by local conditions are called local winds. It may be mentioned that such local winds are departures from general global atmospheric surface circulation (*e.g.* planetary winds—trades, westerlies and polar winds) and are grouped under the category of **tertiary atmospheric circulation.** Though local winds are generally confined to limited territory but sometime they cover very long distances of hundreds to thousands of kilometers. For example, the Northers, a cold powdery polar wind, after being originated in the Arctic Canada reach as far south as the Mexican Gulf in the United States of America and bring the temperatures of Galveston, Houston, Neworleanse etc. below freezing point. There are wide range of variations in the time span and areal coverages. Some of the local winds change direction within 24 hours and complete a diurnal cycle such as land and sea breezes, mountain and valley breezes. Such local winds may be termed **periodic local winds.** On the other hand, a few local winds become active only during a brief period of the year *e.g.* **loo,** a very hot and dry westerly wind, becomes active in the northern plains of India during 3 summer months of April, May and June. Such local winds may be named as **non-periodic local winds.** There are also variations in thermal characteristics of local winds and hence these are divided into **cold** and **hot local winds.**

It may be pointed out that primary cause of the genesis of local winds is variation in air pressures at local levels due to differential heating and cooling consequent upon temperature variations. The topographic characteristics also provide ideal conditions in the origin of local winds on one hand (for example, mountain and valley breezes) and present effective barriers in stopping the spread and influences of a few local winds on the other hand, for example, the Himalayas stop the southward movement of cold Siberian winds and protect the north Indian plain territory being frozen during winter season. Sometime, mountain barriers give typical thermal characteristics to a local wind. For example, the westerly winds coming from over the Pacific Ocean become quite warm while descending through the eastern slopes of the Rockies due to dry adiabatic warming and become **Chinook, a hot** local wind.

Like horizontal extent, the vertical extent of local winds is also limited *e.g.* local winds are vertically confined to height of a few thousand meters only in the lower atmosphere. The local winds affect local weather conditions of the affected locality in both positive and negative manner as regards flora and fauna and ecosystems. In other words, some of the local winds are beneficial to the plants and animals of the concerned localities like chinook in eastern slopes of the Rockies in Canada and the USA and Foehn in Switzerland, Harmattan in north-west Africa mainly in Guinea coastal areas where this is called as **doctor** because being a hot and dry wind it brings much respite to people from hot and humid weather. On the other hand, some of the local winds become notorious and harmful to most of biota in general and human being in particular, like sirocco in Italy, norwester in Australia, loo in India etc. Thus, local winds may be grouped into two types on the basis of their influences on flora and fauna including man viz **positive** and **negative local winds** or **favourable (beneficial)** and **unfavourable (notorious) local winds.**

Thus, the local winds may be classified into two broad categories viz. (i) periodic local winds, and (ii) regional local winds. These may be further subdivided into cold local winds and hot local winds on the basis of thermal characteristics of the concerned wind and its locality, and into beneficial and non-beneficial (notorious) local winds as follows :

(1) **Periodic local winds**

(i) Land and sea breezes

(ii) Mountain and valley breezes

(2) **Non-periodic local winds**

(A) on the basis of thermal characteristics

(a) **hot local winds**

(i) Chinook

(ii) Foehn

(iii) Harmattan

(iv) Sirocco

(v) Norwester

(vi) Brickfielder

(vii) Shamal

(viii) Khamsin

(ix) Doctor

(x) Simoom

(xi) Santa Ana

(xii) Loo, etc.

(b) **Cold local winds**

(i) Mistral

(ii) Bora

(iii) Blizzard

(iv) Northers

(v) Purga

(vi) Bise

(vii) Laventer

(viii) Pampero, etc.

(B) on the basis of impact on flora and fauna and man

(a) **beneficial local winds**

examples :

(i) Chinook

(ii) Foehn

(iii) Doctor, etc.

(b) **non-beneficial (notorious) local winds**

examples :

(i) Northers

(ii) Norwester

(iii) Blizzard

(iv) Sirocco, etc.

Local winds can also be classified on the basis of causal factors and mechanism of genesis as follows :

(1) **Barrier-induced or barrier effect or compressional local winds**

(a) Chinook winds (eastern slopes of Rockies),

(b) Foehn winds (northern slopes of Alps)

(c) Zonda winds (eastern slopes of Andes)

(2) **Channelled local winds**

(a) Santa Ana (southern California)

(b) Yamo (Japan)

(c) Tramontane (Central Europe)

(3) Depression local winds

(associated with low pressure systems)

(a) Sirocco (Italy)

(b) Leveche (Spain)

(c) (Gibli (Tunisia)

(4) Insolational local winds (convection winds)

(originated due to intense heating of ground surface)

(a) Dust devils in deserts

(b) Dust storms

(c) Microbursts (a powerful strong gusty wind radiating from a center on the ground surface)

(i) dry microbursts

e.g. haboob (in Sudan, S.W. United States- Mojave and Arizona deserts, Great Australian desert etc.)

(ii) wet microbursts

(associated with precipitation)

(*e.g.* karaburan (in Tarim basin)

(5) Urban heat island winds or countryside-city breeze

(caused due to intense heating, increased counter radiation, large storage of daylight time insolation, additional heat generated by anthropogenic sources like automobiles, domestic heating, factories etc.)

(6) Advectional local winds

(a) horizontally circulating winds

e.g. land and sea breezes

(b) vertically circulating winds

e.g. mountain and valley winds

A brief characteristic features of a few important local winds and their climatic significance and their influences on flora and fauna in general and human being in particular are discussed below :

7.2 PERIODIC LOCAL WINDS

The winds originating from diurnal temperature and pressure variations are called periodic or diurnal local winds. The daily change in temperature and consequent pressures during daylight and night time are the result of contrasting nature of heating and cooling of two surfaces e.g. land and water or two contrasting topographic features such as mountains and valleys. Such periodic winds experience complete reversal in their direction and velocity within 24 hours period. The important periodic local winds are land and sea breezes or lake breazes, and mountain and valley breezes.

Land and Sea breeze

Land and sea breezes, representing a complete cycle of diurnal winds are, in fact, monsoon winds at local scale because they change their direction twice in every 24-hour period. These local diurnal monsoon winds very commonly known as land and see breezes are found in the coastal areas wherein sea breeze blows from sea to land, during day time and land breeze moves from land to sea during night due to differential heating and cooling of land and water.

The daily local winds in lake shore areas are called **land and lake breezes.** The land and sea breezes or land and lake breezes are the function of diurnal reversal in temperatures and resultant pressures over land and water surfaces due to their contrasting nature of heating and cooling.

Sea Breeze—Land is heated more quickly than the adjacent sea during daylight time, with the result the warm air over the adjacent land is heated and expands and thus low pressure is developed while high pressure is developed over adjacent sea. The pressure gradient from sea surface to land surface causes circulation of relatively cool air from sea to adjacent land (fig. 7.1). Sea breezes begin to flow usually between 10-11 a.m. and become most active in early afternoon usually between 1 to 2 p.m. with maximum velocity ranging between 10 to 20 kilometers per hour and are terminated by 8 p.m. at night. The average depth of sea breeze system ranges between 1000-2000 metres in the coastal regions of the tropical areas while its depth is between 200 and 500 m near the lakes. The cooling effect of sea breezes reaches 50 to 65 km inland in the tropical regions while 15 to 50 km in the middle latitudes. The velocity of these winds varies spatially *e.g.* the velocity varies from

25 to 50 km per hour in the temperate areas while some times sea breezes become stormy in the tropical areas. Sea breezes have cooling effects on the coastal land as the temperature drops by 5°C to 10°C, with the result weather becomes pleasant. Sea breezes are most active during summer season.

Land Breeze—After sunset the sea breezes are weakened because the daylight time low pressure over land is weakened due to rapid loss of heat through outgoing longwave radiation from the land. Consequently, the position of daylight time high and low pressure is reversed. Now high pressure is developed on land against low pressure on the adjacent sea with the result air starts moving from land to sea during night (fig.7.1B). Land breezes are comparatively weaker than sea breezes. These are dry winds.

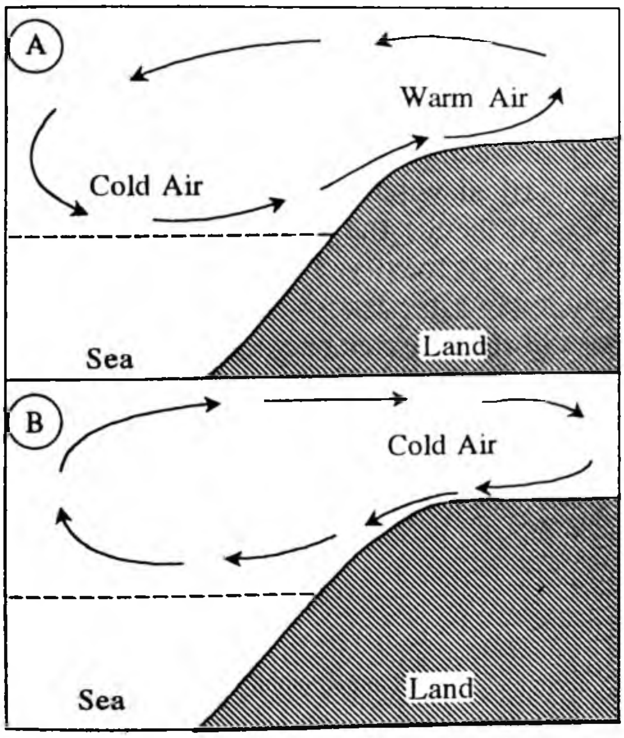


Fig. 7.1 : A = Sea breeze, B = Land breeze.

It may be mentioned that night time low pressure over sea surface in relation to high pressure over land surface is not due to nocturnal heating of sea surface. The high pressure over land surface is caused due to radiation loss of heat while sea surface remains warm because of delayed cooling of sea surface during night. It is also important to note that temperature and consequent pressure variations over sea and adjacent land surface are not so pronounced during night time as during daylight time, and hence land breezes are not as strong as sea breezes. Land and sea breezes are more regular and fully developed around islands in the tropical and subtropical regions but they are absent in high latitude areas because of little variations in temperatures and pressures over land and sea areas. During daylight time a convective cell is developed *i.e.* the onshore surface sea breezes are compensated by offshore breezes aloft. The night time convective cell is less developed. The onshore see breazes form some sort of fronts at the coastal areas and are associated with cumulus clouds. The Coriolis force becomes more effective in the middle latitudes and makes the onshore sea breezes to blow more or less parallel to the coasts in the northern hemisphere.

The land and sea breezes have significant influences on local weather conditions. These winds produce fogs, though of lesser intensity, round the year over the seas and such fogs are transported to the adjacent coastal land by onshore sea breezes in the afternoon but they disappear during night time. Sea breezes bring cooling effect in the coastal lands and thus provide respite from the oppressive heat in the tropical and subtropical regions. Land and sea breezes also help local navigators for handling their small size boats. Such diurnal rhythmic land and sea breezes moderate daylight and nocturnal temperatures in the coastal lands and lower down the daily range of temperature.

Mountain and Valley Breezes

Mountain and valley breezes also known as upvalley (during daylight time) and downvalley (during night) breezes are, in fact, local as well as diurnal (periodic winds, the directions of which are reversed during 24 hours). The slopes and valley floors in the mountainous regions are more heated through insolation during daytime than the free atmosphere at the same elevation. Consequently, the warm air moves upslope (upward). This upslope moving breeze during daytime is called

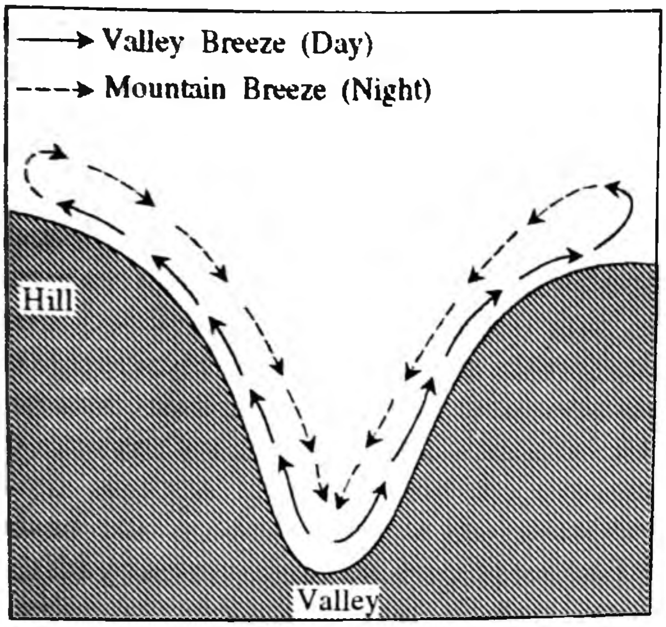


Fig. 7.2 : Mountain and valley breezes.

valley breeze (fig. 7.2) or **anabatic wind**. Valley breezes reach mountain peaks and yield precipitation though cumulus clouds. The valley slopes and upper parts are cooled during night time due to loss of heat through outgoing longwave radiation and thus cool air descends through the valley slopes. Such wind is called downvalley or mountain breeze or **katabatic wind**. The mountain breezes cause inversion of temperature in the valleys. This is why the valley floors are characterized by frost during night while the upper parts are free from frost in cold areas.

It may be mentioned that mountain and valley breezes or upvalley and downvalley breezes are thermally originated via topographic or relief controls. In other words, the temperatures and associated pressure variations along the mountain/hill/ridge slopes and in the valleys are caused due to topographic differences. Valley or **anabatic breezes** are more regular and more intense than mountain or downvalley or **katabatic breezes**. Such breezes develop in the higher mountainous areas in all seasons. The diurnal cycle of valley and mountain breezes causes inversion of temperature (called as valley inversion of temperature) and resultant radiation fog in the lowland area.

7.3 NON-PERIODIC LOCAL WINDS

The local winds, other than diurnal system of air circulation having complete reversal in direction within every 24 hours, are called non-periodic local winds which are both thermally and dynamically originated. In some cases orographically forced ascent and descent of winds also give birth to a special type of local winds (e.g. Chinook and Foehn winds). On the basis of thermal characteristics non-periodic local winds are classified into warm (hot) and cold local winds. Important hot local winds include chinook and foehn, harmattan, sirocco, norwester, brieckfielder, shamal, khamsin, simoom, santa ana, loo etc. while significant cold local winds are mistral, bora, blizzard, northers, purga, bise, laventer, pampero etc. Alternatively non-periodic local winds are grouped into beneficial (chinook, foehn, doctor etc.) and non-beneficial (northers, blizzards, sirocco etc.) local winds.

Chinook and Foehn

Warm and dry local winds blowing on the leeward sides of the mountains are called **chinook** in the USA and **foehn** in Switzerland. These are infact downslope compressional winds. These local vertical winds are of cyclonic origin and largely influence the weather conditions of the affected areas locally. The winds associated with the cyclones after descending through the eastern slopes of the Rockies become warm and dry and thus give birth to chinook. The winds ascend through the western slopes of the Rockies mountains and thus are cooled at the **dry adiabatic rate** of 5.5°F per 1000 feet (10°C per 1000 meters). These winds after reaching higher height become saturated (due to lowering of temperature and hence increase of relative humidity) and yield precipitation. The latent heat of condensation released after precipitation is added to the ascending winds, with the result the temperature of the ascending winds decreases at the **moist adiabatic rate** of 3°F per 1000 feet or 6°C per 1000 meters (fig. 7.3). The westerly winds after crossing over the Rockies descend through the eastern slopes and thus are heated at the dry adiabatic rate of 10°C per thousand meters. These warm and dry winds after reaching the foothill zones of the eastern slopes of the Rockies are called Chinooks.

Chinook winds are more common during winter and early spring along the eastern slopes (leeward side) of the Rocky Mountains from Colorado (USA) in the south to British Columbia (Canada) in the north. Normally, the actual temperature of chinooks is 40°F (4.4°C) but the actual temperature of the affected areas is below freezing point during winter months. Thus, chinook becomes very warm in comparison to prevailing subzero temperature. The rise of temperature in the affected areas by 40°F (4.4°C) after the arrival of chinooks within 24 hours is not unusual. Some times, temperature rises by 30° to 40°F within few minutes. The rise of temperature of the affected area by 20°-22°C within 24 hours with the arrivial of chinook results unusal weather. A rise of temperature of 19°C in Kip (in Montana) within seven minutes and of 14°C at Denever (in Colorado) on January, 27, 1940 within two hours tells the terrific thermal effect of chinook. Thus, snow present on the ground surface melts away due to sudden rise in temperature as if by magic. This is why chinook is also called as **'snow eater'**. This is the impact of chinooks that green pastures are open in a narrow strip along the eastern slopes of the Rockies even during winter season. The rise in temperature due to chinooks also helps in early sowing of spring wheat in the USA.

The severity of winter season in the Great Plains of the USA is remarkably reduced and the weather becomes pleasant on the arrival of chinook winds. Chinook has one negative aspect in that much of the meltwater due to sudden rise in temperature is evaporated even before spring season which results in reduction of soil moisture. Chinook winds are gusty and stormy and occasionally they attain the velocity of 150-160km per hour and large amount of snow is sublimated at their arrival. The temperature of Spearfish in South Dakota of the USA registered a dramatic rise from

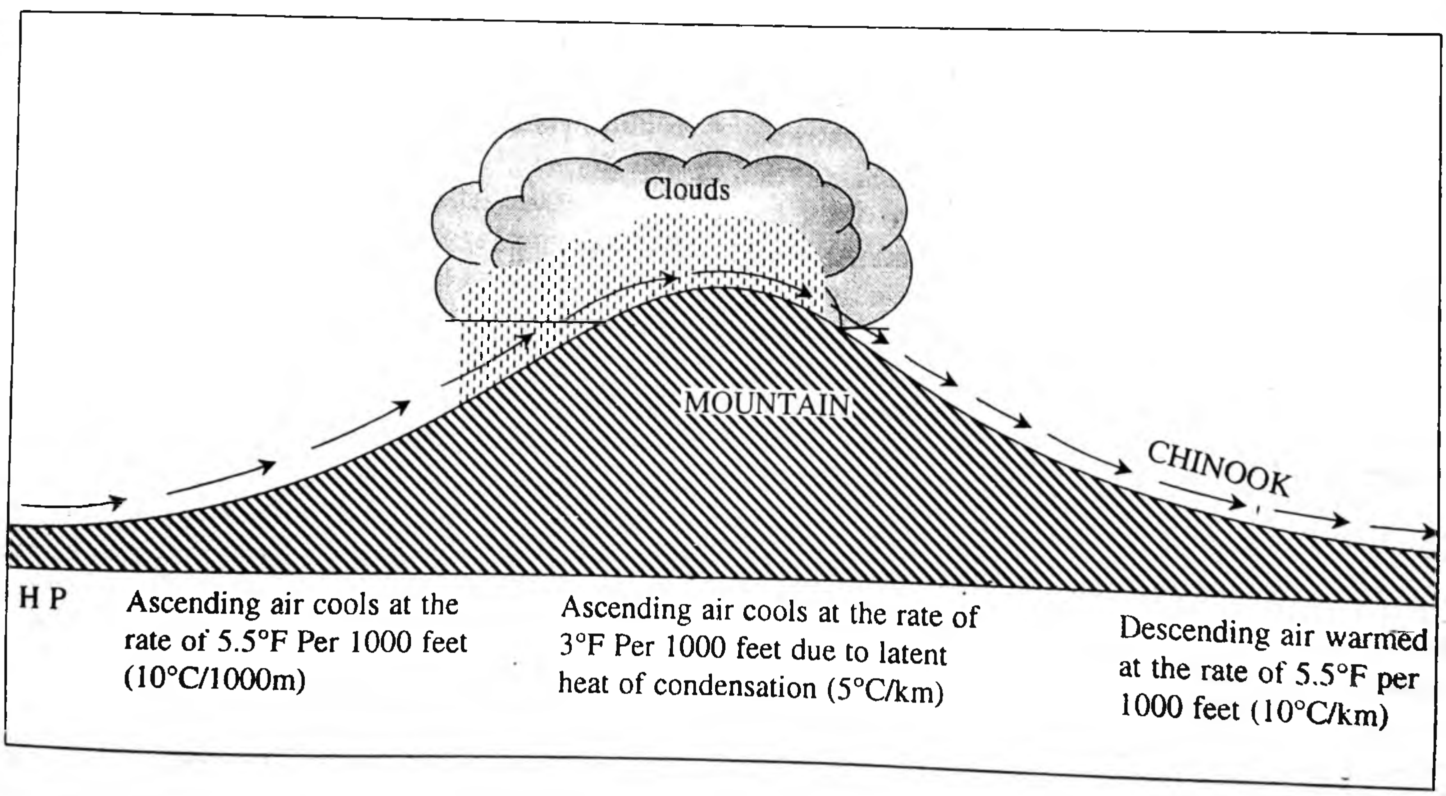


Fig. 7.3 : Origin of Chinook winds.

-20°C at 7.30 A.M. to 7°C at 7.32 A.M. on January 2, 1943,, making a net rise of 27°C within 2 minutes, which definitely appears as an effect of magic.

A warm and dry wind similar to chinook is called **'foehn'** along the northern slopes of the Alps mountains. These are more common during spring and autumn in Switzerland. The weather becomes quite pleasant in the valleys due to melting of snow because of increase in temperature by 40°F after the arrival of foehn winds. This is why valleys of Switzerland are called **'climatic oasis'** during winter season. These winds help in early sowing of spring wheat, ripening of grapes and check autumn frost.

A similar warm and dry downslope compressional wind in Argentina is locally called **Zonda,** which blows on the leeward slope of the Andes. It attains the velocity of 120 kilometers per hour and becomes more vigorous during winter season.

Santa Ana

A downslope compressional but channelled warm and dry air drainage in the Santa Ana valley of the Southern California is locally called Santa Ana. Santa Ana is almost similar to Chinook and Foehn as regards thermal and moisture characteristics but unlike these two regional winds Santa Ana blows as air channel through east-west stretching Santa valley. In fact, this warm, dry and desiccating wind is considered as **climatic hazard** because the soil and vegetation moisture is desiccated (dried) and widespread forest fires result due to extreme aridity and high temperature. Some time Santa Ana winds become gusty and dusty when they are charged with enormous amount of dusts and hence become dust devil. Santa Ana winds are very much injurious to farming mainly to orchards. Similar channelled downvalley air drainage of warm and dry winds is called **Yamo** in Japan and **Tramontane** in central Europe.

Harmattan

The warm and dry winds blowing from north-east and east to west in the eastern parts of Sahara desert are called harmattan. These winds become extremely dry because of their journey over Sahara desert. While blowing over Sahara desert these winds pick up more sands mainly red sands. The western coast of Africa is warm and moist and hence the weather becomes unpleasant because the weather conditions characterized by high temperature and high relative humidity become injurious for human health. The weather becomes suddenly dry and pleasant at the arrival of harmattan as the relative humidity of the air is remarkably reduced due to high temperature and hyperaridity of harmattan. This is why harmattan is known as **'doctor'** in the Guinea coastal area of western Africa. In fact harmattan is very dusty and stormy wind blowing with so gusty speed that trees are uprooted. These winds are usually associated with dust storms resulting into marked reduction in the visibility. Harmattan becomes more vigorous during summer months. In fact, harmattan is a special type of north-east trade wind. It becomes extremely warm wind because of hot and dry desert of Sahara. Similar warm, dry, very strong and dustladen winds are called **'brickfielder'** in Victoria province of Australia, **'blackroller'** in the Great Plains of the USA, **'shamal'** in Mesopotamia and Persian Gulf, and **'norwester'** in New Zealand.

Sirocco

Sirocco is a warm, dry and dusty (full of sands) local wind which blows in northerly direction from Sahara Desert and after crossing over the Mediterranean Sea reaches Italy, Spain etc. Sirocco becomes very strong and active at the time of the origin of cyclonic storms over the Mediterranean Sea. It becomes extremely warm and dry while descending through the northern slopes of the Atlas mountain. There are different local names for sirocco in Africa *e.g.* **khamsin** in Egypt (UAR), **gibli** in Lybia, **chilli** in Tunisia etc. The warm and dry dusty winds in the Arabian Desert are called **'simmom'**. Sirocco, while passing over the Mediterranean Sea picks up moisture and yields rainfall in the southern part of Italy where the rain associated with sirocco is called **'blood rain'** because of fallout of red sands with falling rains. It may be remembered that sirocco while blowing through Sahara Desert picks up red sands which settle down with rains in south Italy. It is apparent that sirocco is very much injurious to agricultural and fruit crops.

The sirocco types of winds are so much laden with sands and dusts that the atmospheric visibility is reduced almost to zero. Such warm, dry and dusty winds are called **leste** in Madeira and Morocco, and **leveche** in Spain. **Khamsin,** hot, dry and dusty southerly wind blows in northern Africa and Arabia. The temperature varies between 38°C-

49°C. This is more vigorous during late winter and early spring. The hot and damp wind laden with sands is called **haboob** in southern margins of Sahara, mainly in Sudan. The average annual frequency of haboob winds is 24 but they are frequent in early summer with northward shifting of the NITC (north inter-tropical convergence).

Mistral

Mistral is a cold local wind which blows in Spain and France from north-west to south-east direction. These winds are more common and effective during winter season because of development of high pressure over Europe and low pressure over Mediterranean Sea. They become extremely cold when they blow through central plateau and descend into Rhone valley on the southern coast of France. While blowing through the narrow valley of Rhone they become stormy northerly cold winds. The average velocity of mistral is 56-64 km per hour but some times it becomes 128 km per hour. These stormy winds adversely affect airflights. The arrival of mistral causes sudden drop in air temperature to below freezing point.

Bora

Bora is an extremely cold and dry north-easterly wind which blows along the shore of the Adriatic Sea. Bora becomes more effective in north Italy where it descends through the southern slopes of the Alps and blow in southerly direction. The velocity of bora ranges between 128 km and 196 km an hour but the average velocity is 52 kilometers per hour in winter and 38 kilometers per hour in summer. Unlike mistral, bora is relatively moist wind because it picks up moisture while coming from over the Adriatic Sea. The name Bora has been derived from Latin word 'boreas' meaning north. It may be mentioned that bora is a down-slope adiabatically warmed wind due to its descent through the southern slopes of the Alps but still its temperature is very low in comparison to the temperature of the coastal area. This means that bora is extremely cold before descending the Alpine slopes but its temperature is a bit increased due to dry adiabatic warming (10°C per 1000 meters). Average annual frequency is 36 but it becomes more frequent in winter season when it reduces the temperature of Adriatic coastal areas below freezing level.

Blizzard

Blizzard is violent stormy cold and powdery polar wind laden with dry snow and is prevalent in north and south polar regions, Siberia, Canada and the USA. The visibility becomes remarkably low because of snow and ice crystals. The velocity ranges between 80-96 km an hour. The arrival of these winds causes sudden drop in air temperature to subfreezing level, thick cover of snow on the ground surface and onset of cold waves. These winds reach the southern states of the USA because of the absence of any east-west mountain barrier. They are called '**norther**' in the southern USA and '**burran**' in Siberia.

Urban Heat Island Circulation and Countryside City Breeze

The urban heat island and associated air circulation is caused by modification in the heating and cooling mechanisms of the atmosphere at local level by the antrhopogenic factors mainly urbanization and related building activities as follows :

The process of urbanization changes the radiation and heat balance at local level which becomes regional in character when the effects are extended to larger areas mainly in big industrial belts. The high temperature in the CBD (Central Business District) or the City Centre (known as Chowk in Indian cities) is very often called as **urban heat island** or simply **heat island**. If we have a 'thermal cross section' of a city it appears that temperature decreases outward from the city centre. The city centre is characterised by highest temperature and the temperature gradually decreases outward in the outer periphery of the city.

It may be pointed out that the temperature decreases slowly from the city centre towards the outer parts of the city but at the boundary of the city and the countryside there is sudden drop in air temperature. The heat island becomes most pronounced at night because the temperature difference between the city centre and the rural surroundings or countryside is normally 6°C in most of the large cities but some times the difference of temperature becomes 12°C or even more. 'The magnitude of the urban heat island shows a clear relationship to city size and to wind speed. The larger the city, the stronger the winds which are necessary to dissipate the heat island effect' (T.R. Oake and F.G. Hannell, 1970; quoted by W.R. Rouse, 1981). It is significant to note that the thermal effect of urban heat island is confined to about 300 m above the city centre and beyond this height temperature continues to decrease upward following the general rule of normal lapse rate.

The radiation and heat balance of an urban centre is modified because of more absorption of incoming shortwave solar radiation which causes higher temperature of the masonry ground surface because of two factors viz. (i) The transformation of natural landscape into urban centre results in the absence of plant cover except a few planted trees, bushes, hedges, grassy lawns and gardens scattered in different parts of the city. Thus the solar radiation in the absence of vegetation reaches the ground surface with almost full intensity. (ii) The masonry structures of the roofs of the buildings, pavements and roads and streets largely absorb incoming solar radiation. Further more, the total lack of moisture does not facilitate evaporation and thus in the absence of evaporative cooling (evaporation involves use of heat to convert water into gaseous form and causes lowering of air temperature. This process is called evaporative cooling of the air) the temperature of the urban centres increases.

The following factors and mechanisms may be held responsible for the creation of an urban heat island.

(i) As referred to above the masonry structures of urban centres absorb solar radiation more efficiently than vegetated covers. Moreover, the incoming solar radiation reaches the city surface with full intensity.

(ii) Man-induced heat mainly in the larger industrial cities and even in other metropolitan cities emitted from industrial processes, space heating and cooling, power stations etc. supplement the heat received through solar radiation. According to the study conducted by J.D. Kalma (1974) about the assessment of man-induced heat in the city centre of Sydney (Australia), man-made heating can exceed 25 watts per square metre which is equivalent to almost 50 per cent of incoming solar radiation during winter season. The contribution of man-induced heat to that of the solar radiation drops to 25 per cent during summer season because of increase in incoming solar radiation and decrease in space heating due to rise in air temperature.

(iii) The construction materials used in modern cities and the walls and the pavements also positively contribute to the heat budget of the urban heat islands. The building construction materials such as bricks, concretes, sands and cements, pebbles, rocks and rock pieces, bitumen etc., absorb more solar radiation more efficiently. Similarly, the masonry surfaces of the vertical walls absorb solar radiation and reflect it to the ground pavement surfaces and to other vertical structures during daytime where the solar energy is properly stored. It may be pointed out that normally one expects lower temperature in the city area than the surrounding countrysides because of expected rapid loss of heat through longwave radiation from the bare and dry surfaces of the city but the heat island is maintained even during night because of the fact that the heat stored in the pavements, walls and ground surfaces during daytime is released during night and hence relatively higher temperature of the urban centre is maintained. So the urban heat island is all-season phenomenon.

(iv) Urban areas are provided with masonry storm drains which are constructed in accordance with the slope gradient of the city area. Consequently, the rainwater and domestic waste water are not allowed to collect rather these are quickly disposed off through efficient and rapid drainage system. Thus the evaporative cooling effects of such waters are reduced. This mechanism ultimately does not help in lowering the temperature.

(v) There is positive relationship between the intensity of urban heat island and the size of human population and density of buildings. Very closely spaced buildings (high density of buildings) and narrow roads and streets tend to increase temperature of the urban centre more than the widely spaced buildings (low density of buildings) and relatively wider roads and streets. 'Measurements in the U.S.A. suggest that a ten-fold increase of city population has an average warming effect on the centre of 1^0C. It is also found that the urban heating effect is removed by winds of sufficient strength ranging from 4.1 $m.s^{-1}$ for a city of 33,000 population to 11.8 $m.s^{-1}$ for a metropolis of 8 million' (T.R. Oake, 1973, 1976, quatoed by J.E. Hobbs, 1980).

Though the presence of urban heat island is all-season and daily phenomenon but its effects are more prominent at night. Urban heat island generates thermal anomaly in he **rurban environments** i.e. between urban area and its surrounding rural countryside area wherein the difference of temperature between these two areas and their corresponding environments (that is urban-rural temperature difference) becomes 5^0 to 6^0C during daytime and rises to 12^0C or even more at nights. This diurnal range of temperature between the urban-rural environments generates convectional air circulation during night because of the formation of low pressure cell in the heat island of the city centre because of high temperature in comparison to the temperature of the surrounding areas.

The air of the heat island is warmed up and thus rises upward to the limit of **pollution dome** (formation of thick cover of polluted air atop of urban centres from where the ascending warm and light air spreads laterally outward in all directions from the city centre-heat island). On the other hand, relatively cooler air of the surrounding rural areas flows inward to converge at the city centre from where it is again warmed up and rises upward. The spreading warm air over the city area is cooled and thus descends in the surrounding rural areas. Thus the mechanism of warm air moving up from the city centre (heat island) and relatively cooler air moving in from the surrounding rural areas towards city centre completes a cycle which is commonly known as **urban wind cell** and the air circulation caused therefrom is called as **weak country breeze or countryside city breeze.**

The **convectional system of air circulation** consequent upon the formation of urban heat island as discussed above results in more cloudiness over urban areas and consequently more precipitation. In fact, the effects of urban agglomerations have been positively correlated with precipitation amount though in spasmodic manner. The climatological studies conducted in the urban areas of central Europe have revealed an increase of annual amount of precipitation by about 10 per cent. The urban environment together with the heat island induces precipitation through (i) increased water vapour input provided from the combustion of hydrocarbon fuels in the power houses and transport vehicles, and thus increase in absolute humidity, (ii) increased number of hygroscopic nuclei due to emission of particulates from factories and combustion engine, (iii) mechanical turbulence caused by the roughness factor of city surface, (iv) increased thermal turbulence and convection caused by higher temperature of the heat island (city centre) etc.

Thermal convection caused by heating of air and consequent uplift due to relatively higher temperature of the city centre intensifies any rainstorm or thunderstorm or cyclone passing through the concerned city and thus causes more precipitation than the normal value. 'For example, it has been found that thunderstorms over the city of London produce 30 per cent more rainfall than thunderstorms over the surrounding countryside. Increased precipitation over an urban area is estimated to average from 5 to 10 per cent over the normal for the region in which it lies.' (A.N. Strahler and A.H. Strahler, 1976). Cloudiness is also reported to increase by 5 to 10 per cent over a city. S.A. Changnon (1969) has also reported based on his 'Recent studies of urban effects on precipitation in the United States of America' that the average annual precipitation over urban centres is usually 7 per cent greater than the surrounding rural areas.

It may be pointed out that a few studies have contradicted the concept of increased precipitation over urban centres because of thermal convection caused by urban heat islands. 'A study in the New York metropolitan area, for example, indicated no effect on daily precipitation patterns. Nevertheless, it does seem likely that convection related to an urban heat island can produce a significant effect on precipitation in some cities such as Washington D.C. where a study by Harmack and Landsberg (1975) showed that the extra increment of heating supplied to a convective cloud by the urban fabrics is often the trigger for the occurrence of convective precipitation' (H.E. Hobbs, 1980).

Dust Devils

Dust devils are rising funnel of air laden with enormous dusts and sands in tropical and subtropical deserts. These are caused due to intense heating of ground surface locally and consequent ascent of warm and light air upward. The updrafts of rising air are more accentuated by rotating airmass aloft (in the lower troposphere). The dust devils are funnel shaped and hence resemble a tornado in appearance and are confined to a maximum height of 300 meters in the lower atmosphere. Sometimes the updraft of air in the dust devil is so powerful and strong that it can uplift the loosely fixed roofs of the houses and small light vehicles.

7.4 OTHER LOCAL WINDS

1. **Purga** : a snow laden cold wind in Russian Tundra.
2. **Bise** : an extremely cold wind in France.
3. **Levanter** : a strong easterly cold wind in southern Spain and Straits of Gibraltar. This is moist and damp wind and causes foggy weather. This is more frequent in early winter to late winter.
4. **Pampero** : a north-westerly cold wind in the '**pampas**' of S. America. Pampero is similar to **northers** of North America and Siberia and is more active during winter season.
5. **Norwester** : a warm, dry and gusty wind in New Zealand.
6. **Papagayo** : a violent north-eastern wind in north-west coast of Costa Rica and Gulf of Papagayo.
7. **Tehuantepecer** : a strong northerly local wind in southern Mexico and northern central America.
8. **Friagem** : a cold wind blowing in Amazon valley.
9. **Yamo** : a warm dry wind in Japan.
10. **Tramontane** : a local warm wind in central Europe.
11. **Zonda** : a warm and dry wind in the leeward slopes of Andes in Argentina. This is similar to Chinook and Foehn as it is downslope compressional warm wind.
12. **Buran** : a very cold wind in Siberia.
13. **Haboob** : a hot and damp wind laden with sands in Sudan, more active in early summer.
14. **Lest** : a warm, dry and dusty wind in Madeira and Morocco.
15. **Khamsin** : a hot, dry and dusty wind in N. Africa and Arabia.
16. **Brickfielder** : a hot, dry, gusty and dust laden wind in Victoria of Australia.
17. **Blackroller** : a hot and dry gusty wind in the Great Plains of the U.S.A
18. **Shamal** : a hot and dry dusty wind in Mesopotamia and Persian Gulf.
19. **Simoom** : a warm and dusty dry wind in Arabian desert.
20. **Gibli** : a warm, dry and dusty wind in Lybia.
21. **Dust storms** : a cloud of updrafted dusts and sands, reduce visibility to one kilometer, if the visibility is reduced to less than one kilometer they are considered severe dust storms.

7.5 SEASONAL WINDS

Seasonal winds may be defined in different ways but here seasonal winds are taken in specific sense. Seasonal winds, thus, may be defined as those large-scale surface winds which reverse their directions atleast by 120^0 twice a year. It is, thus, evident that monsoon winds are primary seasonal winds, the characteristic features of which are discussed below :

7.6 MONSOONS

1. MEANING AND CONCEPT

The word 'monsoon' is used to indicate the winds in the areas where they change their direction twice each year. In fact, the word '**monsoon**', which has been derived from Arabic word '**mausim**' or Malayan word '**monsin**' meaning thereby '**season**', refers to such an atmospheric circulation which reverses its direction completely every 6 months or say during summer and winter seasons. The word 'mausim' was first used by Arab navigators for the winds blowing over the Arabian Sea between Arab and India wherein they blow from north-east to south-west for 6 months during winter season and from south-west to north-east during summer season. On this basis, the word monsoon was applied to all those winds of the globe which had directional change from summer season to winter season and vice-versa. It may be pointed out that there are many such places on the globe where there is complete seasonal reversal in the wind direction *e.g.* the region lying between 60^0-70^0 latitudes in the northern hemisphere is characterized by north-east polar winds during winter season and by south-west westerlies during summer season and the Mediterranean regions (30^0-40^0 latitudes) are characterized by westerlies during winter season and north-east trade winds during summer season but these winds are not called monsoons. It is apparent that directional change of the winds is not the only criterion of monsoons. In fact, the monsoons are surface convective systems which are originated due to differential heating and cooling of the land and water (oceans) and thermal variations. The regions dominated by monsoon winds are called 'monsoon climatic regions' which are more developed in Indian sub-continent, south-east Asia, parts of China and Japan. Besides, southern USA, northern Australia, western Africa etc. also represent pseudo-monsoons.

According to Chang-Chia Ch' eng *monsoon is a flow pattern of the general atmospheric circulation over a wide geographical area, in which there is clearly dominant wind in one direction in every part of the region concerned, but in which this prevailing direction of wind is reversed (or almost reversed) from winter to summer and from summer to winter.*

According to Nieuwolt, the *word monsoon is used only for wind system where the seasonal reversal is pronounced and exceeds a minimum number of degrees (120 degrees).*

2. TYPES AND DISTRIBUTION OF MONSOONS

Regionally, monsoons are divided into 3 broad categories, namely (i) Asian monsoons, (ii) African monsoons, and (iii) American monsoons. Asian monsoons are divided into south Asian monsoons and south-east Asian monsoons. Monsoons are also divided into (1) **traditional monsoons,** e.g south and south-east Asian monsoons, and (2) **pseudo monsoons** e.g. African and American monsoons. It may be mentioned that true monsoons are best developed over Indian subcontinent or say south Asia whereas in other areas monsoons are found in modified form. The monsoon areas are further subdivided as follows :

(1) **True or traditional monsoon areas** include India, Pakistan, Bangladesh, Myanmar (Burma), Thailand, Laos, Combodia, North and South Vietnam, Southern China. Philippines, and Northern coastal areas of Australia.

(2) **Areas of monsoonal tendencies or pseudo monsoons** are found along south-west coast of Africa including the coasts of Guinea, Sierra Leone, Liberia and Ivory Coast; eastern Africa and Western Madagascar (Malagasi).

(3) **Areas of monsoonal effects** include north-east coast of Latin America (e.g. east Venezuela, Guyana, Surinam, French Guyana, and North-east Brazil), Puertorico, and Dominican Republic in the Caribbean Island.

(4) **Areas of modified monsoons** are found in parts of Central America and south-east USA.

Asian Monsoons

Asian monsoons are further divided into (1) South Asian monsoons, (2) S.E. Asian monsoons, and (3) East Asian monsoons. The Asian monsoons are, on an average, the outcome of large-scale seasonal shifting of pressure and associated wind belts and humidity. Much of the northern and central Asia is dominated by winter high pressure and subsiding airmasses resulting in outspread of air circulation towards coastal areas. During winter season, thus, the winds are offshore in south, south-east and east Asia and hence almost dry condition prevails. But the offshore islands receive precipitation because the offshore winds while passing over the oceans pick up moisture through evaporation. The winter conditions are reversed during summer season as the monsoon lands are dominated by thermally induced low pressure systems and strong convergence resulting into strong onshore monsoon winds. These onshore south-west monsoon winds pick up much moisture while passing over the

Indian Ocean and the Arabian Sea and yield precipitation over south Asia mainly Indian sub-continent. The details of Indian monsoon will be discussed in the foregoing section. There are some significant variations in south Asian and East Asian monsoons as follows.

(1) There are variations in summer and winter monsoons over South and East Asia because of varying geographical locations. Most of East Asian monsoon lands (e.g. South Korea, East China, Japan etc.) are located in temperate zone while South Asian monsoon lands are located in tropical and subtropical zones. This is the reason that summer monsoons are not as much strong in East Asia as in South Asia because low pressure system in East Asia is not intensified while it is very much intensified in north-west Indian subcontinent due to intense summer heating (April-June).

(2) The Himalayas and their branches become effective barriers in protecting the Indian subcontinent from the onslaught of cold powdery polar airmasses originated from Siberian and Central Asian high pressure systems during winter season. On the other hand, outward spreading offshore cold winds from Siberian high pressure systems lower the winter temperature in East Asian monsoon lands. It is evident that East Asian monsoon lands are more influenced by continental polar airmasses as elaborated below :

These airmasses originate over extensive areas comprising Siberia and outer Mongolia having very cold ground surface. Initially, the airmasses are very cold and dry in their source regions. The lower portion upto the height of one kilometer is characterized by inversion of temperature. The air masses move eastward and after covering long distances are mechanically modified as mechanical turbulence is produced when these air masses cross over the mountain barriers. This process leads to the disappearance of inversion layer resulting into increase of temperature and humidity in the lower layer. These air masses enter China through two routes viz. (i) through land surface, and (ii) through water surface. When high pressure lies over Mongolia and North China, then these air masses enter China by land route. They are much warmer in China than in their source areas. These air masses are associated with clear sky and dry weather and cold air. When these air masses come with high velocity, they bring with them immense quantity of dust and sands and deposit them as loess. The continental polar air masses in their modified forms affect the weather conditions of most parts of Asia during winter season. These air masses do not enter the Indian Subcontinent because of effective barrier of the Himalayas.

When high pressure lies over Manchuria and Japan Sea, the continental polar air masses enter China by sea route after moving over Japan Sea, and Yellow Sea and thus pick up abundant moisture. These air masses are relatively warmer and more humid than the continental polar air masses coming by land route. Until they are associated with fronts, they are characterized by clear sky and pleasant weather. The lower portion is unstable and thus they give precipitation when they ascend along the mountain barriers. The continental air masses coming through sea and land routes converge along the eastern coasts of Asia and form cyclones through frontogenesis and cause precipitation.

It is evident that winter monsoons are stronger in East Asia than in south Asia.

(3) The summer monsoons are much stronger in south Asia and are weak in East Asia because the maritime tropical airmasses, infact summer monsoon winds, are warmer, more humid and unstable. They yield torrential rainfall when they are forced to ascend by mountain barrier (the Himalayas and their chains). After being originated in southern Indian Ocean they move north and north-eastward, and after entering the mainland (Indian Subcontinent) they are heated from below because of warm ground surface and hence they become unstable and convectional currents are produced. The south-west summer monsoons of Indian Subcontinent are typical representatives of true monsoons. These air masses produce cyclonic conditions when they converge with continental polar airmasses during springs in central China and during middle summer in Manchuria.

North American Modified Monsoons

North American monsoons are in fact modified monsoons in relation to South Asian monsoons and are found over S., S.E. and S.W.

United States. The location of the Rockies Cordillera causes seasonal contrasts in the weather conditions of S.E. and S.W. USA. During northern summer subtropical high pressure shifts northward and lies over western Pacific coast and hence atmospheric stability causes dry condition but the situation to the east of the Rockies is quite different as the S. E. states of the USA are dominated by low pressure system which attracts moisture laden marine winds coming from over the Atlantic Ocean and the Mexican Gulf and pushed by the Atlantic high pressure near Barmuda. The maritime tropical Atlantic air masses originate near Barmuda where high pressure is formed. They move northwestward and control the weather conditions of vast areas of the USA east of the Rocky Mountains during summer months. The thermally induced low pressure over southern and central USA draws maritime tropical air masses (mP) far inland but the existence of polar front in the vicinity of the Great Lakes restricts their entry into Canada. Since temperature and moisture content in the air increases considerably due to arrival of these air masses in the central and eastern USA, the weather becomes oppressive and unpleasant. As these air masses move out of their source areas and enter the USA after crossing over the Gulf of Mexico, surface temperature increases, and they are modified into maritime tropical unstable air masses (mTKu) because the heating of overlying relatively cold air mass causes atmospheric instability. Thus, thunderstorms and cyclones are produced which yield heavy showers. As the air mass moves northward it loses its moisture content and becomes dry in the upper Mississippi valley. When these air masses move westward and rise along the Rocky mountains they yield heavy downpour with cloud burst. Similarly, when they cross over the Appalachians they give heavy showers through thunderstorms.

During winter season the above situation of weather is reversed. The subtropical high pressure and subpolar low pressure systems move equatorward. The S.W. USA, west of the Rockies comes under the influence of subpolar convergence zone (polar front) which is associated with strong cyclonic activities which yield much precipitation in the south-western coastal areas. The region east of the Rockies is dominated by winter high pressure system mainly over the Great Plains and the winds become offshore resulting into less precipitation. It becomes very difficult to the tropical maritime Atlantic air masses to enter the southern and central USA because of the dominance of the continental polar airmass over this area. According to Pierre the seasonal contrasts (summer and winter variations) are not as much marked as in South and South East Asian monsoons because 'the same cyclonic conditions and inconsistency is characteristic (feature) of both winter and summer (seasons).'

Pseudo Monsoons

Areas of monsoonal tendencies or pseudo monsoons are found along south-west coast of Africa including the coasts of Guinea, Sierra Leone, Liberia and Ivory Coast; Eastern Africa and western Madagascar.

West Africa : The coastal areas of west Africa located between 5^0N-20^0N latitudes including Sierra Leon, Liberia, Ivory Coast, Guinea, Senegal, Mauritania etc. are characterized by monsoonal tendencies wherein summer monsoons (June-August) are well marked but winter monsoons (December-February) are not well developed. During the northern summer the subtropical high pressure shifts to the north of Tropic of Cancer in the northern hemisphere whereas the southern subtropical high pressure is located to the north of Tropic of Capricorn. The northward shift of the southern subtropical high pressure pushes the S.E. trade winds northward which after crossing over the equator become south-westerly due to Coriolis effect and Ferrel's law. These surface south-westerlies are overriden by upper air tropical easterlies. Since the surface south-westerlies come from over the Atlantic Ocean and Gulf of Guinea, they pick-up moisture and yield rainfall in the coastal west Africa. These moist winds lose moisture and energy as these move further inland. During winter season, the western coast of Africa is dominated by surface N.E. Trades and hence winters are dry because the tropical easterlies blow over land areas. It may also be mentioned that unlike South Asian monsoon areas, the Guinea coasts are dominated by moist weather throughout the year. The annual weather conditions in the western coast of Africa are characterized and determined by (1) formation of clouds and resultant light rainfall due to frictional convergence within the surface south-westerly monsoon flow and upper air easterlies; (2) low-level convergence of easterly waves having cyclonic circulation; (3) moist air waves associated with summer south-westerlies; (4) north-south Sudan-Sahel belt of cumulonimbus cells; (5) location and movement of monsoon trough; (6) upwelling of cool water (20°C) along the coasts of Senegal and Mauretania during January-April and along the central southern coast located to the west of Lagos during July-October etc.

The average annual rainfall decreases from about 5°N latitude (2000mm-3000mm) to 20°N latitude (1000mm). The rainfall intensity in the immediate vicinity of the coasts is the highest (300 mm per day during summer rainy months) and decreases towards the east. According to R.J. Chorley and R.G. Barry (2002) monsoon rains in Nigeria contribute only 28 per cent of the mean annual rainfall (2000 mm) while remaining amount (72 per cent) is received through thunderstorms (51 per cent) and disturbance lines (21 per cent). If one goes further north, the monsoon contribution to total annual rainfall further decreases e.g. at about 10° N latitude only 9 per cent of annual total is received through monsoon.

East Africa : The east coastal regions of South Africa lying between the latitudes of 5° S and 25°S falling in Tanzania and Mozambique countries and also Madagascar are characterized by monsoon tendencies wherein wet (summer season, southern summer i.e. January) and dry (southern winter, i.e. July) seasons are well marked. With southward migration of the sun after autumn equinox (i.e. after 23 September) during southern summer the intertropical convergence (ITC) shifts to the south of the equator, southern subtropical high pressure shifts southward, south-east tropical trades are pushed southward, consequently tropical easterlies (N.E. Trades) occupy the coastal regions of Tanzania and Mozambique and entire Madagascar. These tropical easterly winds pickup moisture from the Indian ocean and become moist summer north-east monsoons, and bring rains in the eastern coastal regions of South Africa. It may be mentioned that during southern summer South Africa is characterized by low pressure and depressions which draw the moist tropical easterlies which are associated with easterly waves at 850-700 mb level or at the altitude of 200m-3000m above the surface. These easterly waves become more active during southern summer (December to February) and bring much rains (the rainfall intensity reaches 40 mm per day) (Chorley and Barry, 2002). It may be mentioned that the easterly waves are associated with tropical cyclones which are developed in the Southern Indian Ocean in January and February and move west and north-westward towards east African coast under the influence of southern tropical easterlies. During southern winter the above conditions are reversed due to migration of the sun to the north of the equator after spring solstice (21 March). The intertropical convergence (ITC) is pushed to the north of the equator together with northward shifting of the northern subtropical high pressure. The southern sub-tropical high pressure is also pushed to the north of the tropic of Capricorn. Consequently, the eastern coastal plains of South Africa comes under the influence of extratropical (mid-latitude) westerlies. Since these south-westerly winter monsoon winds are offshore and hence are almost dry resulting into almost winter dry season. The high phase of the Walker circulation (Southern Oscillation) during southern summer over South Africa, intensified intertropical convergence and subtropical high pressure cells, strong easterly waves and tropical cyclones originating in the southern Indian Ocean etc. are responsible for high rainfall during summer monsoon (December to February) of eastern Africa.

Australian Monsoon

The Australian monsoon is placed under the category of true or traditional monsoon but it is confined only to the narrow coastal strips of northern Australia wherein active monsoon period is experienced during austral (southern) summer (December to March). The northern Australia is characterized by thermally induced low pressure in late December and early January which attracts low level westerlies overlain by upper tropospheric easterlies. The monsoon sets in late December and retreats in mid-March. On an average, the average active monsoon period is of 75 days but this is highly variable because annual active monsoon period ranges between 10 days and 125 days. The tropical easterlies associated with tropical cyclones and squall lines also bring rains during summer monsoon. The monsoon effect does not have deeper penetration in the northern Australia because the seasonal shifting of intertropical convergence (ITC) is not very effective. During southern winter the coastal northern Australia is characterized by dry continental airmass and hence winters have very little rainfall.

7.7 CONCEPTS OF THE ORIGIN OF MONSOONS

The concept of the origin of monsoon is related to thermal and dynamic factors and thus there are two concepts of the origin of monsoon *e.g.* (1) thermal concept, and (2) dynamic concept.

(1) Thermal Concept

The thermal concept of the origin of monsoon was first propounded by Halley in 1686. According to this concept the monsoons are the result of heterogeneous character of the globe (unequal distribution of land and water) and differential seasonal heating and cooling of the continental and oceanic areas. During northern winters (winter solstice) when the sun becomes vertical over the tropic of Capricorn in the southern hemisphere high pressure areas are developed over Asia due to very low temperature. Two bold high pressure areas are developed near Baykal Lake and Peshawar. On the other hand, low pressure cntre is developed in the southern Indian Ocean due to summer season and related high temperature in the southern hemisphere. Consequently, winds start blowing from the high pressure land areas to the low pressure oceanic areas. These are called north-east monsoons or winter monsoons (fig. 7.4). These are dry winds because they come from over the land.

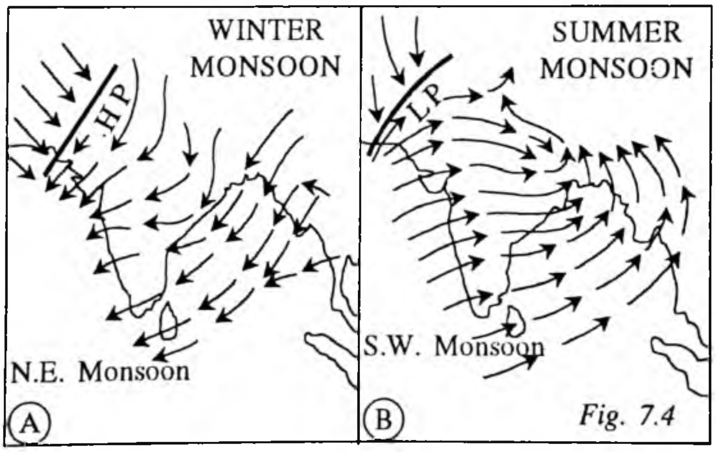


Fig. 7.4 : A-Winter monsoon, B-Summer monsoon.

The aforesaid conditions are reversed at the time of summer solstice when the sun becomes vertical over the tropic of Cancer in the northern hemisphere. Because of high temperature low pressure centres are developed at two places due to the presente of the Himalayas *e.g.* near Baykal Lake and near Multan. Conversely, high pressure centres are developed in the southern Indian Ocean, to the north of Australia and to the south of Japan because of winter season in the southern hemisphere. Consequently, winds blow from Indian Ocean to Asian continent. These winds while crossing the equator become south-westerly due to Ferrel's law. These winds pick up much moisture while passing through the ocean and yield heavy rainfall when obstructed effectively. These are called south-west monsoons or summer monsoons.

2. Dynamic Concept

A host of scientists have refuted the thermal origin of monsoon and have raised the following objections against the old or thermal concept.

(i) If the **'lows'** developed over the land areas are **'heat lows'** (low pressure centres developed due to high temperature), then they should remain stationary at their places for some time but they are never stationary. There is sudden and widespread shifting in their positions. It, thus, appears that the low pressure centres are not related to thermal conditions, rather they represent cyclonic lows associated with the south-west monsoon.

(ii) The rain producing capacity of monsoon winds is also doubtful. In fact, the monsoon rainfall is associated with tropical disturbances.

(iii) If the monsoons are thermally induced then there should be anti-monsoon circulation in the upper air. It may be pointed out that a few meteorologists have also noticed seasonal variations of winds aloft in the troposphere and stratosphere. Such upper air winds, which change their directions seasonally, are called **'upper air monsoon'** or **'aerological monsoon'**.

Based on above objections Flohn rejected the thermal concept of the origin of monsoon winds and propounded his new concept in 1951 which is based on the dynamic origin of monsoons. According to him monsoons are originated due to shifting of pressure and wind belts. Tropical convergence is formed due to convergence of north-east and south-east trade winds near the equator. This is called **intertopical convergence** (ITC). The northern and southern boundaries of ITC are called NITC and SITC respectively (figs. 6.5 and 6.6). There is a belt of doldrum within the intertropical convergence characterized by **equatorial westerlies**. At the time of summer solstice (June 21) when the sun becomes vertical over the tropic of Cancer NITC is extended upto 30^0N latitude covering south and south-east Asia and thus equatorial westerlies are established over these areas. These equatorial westerlies become south-west or summer monsoons. The NITC is associated with numerous atmospheric storms (cyclones) which yield heavy rainfall during wet monsoon months (July to September). Similarly, the north-east or winter monsoon does not originate due to low pressure in the southern hemisphere during winter solstice (southern summer, when the sun becomes vertical over the tropic of Capricorn). In fact, the north-east monsoons are north-east trade winds which are reestablished over south and south-east Asia during northern winter (winter solstice) due to southward shifting of pressure and wind belts and NITC. It is obvious that due to southward movement of the sun at the time of the winter solstice the NITC is withdrawn from over south and south-east Asia and north-east trade winds occupy their normal position. These north-east trades, thus, become winter monsoons. Since they come from over the land, and hence they are dry.

7.8 ORIGIN OF INDIAN MONSOON

The findings of researches conducted in connection with the Indian monsoon after 1950 have revealed that its origin and mechanism are related to the following facts :

(i) The role of the position of the **Himalayas** and **Tibetan plateau** as mechanical barrier or as high level heat source.

(ii) The existence of **upper air circum-polar whirls** over north and south poles in the troposphere.

(iii) The circulation of **upper air jet streams** in the troposphere.

(iv) Differential heating and cooling of **huge** landmass of Asia and Indian Ocean.

(v) The **El Nino-Southern Oscillation** (ENSO) event.

Before 1950 the origin and mechanism of Indian monsoon was related to surface air circulation and thermally induced low and high pressures and thus monsoon was considered to be a simple air circulation system but the studies of air circulation in the middle and upper troposphere have shown that the monsoon is a complex air circulation system. High pressure is developed due to extremely low temperature and descent of air from above in the arctic circle over the poles whereas upper air low pressure is developed in the troposphere just above the surface high pressure area. Thus, upper air circumpolar whirl is developed above the poles wherein winds blow following curved paths in a cyclonic system. In other words, winds blow around upper air low pressure centre in a cyclonic pattern and thus form a whirl. This whirl is called circumpolar whirl. The general direction of air movement over Asia is from west to east. The equatorward winds of this upper air whirl are called **jet streams.**

The jet streams blow in a meandering course. The arctic upper air whirl becomes more prominent and active during winter season in the northern hemisphere (at the time of winter solstice) and thus the upper air westerly jet streams are established in the latitudinal zone of 20^0-35^0N. Because of equtorward shifting of upper air circumpolar whirl the north intertropical convergence (NITC) is pushed further southward from its natural position. North-east trade winds form the surface air circulation over Indian Subcontinent during northern winter (fig. 7.5A).

The upper air westerly jet streams are positioned in Asia at the height of about 12 kilometres in the troposphere. These jet streams are bifurcated due to the mechanical obstruction of the **Himalayas** and **Tibetan plateau** during northern winter. The northern branch blows from west to east in arcuate shape to the north of the Himalayas and Tibetan plateau (fig. 7.5A) while the southern branch moves from west to east to the south of the Himalayas. It may be pointed out that the main branch of upper-air jet streams follows anti-cyclonic path wherein anticyclonic air circulation is developed to the right of the general flow direction of the jet streams across Afghanistan and Pakistan with the result upper air high pressure is formed over them (fig. 7.5A, indicated by High) at the height of 10-12 km and hence winds descend and settle downward. Conversely, the main branch of jet streams to the south of the Himalayas follows cyclonic arc having anti-clockwise air circulation due to mountain barrier. With the result upper air low pressure and cyclonic arc circulation are developed over **Tibetan plateau** (fig. 7.5A, indicated by low).

Let us discuss the general conditions during winter and summer seasons. The upper air westerly jet streams are extended upto 20^0-35^0N latitude due to equatorward shift of upper air north polar whirl during northern winter (October to February). The upper air westerly jet streams are bifurcated into two branches due to mechanical obstructions of the **Himalayas** and **Tibetan Plateau.** One branch is located to the south of the Himalayas while the second branch is positioned to the north of Tibetan plateau (fig. 7.5A). Upper air high pressure and anticyclonic (with clockwise air circulation) conditions are developed in the troposphere over Afghanistan and Pakistan. Consequently, the winds tend to descend over north-western part of India resulting into the development of atmospheric stability and dry conditions. Besides, the upper air westerly jet streams also cause periodic changes in general weather conditions because they lie over the temperate low pressure (cyclonic waves) or cyclones which move from west to east under the influence of upper air westerly jet streams across the Mediterranean Sea and reach Pakistan and north-west India. These storms are not frontal cyclones but are waves which move at the height of 200 metres from mean sea level, while at the surface there are north-east trade winds. The arrival of these temperate storms causes precipitation and abrupt decrease in air temperature. The weather becomes clear after they pass away. On an average 4 to 8 cyclonic waves per month reach north-western India between October and April each year. They affect the weather conditions during winter seasons upto Patna.

Now question arises as to why there is no regularity and continuity in the winter cyclonic waves? As stated earlier the upper air high pressure and anticylonic systems are positioned above the ground surface frequented by cyclonic waves. This is why the winds descend and the cyclonic waves located at the height of 200 m from the surface are unable to ascend because the winds descending from the upper air high pressure obstruct them. Simultaneously, the surface trade winds positioned below the cyclonic waves also cool them from below. Consequently, most of the precipitation from these cyclonic waves is orographic in character (the winds rise along the Himalayas and yield precipitation due to cooling and increase in relative humidity). On an average, most parts of India remain dry during winter season except Tamil Nadu coast which receives much rainfall during October-November.

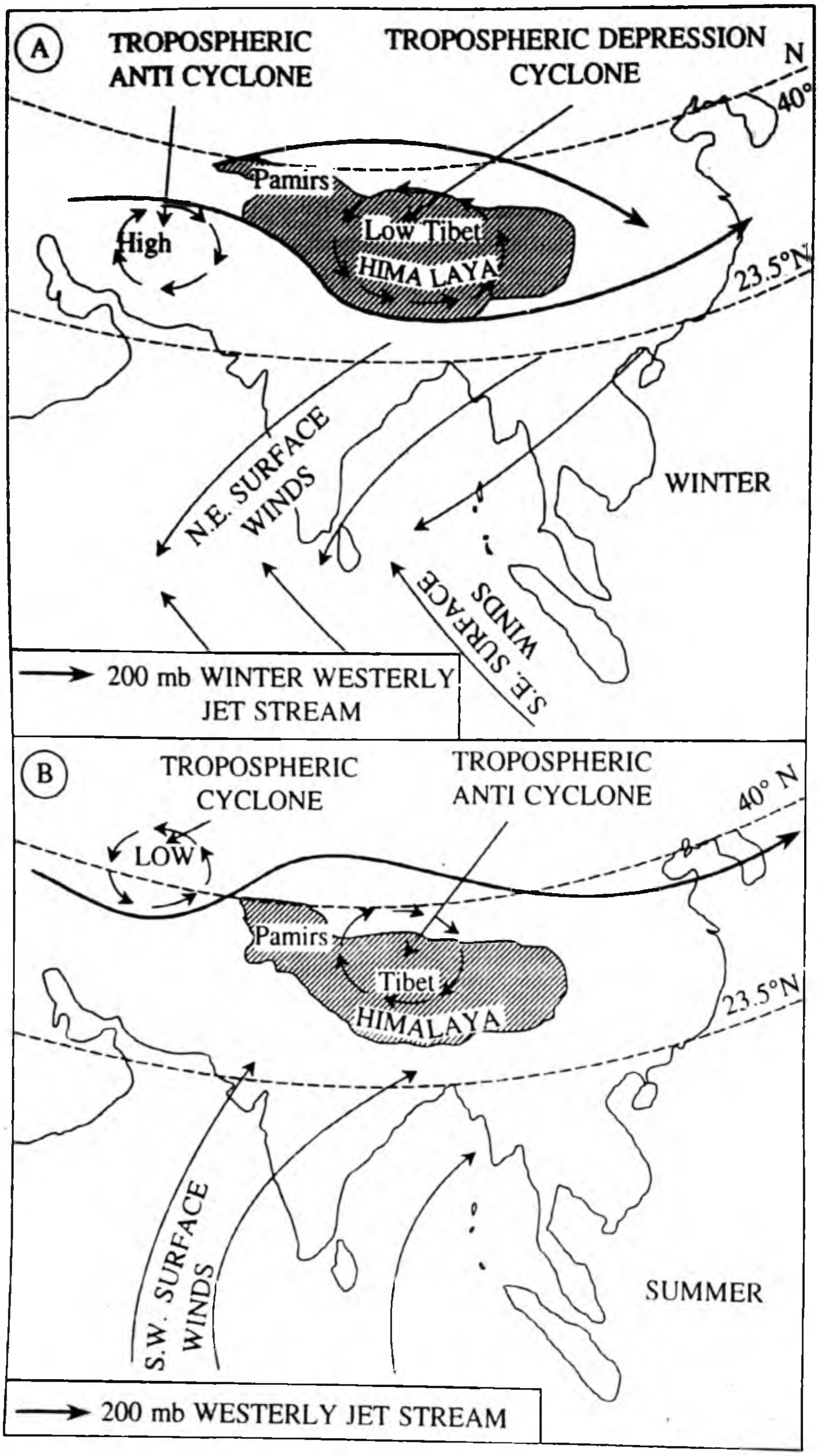


Fig. 7.5 : Origin of Indian Monsoon, A-conditions during winter season, and B-conditions during summer season.

After vernal equinox (21 March) sun moves northward and becomes vertical over the tropic of Cancer (at the time of summer solstice, 21 June) with the result the polar surface high pressure is weakened and upper air circum-polar whirl which extended upto 20^0-35^0N latitudes during winter season shifts northward due to which upper air westerly jet streams are also withdrawn and shift northward. Thus, the dynamic force of the polar whirl is weakened. Consequently, the upper air circum-polar whirl becomes unable to maintain the southern branch of the westerly jet streams (to the south of the Himalayas, fig. 7.5A) and thus they (jet streams) shift to the north of the Himalayas and Tibetan plateau (fig. 7.5 B). Final withdrawal of upper air streams from over India is completed by middle of June.

Low pressure areas are developed at the ground surface in north-west Pakistan and north-west India due to intense heating of ground surface during April-May. But so long as the position of upper air jet streams is maintained above the surface low pressure (to the south of the Himalayas), the dynamic cyclonic conditions persist over Afghanistan, north-west Pakistan and north-west India. The winds descending from the upper air high pressure obstruct the ascent of winds from the surface low pressure areas, with the result the weather remains warm and dry. This is why the months of April and May are dry inspite of high temperature and evaporation. It may be pointed out that monsoon arrives in May in Myanmar but north-west India remains dry. Upper air low pressure is formed to the east of the eastern limit of the Himalayas due to upper air jet streams, with the result the winds coming from south in Myanmar are forced to ascend and yield copious rainfall. The Myanmar monsoon also affects Bangladesh and adjoining Indian territory which receives premonsoon rainfall.

The upper air westerly jet stream (southern branch of winter jet stream) is withdrawn from over India by the middle of June (fig. 7.5 B), reason has already been explained above. Now, the jet stream is positioned to the north of Tibet and the trajectory of its flow becomes opposite (fig. 7.5B) to the flow curvature during winter season (fig. 7.5A). The flow path of upper air westerly jet stream becomes cyclonic curve (anticlockwise movement of free air) over Iran and Afghanistan due to which dynamically induced low pressure is formed in the upper air (in the troposphere, called as tropospheric low or cyclone, fig. 7.5B) and thus cyclonic conditions dominate the upper atmosphere. It may be remembered that there is high pressure and anticyclonic conditions during winter season in the areas of summer upper air tropospheric low pressure and cyclonic condition. This upper air low pressure is also extended over Pakistan and north-west India. There is already thermally induced low pressure at the ground surface located below the upper air low pressure. Consequently, the surface warm winds rise upward. The ascent of surface warm air is further accelerated because the upper air low pressure sucks the air from the ground surface. This mechanism causes sudden burst of south-west monsoon.

It may be remembered that during northern summer there is winter season in the southern hemisphere, with the result southern polar whirl is more developed and is extended upto the equator. Consequently, the intertropical convergence (ITC) is pushed to the north of equator. Because of the push factor of the southern polar whirl the south-east trade winds are forced equatorward and while crossing over the equator they become south-westerly due to Coriolis force (deflective force caused due to the rotation of the earth) and rush towards India. It may be pointed out that rapid advance of inter-tropical convergence northward is because of the push factor of the southern circumpolar whirl and not because of sucking by the thermally induced surface low pressure over north-west India. No doubt, this surface low pressure accelerates the advance of intertropical convergence northward. Intertropical convergence is characterized by dynamically induced waves and not by frontal cyclones. These dynamically induced waves after coming over India become cyclone vortices. The summer monsoon rains of India result from these cyclonic vortices. In other words, the development of cyclonic vortices is followed by wet weather while their occlusion causes dry weather which continues till new cyclonic vortex is formed.

There is much spatial and temporal variation of monsoon rainfall in India. Topographic factor plays a major role in such variation. For example, the Arabian Sea Branch of south-west monsoon rises abruptly after being obstructed by the Western Ghats and yield heavy rainfall while the regions located to the east of the Western Ghats receive meagre amount of rainfall because the winds descend along the eastern slopes and thus are warmed due to which relative humidity decreases and aridity increases. Such regions of low rainfall are called **'rain shadow regions'**. The Himalayas affect the Bay of Bengal Branch of south-west monsoon in two ways *e.g.* (i) the air ascends due to obstruction of the mountain and yields heavy rainfall, and (ii) the obstruction by the Himalayas causes channel effects due to which winds blow westward along the mountains. Consequently, the monsoon reaches northwestern India through the Ganga valley. Inspite of strong surface low pressure over Rajasthan and adjoining Pakistani territory the rainfall is minimum. Generally, the lowest amount of rainfall over north-west India is related to the parallel position of the Aravallis to the Arbian Sea Branch of south-west monsoon but the real cause is related to the depth of monsoon drift which depends on the position of upper air dynamic anticyclonic condition above surface low pressure.

The upper air high pressure obstructs the upward movement of surface winds. Whenever this upper air high pressure shifts westward, monsoon winds rise rapidly and yield heavy rainfall even in Rajasthan.

Tibetan Plateau and Monex

The monsoon expedition (MONEX), under the joint auspices of the Russian and Indian scientists, organized in 1973, revealed certain new information about the weather conditions over the Indian subcontinent based on weather data collected from Arabian Sea and Indian ocean through the application of advanced modern weather equipments. The meteorologists, based on data received from MONEX, propounded that the Indian monsoons are related to the heating and cooling of Tibet Highland having a width of 1000 km in the east and 600 km in the west, a length of 2000 km and height ranging between 4000-5000m at a.m.s.l. It may be pointed out that P. Koteswarm, an Indian meteorologist, recognised in 1958 the Tibetan plateau as the most important factor in the origin and mechanism of Indian Monsoon. As mentioned in the beginning the Tibet Highland acts (a) as a potent mechanical barrier, and (b) as a high level heat source. The role of the Himalayas and the Tibet Highland has already been explained above.

El Nino-Southern Oscillation (ENSO) Event

As discussed in chapter 6 the phases and strengths of the Southern Oscillation (SO) in terms of spatio-temporal shifting of high and low pressure systems between tropical eastern and western Pacific Ocean are determined on the basis of differences of air pressures between these two areas and resultant air circulation. The phases of the SO (i.e. strong and weak) are termed as Southern Oscillation Index (SOI) wherein two phases are most significant, namely **high phase** (strong SO) and **low phase** (weak SO). The high phase of SO causes strong monsoon over South and South-East Asia. In fact, high phase of SO indicates normal condition or Non-ENSO phase wherein tropical eastern and south-eastern Pacific Ocean is characterized by strong high surface pressure system whereas low pressure system develops over tropical western Pacific Ocean (fig. 6.11A, chapter 6), strong easterly winds dominate over the ground surface (including both land and sea surfaces), tropospheric (upper atmosphere) subtropical westerly jet streams are weakened and shift poleward in both the hemispheres, La Nina becomes strong which induces strong monsoon resulting into copious rainfall in the south and south-eastern Asian regions but there is drought conditions in the western coastal areas of South America (mainly Peru and Chile). It is obvious that weak El Nino but strong La Nina are responsible for strong Indian monsoon, as well as for South and South-East Asian regions.

On the other hand, low phase (weak) of SO (fig. 6.11B, chapter 6) is indicative of reversal of above mentioned Non-ENSO phase and onset of El Nino phase characterized by the development of high pressure system over tropical western Pacific Ocean and low pressure system over tropical eastern Pacific Ocean, dominance of strong El Nino event off the Peruvian and Chilean coasts and accentuated rainfall therein but disappearance of La Nina phenomenon from the tropical western Pacific Ocean. This situation weakens Indian monsoons resulting into low rainfall over south and south-east Asia.

7.9 SEASONAL CHARACTERISTICS OF INDIAN MONSOON

The weather conditions are characterized by seasonal rhythms over monsoon land of India. Two seasons are well marked, namely winter season and summer season which are separated by transitional seasonal characteristics of spring and autumn seasons. On an average, summer season is wet while winters are dry. It may be mentioned that neither the entire summer season is wet, nor the whole winter season is dry. These two major seasons also have dry and wet phases. The Meteorological Department of India has identified the following four seasons to distinguish the annual weather changes over Indian monsoon land : (1) the cold season or winter season, from mid-December to mid-March, (2) the hot dry season, from mid-March to May, (3) the wet or rainy season (also, wet summer season), from June to September, and (4) the post-monsoon season or retreating monsoon season, from October to Mid-December.

(1) Winter (Cold) Season

The cold weather season covers the entire Indian territory when the overhead sun is vertical on the Tropic of Capricorn though cold season begins from November in north India. The upper air north polar whirl spreads equatorward, with the result the upper air westerly jet streams are extended upto 20^0-35^0N latitude. The tropospheric (upper air) westerly jet streams are bifurcated into two branches due to mechanical obstructions of the Himalaya and the Tibetan plateau. One branch is located to the south of the Himalaya while the second branch is positioned to the north of Tibetan plateau (fig. 7.5). Upper air high pressure and anticyclonic (with clockwise air circulations) conditions are developed in the troposphere over Afghanistan and Pakistan. Consequently, the winds tend to descend over north-western part of India resulting into the development of atmospheric stability and dry conditions. Besides, the upper air westerly jet streams also cause periodic changes in general weather conditions because they lie over the temperate low pressure (cyclonic waves) or cyclones which move from west to east under the influence of tropospheric jet streams across the Mediterranean Sea and reach Pakistan and north-west India. These cyclones, very often called as **western disturbances**, are not frontal cyclones but are waves which move at the height of 200 meters from mean sea level, while at the surface there are north-east trade winds which are called **north-east monsoons**. The arrival of these western disturbances causes precipitation and sudden decrease in air temperature. On an average, 4 to 8 cyclonic waves per month reach north-western India between October and April but they are more frequent during January, and February. They influence the weather conditions of northern plains of India upto Patna during winter season.

It may be mentioned that during winter season, the Intertropical Convergence (ITC) is withdrawn from over India due to southward shifting of pressure belts consequent upon southward movement of the overhead sun and hence north-east trade winds are reestablished over Indian subcontinent, high pressure system and anticyclonic conditions are developed over north-west India (fig. 7.6) which cause almost dry weather condition over most part of India.

The average temperature during winter season increases southward. The 21^0C January isotherm passing through the middle of the country is positioned to the south of the Tropic of Cancer and is almost puralled to it. It bisects the country almost in two equal halves. Jammu and Kashmir, Himachal Pradesh and Uttaranchal record lowest winter temperature, *i.e.* less than 10^0C (*e.g.* Leh, daily min -13^0C and daily max. -1^0C; Shimla; daily min. 2^0C, daily max., 8^0C) while Punjab, Haryana, North Rajasthan and Western Uttar Pradesh, South Sikkim, and Arunachal Pradesh have mean winter temperature between 10^0C and 15^0C but sometimes lowest temperature touches 1^0C or even below freezing point at certain locations like Amritsar in Punjab. The north-west India upto Gaya in the east experiences occasional severe **coldwaves** during winter season causing ground frost conditions at several places in the northern plains. The winter season is also characterized by inversion of temperature and dense fogs. Most of the northern plains experienced intense fogs from middle of November to the end of January during 2002-2003 and 2003-2004.

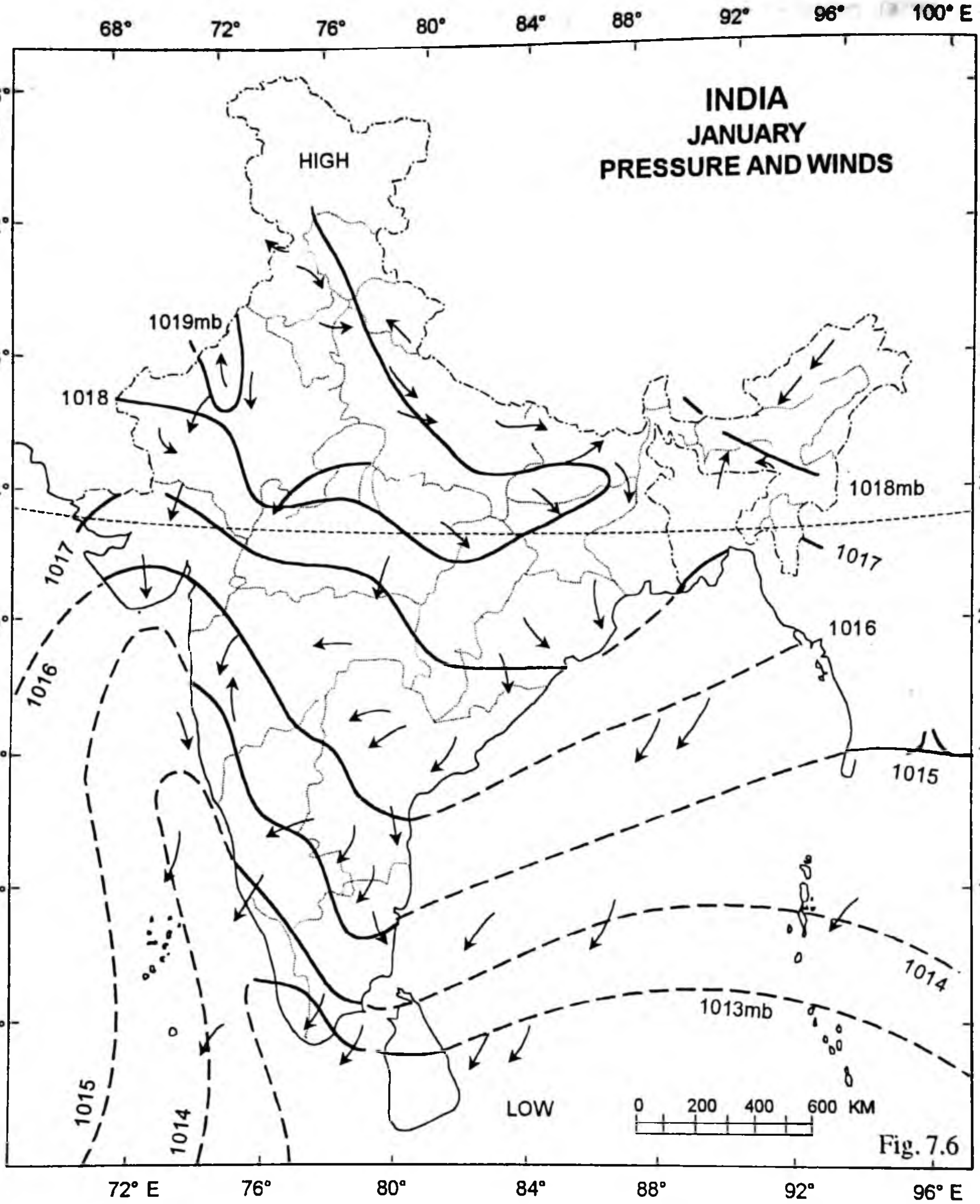


Fig. 7.6 : Air pressure and surface winds during winter season (January) in India. After R.C. Tiwari, 2004.

It may be mentioned that cold weather season is not well marked in Peninsular India as mean January temperature ranges between 20⁰ and 31⁰C (e.g. Chennai; mean daily max. 29⁰C, mean daily min. 19⁰C; Pune, mean daily max. 31⁰C, mean daily min. 12⁰C, mean January, 22⁰C; Mumbai, mean daily max. 28⁰C; mean daily min. 19⁰C, mean January, 24⁰C,; Bangalore, mean daily max. 27⁰C, mean daily min. 14⁰C, mean January, 21⁰C; Kochi, mean daily max. 32⁰C, mean daily min. 22⁰C, mean January, 27⁰C etc.)

As regards pressure system during winter season, the January isobars are taken as indicators of winter pressure system. Since there is inverse relationship between air temperature and air pressure, the winter pressure decreases southward in Indian monsoon land in response to increase in air temperature from north to south. It is apparent from fig. 7.6 that north-west and north-east India is represented by high pressure system where January pressure exceeds 1018 mb while 1013 mb isobar passes through the southernmost part of India. It is evident from fig. 7.6 that the pressure gradient is from north-west to south-east in the north-western and central India, from north-east to south-west in N.E. India, and Peninsular India. This pressure gradient generates surface winds which spread outward and becomes offshore and hence are dry. Though the north-west India is characterized by winter high pressure and anticyclonic conditions but the western disturbances (cyclonic waves) as stated above originating from the Mediterranean Sea and in West Asia also invade north and north-west India during winter season. It may be mentioned that so long as the westerly jet streams are positioned south of the Himalaya, these western disturbances continue to invade north and north-west India.

On an average, winter season of Indian monsoons is characterized by marked contrasts in temperatures between north-west and north India (severe cold) and Peninsular India (winters not well marked), foggy weather in north India but fine weather in central and south India, almost clear sky except in the Ganga valley which becomes foggy, low humidity and rainfall except Tamil Nadu coast, and large daily range of temperature. North-west and north India receives some rainfall through western disturbances (cyclones) while higher regions of Jamnu and Kashmir, Himachal Pradesh and Uttaranchal receive precipitation in solid form (snowfall). The Tamil Nadu coastal plains receive copious rainfall through easterly depressions (cyclones).

2. Hot Dry Season

The hot and dry season continues from mid-March to the end of May. In fact, with the northward march of the overhead sun after vernal equinox (March, 21) temperature rises abruptly mainly over north India and continues to rise upto June, when the sun is vertical over the Tropic of Cancer (summer solstice, 21 June). Generally, May becomes the hottest month when major part of north-west (Rajasthan, Punjab and Haryana), north (Uttar Pradesh, Bihar and Orissa), and central India (Madhya Pradesh, Chhattisgarh, Maharashtra etc.) record maximum daily temperature between 40°C and 47°C (e.g. Jodhpur, mean daily max. 41°C, mean daily min 26°C; Ahemdabad, mean daily max. 42°C, mean daily min. 26°C; New Delhi, mean daily max. 41°C, mean daily min. 26°C; Nagpur, mean daily max. 43°C, mean daily min. 28°C; Allahabad, mean daily max. 42°C; mean daily min. 27°C etc., all temperatures for the month of May). It is evident that mean daily minimum temperature also stands above 26°C. The Ganga plains are under the grip of **heat waves** locally known as **loo** due to which the weather becomes oppressive. Similarly, Rajasthan, Punjab and Haryana are affected by dust storms.

On an average, the weather is characterized by almost dry condition, very low relative humidity ranging between 5 per cent and 30 per cent, very low rainfall ranging from less than 25 mm in north-west India (Rajasthan, Punjab, Gujarat and Haryana) and Central India (Madhya Pradesh and Maharashtra), 50 mm to 250 mm in Uttaranchal and Tarai region of Uttar Pradesh, Bihar and Orissa, 150 mm to 250 mm in the western coastal plains, more than 500 mm in N.E. India mainly in Assam. North India receives rains mostly through western disturbances till the position of the tropospheric westerly jet streams is maintained to the south of the Himalaya. Besides, the northern plains also receive rains through occasional convective thunderstorms. Sometimes West Bengal receives rains through **norwesters** (duststorms) when they are associated with convective systems. The summer rains are called **'cherry blossoms'** in Karnataka, **'mango showers'** in south India, **kalbaisakhi rains** is North India etc. The excessive hot season associated with heat waves is health hazard mainly in North India because it causes heat strokes (sunstrokes) and dehydration.

3. Wet Season or Summer Monsoon Season

Wet season or summer monsoon season begins from the beginning of June and continues upto September. The sun is vertical over the Tropic of Cancer (June 21). The low pressure system is well developed and intensified over western Rajasthan (fig. 7.7). The tropospheric westerly jet streams are completely withdrawn from North India and are positioned to the north of the Himalaya. The intertropical convergence (ITC) moves northward upto 20°-30°N latitudes. Now, the upper air jet streams are positioned to the north of Tibet and the trajectory of its flow becomes opposite (fig. 7.5 B) to the flow curvature during winter season (fig. 7.5.A). Dynamically induced tropospheric (upper air) low pressure is developed over Pakistan and north-west India. As mentioned just above there is already thermally induced low pressure at the ground surface located just below the upper air (tropospheric) low pressure. Consequently, the surface warm winds ascend upward. The ascent of surface warm winds is further accelerated because the upper air low pressure sucks the air from the ground surface. This mechanism causes sudden burst of south-west monsoon. **Burst of monsoon** is defined as sudden and powerful outbreak and surging of southwest monsoon in June over Indian monsoon land.

It may be remembered that during northern summer there is winter season in the southern hemisphere, with the result southern polar whirl is more developed and is extended upto the equator. Consequently, the intertropical convergence (ITC) is pushed to the north of equator. Because of the push factor of the southern polar whirl the south-east trade winds are forced equatorward and while crossing over the equator they become south-westerly due to coriolis force (deflective force caused due to the rotation of the earth) and rush towards India. It may be pointed out that rapid advance of inter-tropical convergence northward is because of the push factor of the southern circumpolar whirl and not because of sucking by the thermally induced surface low pressure over north-west India. No doubt, this surface low pressure accelerates the advance of intertropical convergence northward. Intertropical convergence is characterized by dynamically induced waves and not by frontal cyclones. These dynamically induced waves after coming over India become cyclone vortices. The summer monsoon rains of India result from these cyclonic vortices. In other words, the development of cyclonic vortices is followed by wet weather while their occlusion causes dry weather which continues till new cyclonic vortex is formed.

According to Flohn the onset of Indian monsoon is because of shifting of pressure and wind belts together with the intertropical convergence (ITC). Due to northward migration of the overhead sun during summer season, the northern subtropical high pressure is pushed northward, the ITC and the doldrum having equatorial westerlies are also pushed to the north of the equator. Consequently, south-east trade winds after crossing over the equator become south-westerly monsoon under the influence of Coriolis force (Ferrel's law). These are the south-west monsoons of India.

The tapering end of the Indian peninsula divides southwest monsoon into two branches, namely (1) **Arabian Sea branch** and (2) **Bay of Bengal branch.**

The Arabian Sea Branch of southwest monsoon strikes first the country in the 1st week of June and breaks in Kerala coast (fig. 7.8). The Arabian Sea branch strikes the Western Ghats at almost right angle. The tentative dates of the onset of Arabian Sea branch monsoon are June 1 in Kerala, June 5 in Karnatka, June 10 in Maharasthra and Goa and June 15 in Gujarat. Since the monsoon currents (rather waves) come from over the Indian Ocean and Arabian Sea, they are laden with moisture and after being obstructed by the Western Ghats, they are forced to ascend and hence are cooled adiabatically and yield heavy precipitation in the form of heavy downpour along the western slopes of the Western Ghats. Thus, the windward slopes receive maximum rainfall. After crossing over the Western Ghats, the monsoon winds descend along the eastern slopes *i.e.* leeward slopes, are warmed up adiabatically (dry), lose moisture and hence rainfall decreases. This is why the leeward slopes (eastern slopes) of the Western Ghats are **rainshadow regions.** For example, Mangalore located on the western slope (windward slope) of the Western Ghats receives mean annual rainfall of

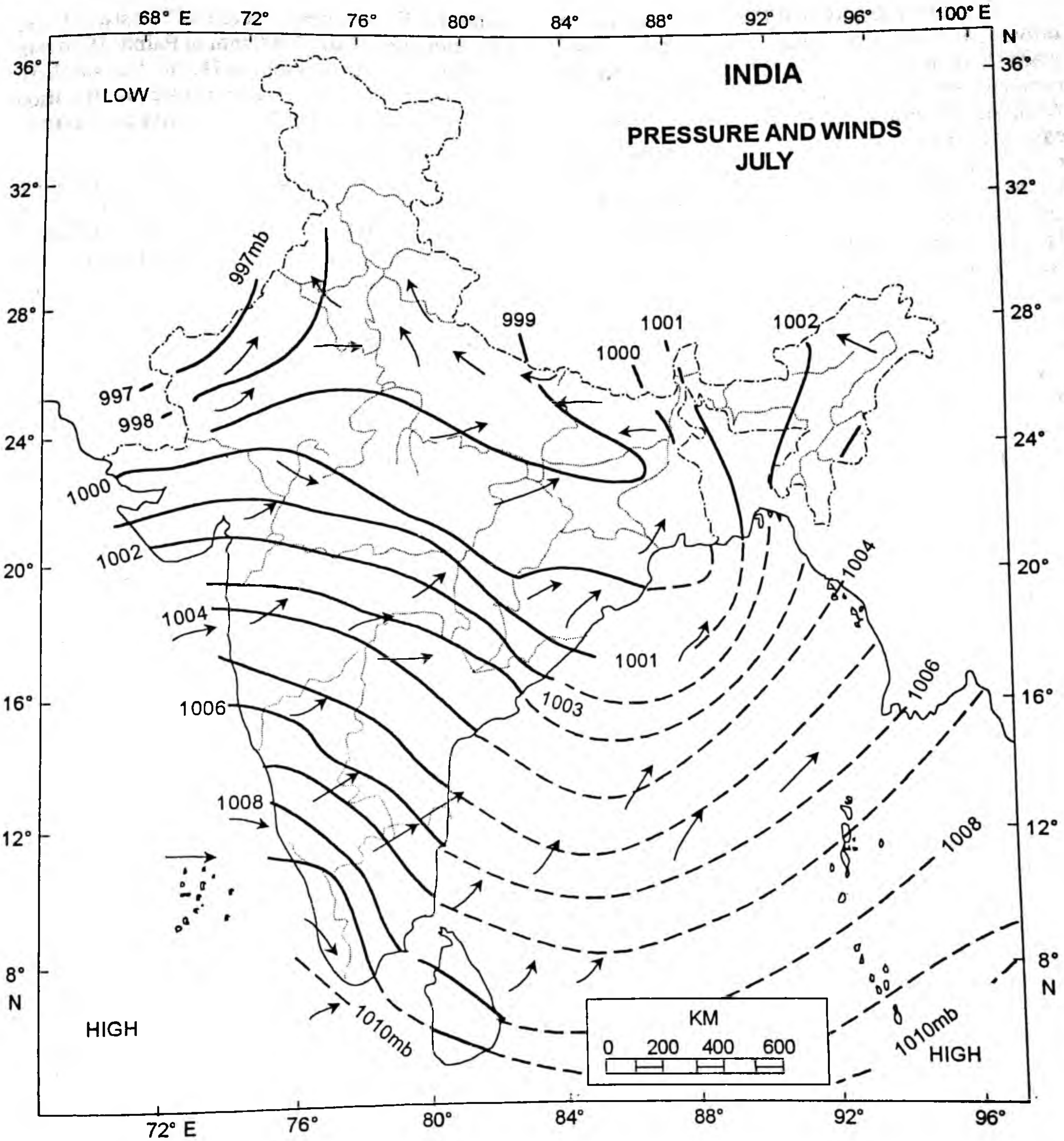


Fig. 7.7 : Air pressure and surface winds in July. After R.C Tiwari, 2004.

above 2000 mm whereas Bangalore situated in the rain shadow region gets only 500 mm of mean annual rainfall. The amount of rainfall increases with increasing height. The Mahabaleshwar Plateau receives annual rainfall of 6500 mm whereas the Panchgani plateau falling in rain shadow region (located only 16 km to the east of Mahabaleshwar) gets only 1700 mm of annual rainfall.

It may be mentioned that the main branch moves eastward and rainfall also decreases eastward. It meets the Bay of Bengal branch in the eastern part of South India. One off shoot of the Arabian Sea branch moves north-eastward into eastern Maharashtra and even reaches Chotanagpur region through Narmada-Tapi gap. Yet another offshoot moves northward and northeastward through Gujarat, Rajasthan and reaches Kashmir. This sub-branch yields rainfall in Gujarat but little rainfall in Rajasthan because the Aravallis are parallel to monsoon currents and hence in the absence of orographic obstruction these currents move towards Kashmir without giving much rains to Rajasthan. It may be pointed out that Rajasthan, Punjab and Haryana receive rains through Bay of Bengal branch of monsoon.

The **Bay of Bengal Branch** strikes the western coasts of Mynmar and gives heavy rains on the western slopes of Arakan Yoma and Tenasserim mountains. After being obstructed by the Burmese hills the monsoon currents are deflected northwestward and are trapped in by Assames hills of Garo, Khasi and Jayantia wherein monsoon currents unleash heavy downpour in the valley surrounded by the Garo, Khasi and Jayantia hills from three sides. Here, the monsoon currents are forced to ascend abruptly by these hills and hence there occurs the **world highest annual rainfall** of 1141cm at Mawsynram (also **Mausinram**, near Cherrapunji; 11410 mm) and of 1087 cm (10870 mm) at Cherrapunji. A record rainfall of 104 cm (1040mm) was received on a single day of June 14 in the year 1876. The Meghalaya plateau falls under rainshadow region and hence Shillong and Guwahati receive comparatively less rainfall i.e. 1430 mm and 1610 mm respectively. After being obstructed by the Assam hills the monsoon currents are deflected westward and move in the Ganga plains parallel to the Himalaya. The onset of monsoon currents is delayed as one proceeds westward *e.g.* the tentative onset dates are 7 June at Kolkata, 11 June at Patna, 15 June at Varanasi, 16 June at Allahabad and so on. It may be mentioned that two branches *i.e.* the Arabian Sea branch and the Bay of Bengal branch ~~morge~~ merge together in the Ganga plains and northern margin of the plateau region and ultimately they spread out over Madhya Pradesh, Western Uttar Pradesh, Haryana, Punjab, Delhi and Eastern Rajasthan. The summer monsoon rainfall (June to September) decreases westward *i.e.* 1150mm at Kolkata, 1000 mm at Patna, 1050 mm at Allahabad and 650 mm at Delhi. The southern slopes of the Himalaya receive more precipitation *e.g.* 1520 mm at Shimla, 2000 mm at Nainital, 3150 mm at Darzeeling, etc.

It may be pointed out that the monsoonal rainfall is associated with tropical depressions (cyclones) which originate in the Bay of Bengal and the Arabian Sea. It is said that these tropical cyclones are associated with intertropical convergence (ITC) and are dynamically drawn over India due to northward shifting of ITC during northern summer. The average wet monsoon period frequency of these cyclones ranges between 20-25 per season. Sometimes these cyclones become disastrous due to high velocity winds and heavy downpour through severe thunderstorms. Sometimes they become stationary for few days and inflict heavy loss to the health and wealth of the affected people.

The wet monsoon season is characterized by short to long dry spells between rainy spells, light to heavy rainfall, early onset and late withdrawal of monsoon currents, late onset and early withdrawal, long continued heavy rainfall followed by accelerated surface runoff resulting into soil erosion and moderate to severe floods in alluvial rivers, frequent drought conditions mostly in Rajasthan, Gujarat, Maharashtra (except coastal areas), interior Andhra Pradesh and Karnatka etc.

About 80 per cent of mean annual rainfall is received during four wet monsoon months (June to September) within 80 to 120 rainy days. Consequently, most of the rainwater becomes effective runoff and causes severe floods and accelerated soil erosion. The spatial distribution of wet season rainfall is quite uneven. Western coastal areas, Sahayadris, and north-east India (Sikkim, part of Assam and Meghalaya, Arunachal Pradesh, Sub-Himalayan West Bengal—Darzeeling hills) get more than 2000 mm of rainfall during June—September. Nagaland, Mizoram, Tripura, Assam, West Bengal, east Bihar, Jharkhand, Orissa, Chattisgrah, east Madhya Pradesh, Tarai region of Uttar Pradesh, Uttaranchal etc. receive rainfall between 1000-2000 mm (June to September). The region comprising southern and coastal Andhra Pradesh, southern and central Maharashtra, southern and western Uttar Pradesh, northern, central

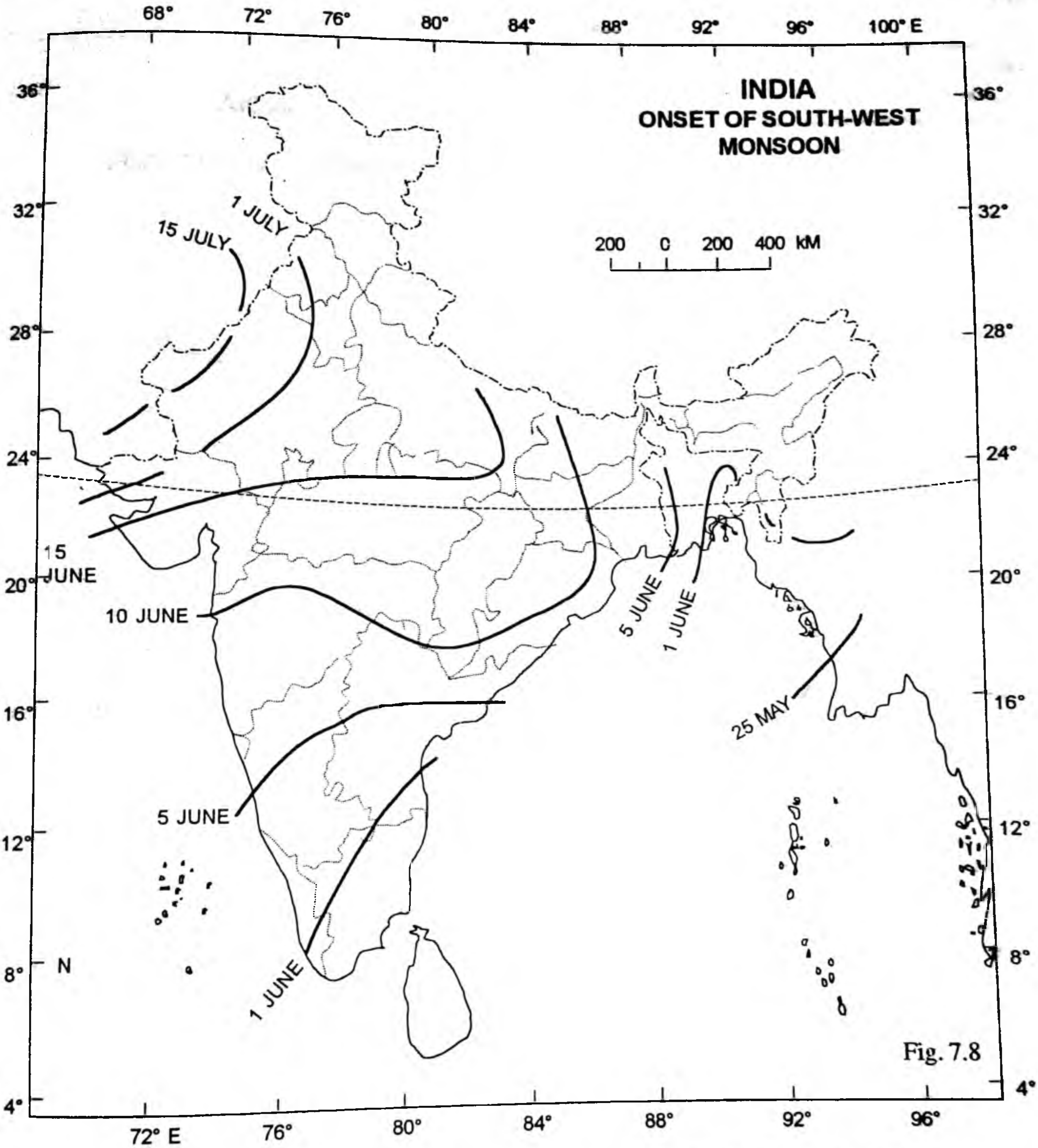


Fig. 7.8 : Dates of onset of South-West Monsoon in India. After R.C. Tiwari, 2004.

and western Madhya Pradesh receives mean wet seasonal rainfall between 600 mm-1000 mm while Gujarat, eastern Rajasthan, southern Andhra Pradesh, northern Karnataka etc. get wet season rainfall of 400mm-600mm. The Kutch region, central Rajasthan, southern Karnataka, Tamil Nadu etc. receive rainfall of less than 400 mm (fig. 7.9).

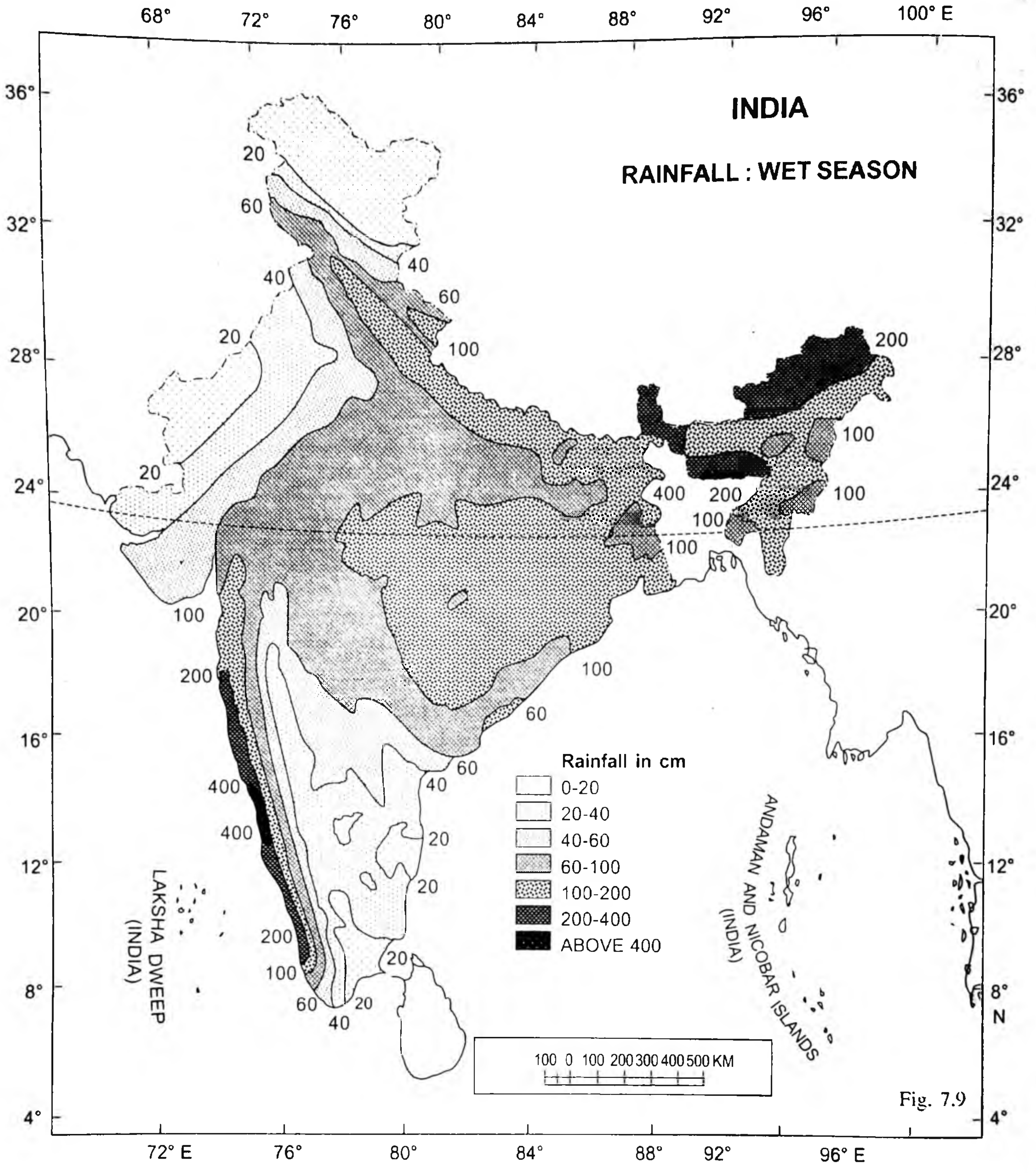


Fig. 7.9 : Distribution of wet monsoon season rainfall (June-September) in India. After : R.C. Tiwari, 2004.

4. Post-Monsoon Season

The post-monsoon season or retreating monsoon season stretches from October to mid-December or upto November. After autumnal equinox (23 September), when the sun is at the equator, the south-west monsoon begins to with-draw due to weakening of low pressure system in the north-western part of India consequent upon southward migration (from the equator) of the overhead sun and withdrawal of intertropical convergence (ITC) from over India. The south-west monsoon is finally withdrawn from north-west India by the end of September resulting into clear weather. It may be mentioned that while the arrival of monsoon is sudden and abrupt, its withdrawal is rather gradual. By the second week of October the south-west monsoon is withdrawn from about two third territory of India. The withdrawal of Intertropical Convergence (ITC) from over Indian subcontinent and its shifting to the south of the equator results in the equatorward extention of the **northern polar whirl**, repositioning of tropospheric westerly jet streams to the south of the Himalaya, and reestablishment of north-east trade winds over Indian subcontinent. The north-west India is now under the grip of the anticyclonic conditions giving birth to westerly dry winds in the Ganga plains. The north-easterly winds while travelling over Bay of Bengal pick up moisture and give much rainfall in the coastal plains of Andhra Pradesh and Tamil Nadu. This is considered as retreating monsoon rain. The general air circulation pattern in the country is westerly in the north-western part and the Ganga plains, north-easterly in eastern and Peninsular India and easterly in the coastal plains. The weather of the eastern coastal regions and south India (mainly Tamil Nadu, Karnataka and Andhra Pradesh) are largely influenced by tropical depressions (cyclones) which originate in the Bay of Bengal and create havoc in the east coastal land of the country between October-December.

The tropical cyclones become more disastrous natural hazards because of their high wind speed of 180 to 400 kilometers per hour, high tidal surges, high rainfall intensity, very low atmospheric pressure causing unusual rise in sea level, and their persistence for several days or say about one week in a particular locality.

The total cumulative effects of high velocities of wind, torrential rainfall and transgresion of sea water on to the coastal land become so enormous that the cyclones cause havoc in the affected areas and thus tremendous loss of human lives and property is the ultimate result of such atmospheric deluge. The **'storm surge'** or **'tidal surge'** refers to unusual rise in sea-level caused by very low atmospheric pressure and the stress of the strong gusty winds on the sea surface. These storm surges or tidal surges, when coincide with high tide, are further intensified and after intruding into the coastal land cause widespread inundation of coastal areas and great damage of human lives and property. The following case histories of a few most powerful and disastrous tropical cyclones may unravel the magnitude of destructions wrought by these natural atmospheric disturbances.

Cyclonic hazards very often visit the eastern coastal areas of India and the southern coastal areas of Bangladesh. The disaster of the deadliest storm in the recorded history occurred on November 12, 1970 in the coastal lowland of Bangladesh. This Bay of Bengal disastrous cyclone tells the magnitude of environment hazards in respect of its killer impact on the affected people as it caused as many as 300,000 deaths (some sources put the figure between 300,000 and 1,000,000 deaths in Bangladesh and West Bengal of India) wherein most of the deaths were caused by drowing in the storm surge of oceanic water (20 feet) on the land. The official record of Bangladesh presented the total loss as death of people-200,000, missing persons, 50,000 to 100,000, cattle death-300,000, houses destroyed-40,000, crops losses of 63,000,000 US dollars, fishing boats destroyed-9000 (offshore) and 90,000 (inland water).

The tropical cyclones coming from over the Bay of Bengal also become hazardous to the east coastal lands of India (West Bengal, Orissa, Andhra Pradesh and Tamil Nadu). The deadliest Hazardous cyclone struck the east coast in 1737 and claimed the lives of 3,00,000 people. Other disastrous cyclones occurred in 1977 (55,000 death), 1864 (50,000 deaths), 1839 (20,000 deaths), 1789 (20,000 deaths) etc., The November 1977 cyclonic storm struck Andhra coast and generated three successive 'storm surges' of which the biggest surge of 6m height was recorded in the last. This deadly storm moved with a speed of 175 kilometres per hour. The biggest surge raced into the coastal low lying areas up to 20 kilometres inland and thus killed 55,000 inhabitants through drowing caused by sudden inundation, destroyed the homes of 2,000,000 people, ruined 1,200,000 hectares of agricultural crops and made most of the coastal land barren and wasteland because of deposition of thick layer of salt on the soils by storm surges. The saline land could be reclaimed only after three years.

The strongest and most notorious cyclone hit the Andhra coast on May 9, 1990 (though this does not come under this season rather this falls under hot and dry season but it is desirable to describe it). It was 25 time stronger and more disastrous than the deadliest cyclone of November 1977 (which also struck the Andhra coast as referred to above) but could claim the lives of only 598 people (official figure but the actual figure might have crossed 1000 deaths.) Besides killing 598 people, it adversely affected 3,000,000 people, rendered 300,000 people homeless, perished 90,000 cattle and caused loss of 1000 crore rupees worth of property. Very low figure of human casualties (598 deaths) in comparison to the killer cyclone of 1977 (55,000 deaths) inspite of 25 times more intensity of May, 1900 cyclone than the latter was particularly because of the advance monitoring and prediction of the cyclone from the time of its formation in the Bay of Bengal off the southern coast of Tamil Nadu on May 5, 1990.

This cyclone is termed most notorious in the sense it shifted its course almost by 90 degree. But more than 100 direct warning systems and even dying INSAT-1B provided direct audio-broadcasts from meteorological stations in Chennai and Hyderabad and 6 cyclone detection radars fitted all along the coastline provided minute by minute information about the movement of incoming cyclone. Initially, the cyclone was moving westward and was expected to strike the southern coast of Tamil Nadu near Nagapattinam but after May 6 it suddenly shifted its course northwards and eventually hit the coastal districts of Andhra Pradesh and unleased the devastating force of its fury on five districts viz. Krishna, Guntur, East Godawari, West Godawari and Visakhapatnam. It may be pointed out that the cyclone was so strong and enormous that some of the major towns of Krishna and Guntur districts such as Vijayawada, Machlipatnam, Pamarru, Guntur, Bapatia, Repalle and Tenali, which could not be affected by the deadliest 1977 cyclone and tidal wave, were also hit this time by the powerful storm surges (tidal waves) caused by gale winds with a speed of 220 to 250 kilometres per hour.

Super Cyclone of Orissa, 1999

The 29th October, 1999 proved a black and killer day for the inhabitants of the coastal region of Orissa (India) when the strongest cyclone in the cyclone history of India struck the Orissa coast and caused a havoc of mass destruction through its notorious acts from October 29 to 31, 1999. Nearly one third of Orissa plunged into gloom and dispair. Prior to the final assault by this killer cyclone, a strong cyclone already knocked at the door of Orissa on October 18, 1999 with a velocity of 200 km per hour. This cyclone claimed the lives of 200 people, damaged 460 villages and adversely affected 5,00,000 people in Ganjam district. The people of Orissa were yet to recover from the trauma of this cyclone, the killer super cyclone hit the Orissa coast on October 29. The successive phases of the formation and advancement of super cyclone maybe outlined as follows : (1) **October 25 :** A **depression** was formed 500 km east of Portblair in Andman Sea, which started to move in N-W direction from the midnight and soon turned into a **deep depression.** (2) **October 26 :** The deep depression changed into a **cyclonic storm** by the morning of October 26 which was stationed about 350 km away from Portblair. The Indian Meterological Department started to issue warning of advancing cyclonic storm. (3) **October 27 :** By the morning of October 27, this cyclonic storm changed to **severe cyclonic storm** and was positioned 750 km away from Paradeep port. It remained stationary for 6 hours at the distance of 600 km from Paradeep. (4) **October 28 :** Advancing towards north-west this severe cyclonic storm became a fully developed **super cyclonic storm** and moved towards Paradeep with a velocity of 260 km. per hour. (5) **October, 29 :** Indian Meteorologial Department (IMD) issued an alarm of warning about the arrival of the super cyclone between Paradeep and Puri. Though the Govt. of Orissa was posted with this warning by 5.30 AM but this warning could not be conveyed to the general public due to lack of radio network

Ultimately, the super cyclone entered Orissa on October 29, 1999 and began to play its game of destruction in 10 coastal districts. Moving with a velocity of 300 km per hour the cyclone became stationary for 8 hours over this vast area. This disastrous cyclone generated 9 m high tidal surges which transgressed upto 15-20 km inside coastal region. Kendrapara, Jagatsinghpur, Balosore, Paradeep, Bhadrak and Khurda were worst affected. According to official sources more than ten thousand people were killed and 200 villages were completely washed out but the unofficial sources put human death toll at about hundred thousand. More than 6000 people were killed in Jagatsinghpur alone. Several hundred thousand cattle perished and countless people were rendered homeless. The standing kharif crops over 1.75 million hectares were destroyed. The loss of property mounted to about 10,000 crore rupees (1000 billion rupees). The severe super cyclonic storm resulted into the disruption of the supply of water and electricity. The communication system was thrown out of gear. Destruction and obstruction of roads and rails brought a grinding halt to rail and road transport which continued for weeks. Thousands of families suffered from mental agony due to separation of their kith and kins. Paradeep port was so greatly damaged that it became non-operational for weeks. Most of the trees were uprooted. Surface and groundwater was so greatly polluted due to dead bodies (both human and animals) that it became unsuitable for domestic uses and gave birth to the outbreak of epidemics. Though the cyclone vanished by October 31, but it left behind the ugly scene of destruction and tragedy of epidemic, hunger, and pollution which broke the backbone of already poor inhabitants.

7.10 IMPORTANT DEFINITIONS

Aerological monsoon : The upper air (tropospheric) winds which change their directions seasonally are called 'upper air monsoons' or 'aerological monsoons.'

Blood rain : The fallout of red sands with falling rains associated with 'sirocco' local wind is south Italy is called blood rain.

Burst of moonsoon : Burst of monsoon is defined as sudden and powerful outbreak and surging of south-west monsoon in June in Indian subcontinent.

Cherry blossoms : The rain during hot and dry summer season (mid-March to mid-June) in Karnataka is called cherry blossoms and **mango rains** in south India & some parts of north India.

Chinook/Foehn : Warm and local dry winds blowing on the leeward slopes of the mountains are called 'chinook' in the USA and foehn in Switzerland.

Doctor : Warm, dry and sandy winds are called **'harmattan'** or 'doctor' in the western Sahara of Africa.

Heat island : The higher temperature in the CBD or the city center is called 'urban heat island' or simply 'heat island.'

Monsoon : The word 'monsoon' is used to indicate the wind system in the regions where they change their directions twice a year.

Snow eater : Warm chinook wind is called snoweater because snow melts as if by magic on its arrival.

Tidal surge : The 'tidal surge' or 'storm surge' refers to unusual rise in sea level caused by very low atmosphiric pressure and the stress of strong gusty winds on the sea surface.

Western disturbances : The cyclonic waves visiting north-west India and the Ganga plains during winter and early summer seasons are called western disturbances.

8

ATMOSPHERIC HUMIDITY AND CONDENSATION

8.1 HUMIDITY : MEANING AND IMPORTANCE

Atmospheric humidity refers to the content of water in gaseous form (water vapour, but generally quoted as only vapour) in a parcel of air having definite volume and temperature at a particular time and place. The atmospheric humidity is obtained through various processes of evaporation from the land and water surfaces of the earth. The humidity or vapour content in the atmosphere ranges between zero to 5 percent by volume. Climatically, water vapour is very important constituent of the atmosphere. Vapour depends on temperature and therefore it decreases from the equator poleward in response to decreasing temperature from the equator towards the poles. The content of vapour in the surface air in the moist tropical areas, at 50^0 and 70^0 latitudes is 2.6 per cent, 0.9 per cent and 0.2 per cent (by volume) respectively.

The content of atmospheric vapour also decreases upward. More than 90 per cent of the total atmospheric vapour (humidity) is found upto the altitude of 5 km. Suppose, if there is condensation of all the atmospheric vapour at a time, there would result a 2.5 cm thick layer of water around the earth. Even this meagre amount of water vapour in the atmosphere is responsible for various types of weather phenomena. The moisture content in the atmosphere creates several forms of condensation and precipitation *e.g.* dew, fog, cloud, rainfall, frost, ice, snowfall, hailstorms etc. Vapour is almost transparent for incoming shortwave solar radiation so that the electromagnetic radiation waves reach the earth's surface without much obstacles but the vapour is less transparent for outgoing shortwave terrestrial radiation and therefore it helps in heating the earth's surface and lower portion of the atmosphere because it absorbs terrestrial radiation and also reradiates terrestrial radiation back to the earth's surface. It is, thus, evident that water vapour also helps in intensifying **green house effect** of the atmosphere.

The process of transformation of liquid (water) into gaseous form is called **evaporation**, the amount and intensity of which depend on aridity, temperature and velocity of winds, the higher the rate and amount of evaporation, the higher the content of atmospheric vapour because dry air with high temperature is capable of retaining more moisture (vapour) as dry air requires more time and moisture to become saturated. A stable air becomes saturated soon because there is no transfer of moisture while unstable air attains saturation quite late because there is much transfer of moisture. There is more evaporation from oceanic surfaces than from land surfaces. There is maximum evaporation from the lands between 10^0N and 10^0S latitudes whereas maximum evaporation occurs from the oceans between 10^0-20^0 latitudes in both the hemispheres.

The process of conversion of vapour into liquid (water) and solid form (ice, snow, forst) is called **condensation**. It is apparent that evaporation and condensation are opposite processes wherein the former involves conversion of liquid (water) into gaseous form (vapour form) while the latter refers to conversion of water vapour into liquid or solid form. It may be concluded that the presence of water vapour in the atmosphere is of vital climatic significance because all forms of condensation result from vapour.

8.2 WATER : SIGNIFICANCE AND CHANGE OF STATE

About one third of the important 100 elements which occur naturally in earth's crust are very important for the sustenance of life in the biosphere. Out of these essential elements oxygen, carbon and hydrogen are by far the most essential elements for the existence of living organisms because these three elements make up 90 per cent of dry weight of the organic matter in the biosphere. Out of these three essential elements, hydrogen in the form of water and oxygen constitutes 85.5 per cent of the total weight of all the living organisms. The water (H_2O) resulting from the association of hydrogen (2 atoms, H_2) and oxygen (one atom, O) (H_2O) is by far the most fundamental and abundant substance in the biosphere. The water is found on the globe in three forms (states) *e.g.* gaseous state (vapour), solid state (ice), and liquid state (water). The water is found in different locations *e.g.* lakes, ponds, tanks, rivers, oceans, groundwater, soils, surface and subsurface rocks, living organisms, as water vapour in the atmosphere, as snow and ice in high latitudes (polar areas) and high altitudes (hills and mountains) areas. Water is very important substance for the biosphere because (i) it is able to dissolve almost all substances, (ii) it has great ability to store heat, (iii) it takes part in the nourishment of organisms, (iv) it helps in the circulation of elements in the biosphere etc.

The water undergoes phase changes through the exchange or transfer of heat energy as follows :

(1) **Liquid phase to gaseous phase** requires absorption of 540-607 cal/g heat in the form of **latent heat of vapourization.**

(2) **Solid (ice) phase to liquid phase** (water) requires 79-80 cal/gram heat in the form of **latent heat of fusion.**

(3) **Solid (ice) phase to gaseous phase** (water vapour) requires the absorption of 680 cal/gram in the form of **latent heat of sublimation.**

(4) **Gaseous phase** (water vapour) to liquid phase (water) releases 540-607 cal/gram heat in the form of **latent heat of condensation.**

(5) **Liquid phase** (water) to solid phase (ice) releases 79-80 cal/gram heat in the form of **latent heat of fusion.**

(6) **Gaseous phase** (water vapour) to solid phase (ice) releases 680 cal/gram heat in the form of latent heat of sublimation.

It may be mentioned that first three phases (1 to 3) absorb heat while the latter three phases (4 to 6) release heat. The latent heat/energy is further elaborated in the following section.

8.3 LATENT HEAT

Energy in the form of heat required (to be absorbed) for the conversion of water (liquid phase) into vapour (gaseous phase); ice (solid state) into water (liquid phase/state); and ice (solid phase/state) into vapour (gaseous phase/state) is called **latent heat** which falls into three categories *e.g.* **laten heat of vapourization**, (2) **latent heat of fusion**, and (3) **latent heat of sublimation** as elaborated in the first three phases (respectively). Conversely, the relased heat from vapour to water, from water to ice, and from vapour to ice is called (1) **latent heat of condensation**, (2) **latent heat of fusion**, and (3) **latent heat of sublimation** respectively.

It is evident that the amount of heat spent during the process of evaporation is never lost, rather it is always associated with water vapour. There are several evidences which demonstrate the use of heat energy at the time of evaporation, *e.g.* (1) one feels cooling effect when one sits before a fan or in shady open air after sweating in summer months because the sweats are evaporated, (2) there is cooling effect when drops of sprit are kept on the palm of human hand because sprit is evaporated etc. On the other hand, heat energy is released at the time of condensation (conversion of vapour into liquid-water or solid form-ice). This energy, released after condensation, is called **latent heat of condensation.** It may be mentioned that when the heat energy is absorbed in conversion process, it is called **latent energy** (latent heat) and when the conversion phase is reversed, the latent energy is released and goes back to the atmosphere. The release of heat (latent) energy is climatically very important beause 'it provides energy to form thunderstorms, tornadoes, and hurricanes. It also plays a critical role in the redistribution of heat energy over the earth's surface' (J.E. Oliver and J.J. Hidore, 2003).

8.4 HYDROLOGICAL CYCLE

The hydrological cycle refers to a model of exchange of water over the surface of the earth from oceans via atmosphere, continents (land surface), and back to the oceans. Thus, the hydrological cycle at global scale involves the mechanism of (1) evaporation of water from oceanic water through insolation (solar energy), (2) conversion of water into water vapour or humidity (first and second phases are almost the same, (3) horizontal transport of atmospheric moisture over the oceans and the continents by atmospheric circulation (advection), (4) release of atmospheric mositure in the form of precipitation (either in liquid form as water, or in solid form as snow and ice and other minor forms as dew, fogs etc.) over the continents and oceans, and (5) eventual transfer of water received at the earth's surface to the oceans via various routes and hydrological processes, important being surface run off and rivers (fig. 8.1).

The mechanisms of global hydrological cycle can be presented in the following manner :

Oceanic water is heated by insolation (solar heat energy) and thus water is transformed (only a small fraction of oceanic water) into gaseous form -water vapour or moisture. This moisture is horizontally trasported across the oceans and over the continents by atmospheric circulation (winds). The air is cooled because of its ascent and thus the moisture is released as precipitation over the oceans and the continents. The precipitation falls on the land in a variety of ways *e.g.* (i) Some precipitation falls directly in the streams, lakes and other bodies. This precipitation fall is called **direct fall** which is directly disposed off back to the oceans. (ii) Some portion of rainfall is intercepted by vegetation.

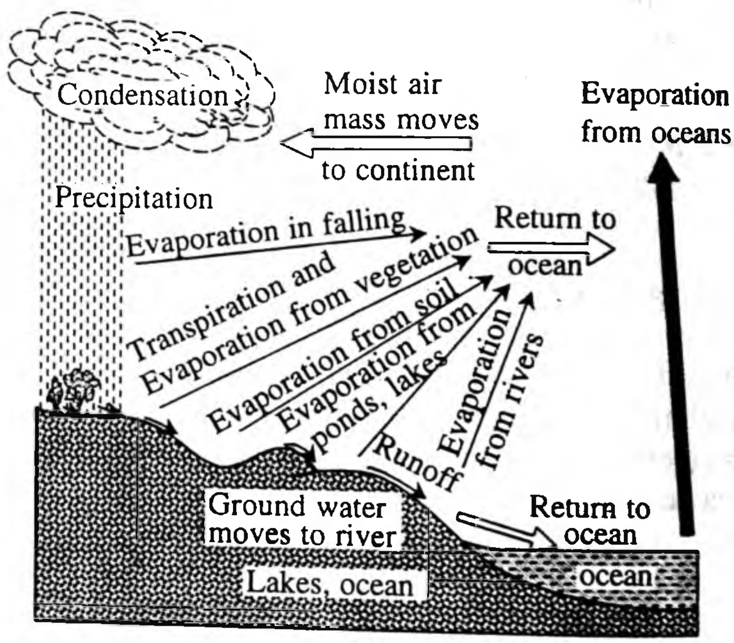


Fig. 8.1 : Global hydrological cycle involving different pathways of water e.g. from the ocean through the atmosphere and the lithosphere back to the ocean.

Some portion of this intercepted rainfall is evaporated from the leaves and the remainder reaches the ground through the branches and stems of plants as **stem flow or aerial streams.** (iii) Some portion of rainfall reaches the ground directly as **throughfall.** Some portion of rainfall is lost to the atmosphere through evapo-transpiration from the vegetation. Some water is also lost to the atmosphere through evaporation from the lakes, ponds, tanks and rivers.

A sizeable portion of rainfall reaching the ground surface becomes effective **overlandflow** which reaches the streams as **surface runoff**. Some portion of rainwater received at the ground surface enters the soil zone through **infiltration** and thus forms **soil moisture storage** of which some portion is again lost to the atmosphere through evaportion and plant transpiration, some portion reappears as seepage and springs via **throughflow** and **interflow** while some portion percolates further downward to form **groundwater storage** of which some portion reaches the channel through **base flow**, some portion moves upward as capillary rise to reach 'soil moisture storage' and some portion is

Natural Hydrological System

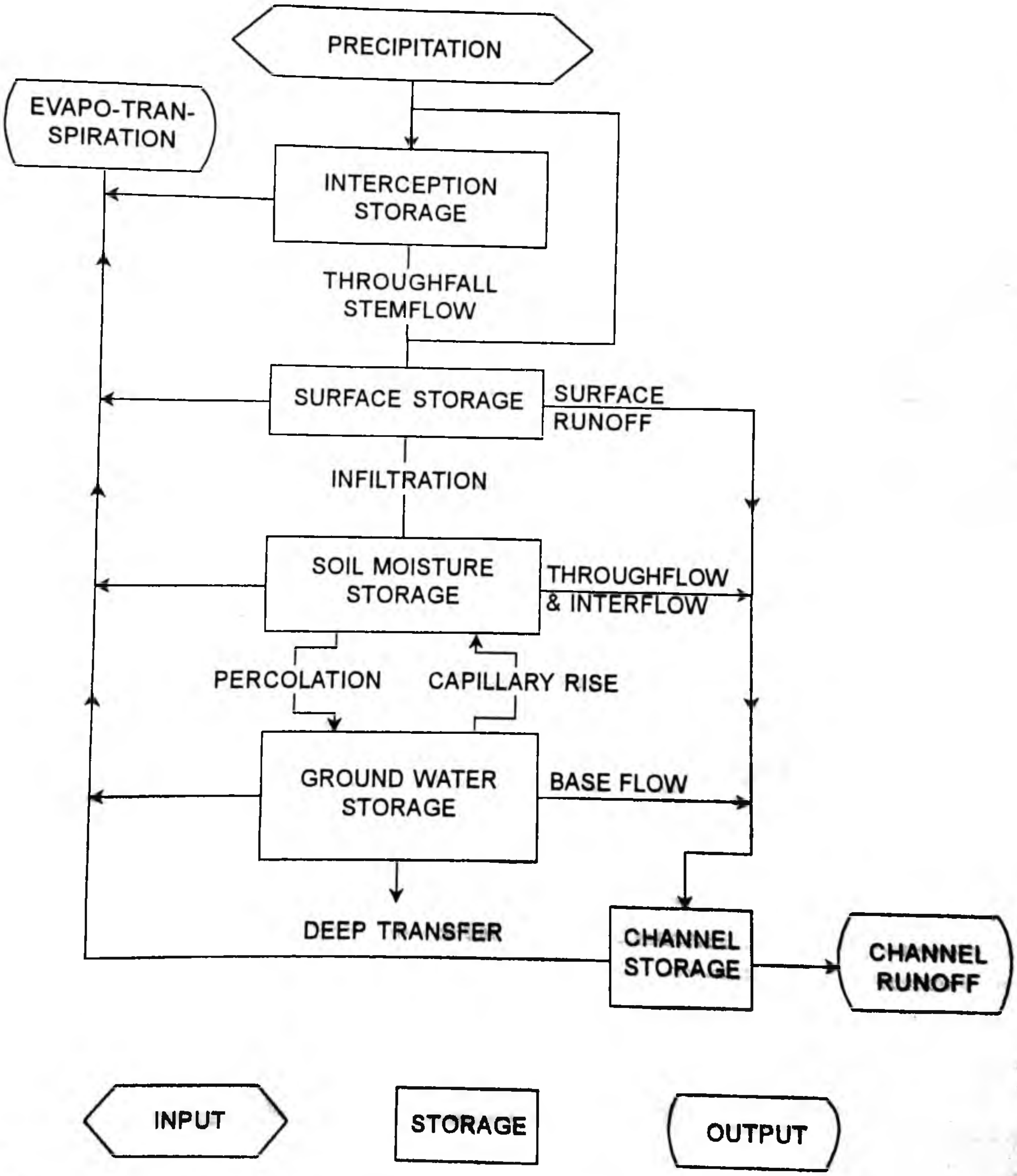


Fig. 8.2 : Natural hydrological Cycle.

routed further donward through **deep transfer** and enters the underlying bedrocks. The **channel storage** receives water from **surface storage** through surface runoff, from **soil moisture storage** through **interflow** and **through flow** and from **groundwater storage** through **base flow.** Thus the initial input of precipitation finds exit through two paths of output *e.g.* (i) to the atmosphere through evaportion from rivers, lakes, ponds, soil, evapotranspiration from vegetation and evaporation of falling rains, and (ii) to the oceans through channel runoff or stream flow. This process is repeated every year to make the water or hydrological cycle at global scale effective (fig. 8.2).

It may be pointed out that though the different hydrological processes as elaborated above maintain the global hydrological cycle through the oceans, the atmosphere and the continents but out of the total moisture of the biosphere 95 percent is never available to hydrological cycle because it is (estimated quantity being 2,50,000 × 10^{20} grams) locked in the rocks of the earth's crust. Thus only 5 per cent of the total moisture of the biosphere is available to the global hydrological cycle. Of this 5 per cent of moisture about 97.2 per cent is stored in the oceans and the remainder 2.8 per cent is represented by 2.15 per cent moisture stored in polar icecaps and permanent glaciers, 0.62 per cent moisture in the form of groundwater (which is in circulation) and 0.03 per cent moisture in the streams, soils, freshwater lakes, saline lakes and inland seas.

It is believed that the global hydrological cycle involves the balance between evaporation and precipitation over the earth's surface but the pattern of balance between evaporation and precipitation is not uniform over the oceans and the land. According to the estimate of M.L. Budyko (1971) evaporation exceeds precipitation over the oceans because 455,000 cubic km of water is evaporated from the oceans every year whereas only 409,000 cubic km of water is returned to the oceans through precipitation per annum. Thus there is net loss of 46,000 cubic km of water from the oceans every year. On the other hand, 62,000 cubic km of water is evaporated from different water bodies of the land annually but 108,000 cubic km of water is annually received at the land through precipitation. Thus there is a net gain of 46,000 cubic km of water on the land every year. This is because of the fact that 46,000 cubic km of evaporated water from the oceans is added to atmospheric budget of moisture over the land. The additional amount of 46,000 cubic km of water is disposed off to the oceans through stream runoff every year (fig. 8.3).

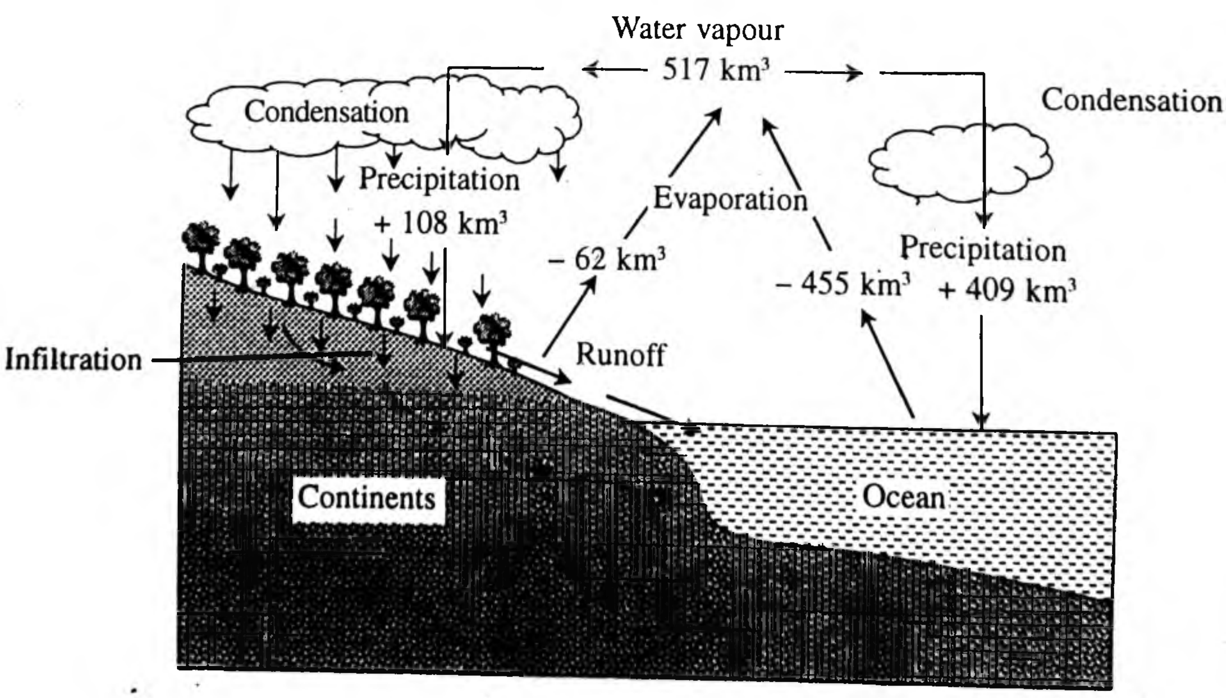


Fig. 8.3 : Global hydrological balance. Source : data from M.L. Budyko (1971).

Hydrological cycle is very important mechanism for various biological processes in the biosphere because no life is possible without water. Though the interaction between vegetation and hydrological cycle is very limited but the effect of hydrological cycle on the biosphere (viz. vegetation) is enormous because the vegetation is an effective medimum for the circulation of sediments and chemical elements through biogeochemical cycles in the biosphere and all these cycles become possible only through the movement of water. Though human activities have not adversely affected the hydrological cycle at present to a significant level but man through his everincreasing economic activities may affect various components of hydrological cycle in a variety of ways as elaborated below :

Man affects and modifies the internal processes of hydrological regime of drainage basins in a variety of ways. These modifications have both positive and negative effects. The input of precipitation in the hydrological cycle of a drainage basin is modified through **'cloud seeding'** for induced precipitation (increase in input), atmospheric pollution (both increase and decrease in precipitation input), modified atmospheric circulation (*e.g.* urbanisation induces vertical convective currents and thus increases precipitation), forest clearance (decrease in precipitation), vegetation modification (changes in precipitation) etc. Additional input of water on ground surface is provided through irrigation of crops and effluent disposal from urban areas. **Interception storage** is modified by forest clearance (reduction in interception storage) and vegetation modification. **Surface storage** is modified by land clearance, cultivation, urbanisation, land drainage, mining etc. while **surface runoff** is increased due to deforestation and cultivation and is supplemented by additional input through channeled irrigation for cropland and effluent disposal from urban areas. **Infiltration** is modified through devegetation (decrease in infiltration), urbanisation (decrease), afforestation and reforestation (increase) and irrigation (increase). **Soil moisture storage** is positively affected by irrigation, planting of grasses and plants, artificial recharge, seepage from water supply systems, soakpits, cesspools etc. while it is negatively affected by land clearance through deforestation, burning of grasslands, urbanisation etc. **Groundwater storage** is modified through extraction of groundwater for domestic use and irrigation purposes while **channel storage** is modified through flood plain development, channel modification (shortening or lengthening of channels), river regulation, construction of dams and reservoirs etc. The impact of man's activities on different components of basin hydrological cycle may 'include increased flood hazard and other changes in river regime, reduced availability of groundwater, deterioration of water quality and widespread eutrophication of water bodies and river systems in response to increased nutrients' (K.J. Gregory and D.E. Walling, 1981).

8.5 HUMIDITY CAPACITY

The moisture content in the atmospheric air is measured in grain per cubic foot or in gram per cubic centimeter volume of air or in gram per kilogram of air at given temperature. The moisture retaining (holding) capacity or **humidity capacity** refers to the capacity of a parcel of air of certain volume at certain temperature at any point of time to retain or hold maximum amount of moisture content. Evaporation is the main mechanism through which water and ice are converted into water vapour (humidity). Since temperature and evaporation are directly positively related (*i.e.* evaporation increases with increasing temperature) and hence atmospheric humidity is also positively related to temperature *i.e.* higher the air temperature, higher the moisture holding capacity of the air and lower the temperature, lesser the moisture holding capacity. Tables 8.1 and 8.2 denote humidity capacity of air in grain per cubic foot of volume at different temperatures in ^{0}F (table 8.1) and in gram per kilogram of air at different temperatures (table 8.2) in ^{0}C respectively.

Table 8.1 : Humidity Capacity in One Cubic Foot Volume of Air

Temperature (°F)	Humidity Capacity (grain)	Difference at the interval of 10^0F	Eastimated absolute humidity
30	1.9	...	...
40	2.9	1.0	...
50	4.1	1.2	4.0
60	5.7	1.6	4.0
70	8.0	2.3	4.0
80	10.9	2.9	4.0
90	14.7	3.8	4.0
100	19.7	5.0	4.0

Table 8.2 : Humidity Capacity of Air in Gram per Kilogram

Temperature (°C)	Humidity capacity (gram/kg)	Difference at the interval of 10^0C	Eastimated absolute humidity (gram/kg)
– 40	0.10	...	...
– 30	0.30	0.20	...
– 20	0.75	0.45	...
– 10	2.00	1.25	...
0	3.50	1.50	...
5	5.00	...	...
10	7.00	3.50	4.0
15	10.00	...	4.0
20	14.00	7.00	4.0
25	20.00	...	4.0
30	26.50	12.50	4.0
35	35.00	...	4.0
40	47.00	20.50	4.0

It is evident from tables 8.1 and 8.2 that moisture holding capacity (humidity capacity) is increasing with increasing air temperature. For example, the humidity capacity of an air having the volume of one cubic foot and temperature of 30^0F is 1.9 grain whereas it becomes 2.9 grain when temperature becomes 40^0F (an increase of 10^0F). It may be pointed out that the ratio of increase of humidity capacity also increases with increasing temperature (tables 8.1 and 8.2). For example, the net increase of humidity capacity from 30^0F to 40^0F is one grain while it become 5 grain from 90^0F to 100^0F (table 8.1). Similarly, humidity capacity becomes higher during summer months than during winter months and during daytime than nights. The extent of land and water and wind velocity also influence humidity capacity. Oceanic and coastal areas record higher humidity capacity of air than the remote areas of the continents. Humidity capacity decreases from equator poleward. The air having moisture content equal to its humidity capacity is called **saturated air.**

The difference between the moisture retaining capacity (humidity capacity) and actual humidity (absolute humidity) of a given volume of an air at given temperature and time is called **saturation deficit.** For example, the saturation deficit of an air of one kilogram at 10°C temperature is 3 gram/kg as its absolute humidity is 4 grams against its humidity capacity of 7 grams (table 8.2). The temperature at which the given air is saturated *i.e.* the humidity capacity and absolute humidity become equal, is called **dew point.** It may be mentioned that the temperature of ascending air decreases (at the adiabatic rate of 10°C per 1000 meters) *i.e.* the ascending air cools aloft and hence its dew point also decreases with increasing altitude at the rate of 2°C per 1000 meters.

8.6 TYPES OF HUMIDITY MEASUREMENT

The content of moisture in the atmosphere is measured and expressed in a number of ways, namely vapour pressure, absolute humidity, specific humidity, relative humidity, mixing ratio etc. These are briefly described below :

1. Vapour Pressure

Vapour pressure refers to the pressure exerted by water vapour of a given parcel of air. In fact, vapour pressure represents the part of the total atmospheric pressure contributed by the amount of water vapour present in the atmosphere. 'At any given temperature, there is a limit to the density of water vapour in the air, with a consequent upper limit to the vapour pressure. This is termed as **saturation vapour pressure**' (R.G. Barry and R.J. Chorley, 2002).

2. Absolute Humidity

The total weight of moisture content (water vapour) per volume of air at definite temperature is called absolute humidity. Generally, absolute humidity does not change with increase or decrease of temperature, if no additional vapour is added through additional evaporation, but it changes with contraction (after descent) or expansion (on ascent) of air. The absolute humidity decreases from equator towards the poles and from oceans to the continents. The possibility of precipitation largely depends on absolute humidity. In a simple term absolute humidity may be defined as a mass or weight of water vapour per unit volume of air at a given temperature. This is generally expressed in gram per cubic meter volume of air. It appears that vapour pressure and absolute humidity are more or less same measures of humidity.

3. Specific Humidity

Specific humidity is defined as the mass of water vapour in grams contained in a kilomgram of moist air and it represents the actual quantity of moisture present in a definite moist air. 'In fact, specific humidity is a ratio of water vapour to the weight of moist air.' Specific humidity is seldom affected by changes in air pressure or air temperature because it is measured in the units of weight (grams). It is directly proportional to **vapour pressure,** which is 'the partial pressure exerted by water vapour in the air and is independent of other gases' and is inversely proportional to air pressure. Specific humidity decreases from equator poleward. For example, extremely cold and dry air over arctic region during winter generally has specific humidity of 0.2 gram per kilogram of air while it becomes as high as 18 grams per kilogram of extremely warm and moist air over equatorial regions. 'In a real sense, specific humidity is a geographer's yardstick of a basic natural resource-water-to be applied from equatorial to polar regions. It is a measure of the quantity of water that can be extracted from the atmosphere as precipitation' (A.N. Strahler and A.H. Strahler, 1978).

4. Relative Humidity

Relative humidity is defined as a ratio of the amount of water vapour actually present in the air having definite volume and temperature (*i.e.* absolute humidity) to the maximum amount the air can hold (*i.e.* humidity capacity). In other words, relative humidity is the proportion of absolute humidity of an air of definite volume at a given temperature to the humidity capacity of that air. Relative humidity is generally expressed as percentage. For example, if the humidity capacity and absolute humidity of an air having temperature of 20°C are 8 grains and 4 grains per cubic foot respectively, then the relative humidity will be as follows :

$$\text{Relative humidity} = \frac{\text{Absolute humidity}}{\text{Humidity capacity}} \times 100$$

$$\frac{4}{8} \times 100 = 50\% \, or \, 1/2 \, or \, 1:2$$

or

$$\text{Relative humidity} = \frac{\text{vapour pressure}}{\text{saturation vapour pressure}} \times 100$$

There is inverse relationship between air temperature and relative humidity *i.e.*, relative humidity decreases with increasing temperature while it increases with decreasing temperature (table 8.3).

Table 8.3 : Temperature, Humidity Capacity and Relative Humidity

Temperature (°F)	Humidity Capacity (grain per cubic foot)	Absolute Humidity (grain per cubic foot)	Relative Humidity (%)
30	1.9	1.9	100.0
40	2.9	1.9	65.5
50	4.1	1.9	46.3
60	5.7	1.9	33.3
70	8.0	1.9	23.7
80	10.9	1.9	17.4
90	14.7	1.9	12.9
100	19.7	1.9	9.6

When the humidity capacity (saturation vapour pressure) and absolute humidity (vapour pressure) of the air are the same, the air is said to be saturated and the relative humidity becomes 100 per cent. Relative humidity changes in two ways viz., (i) if the absolute humidity increases due to additional evaporation or (ii) if the temperature of the air decreases so that humidity capacity also decreases. For example, the relative humidity of the air with 50°F temperature is 46% because humidity capacity and absolute humidity are 4.1 grins and 1.9 grains respectively (table 8.3) but if the temperature of that air decreases due to ascent to 40°F, the relative humidity becomes 65.5% because the humidity capacity decreases to 2.9 grains per cubic foot.

Importance of Relative Humidity—Relative humidity has a great climatic significance because the possibility of precipitation depends on it. High and low relative humidity is indicative of the possibility of wet (precipitation) and dry conditions respectively. The amount of evaporation also depends on relative humidity. Evaporation decreases with high relative humidity while it increases with low relative humidity. Relative humidity is directly related to human health and comfort. Very high (above 60%) and very low humidity is injurious to human health. This is why the equatorial regions with high temperature and high relative humidity and tropical hot deserts with very low relative humidity are unfavourable for human health. Relative humidity also affects the stability of different objects, buildings, electrical appliances, radio etc.

Distribution of Relative Humidity—The horizontal distribution of relative humidity on the earth's surface is zonal in character. Equatorial regions are characterized by highest relative humidity. It gradually decreases towards subtropical high pressure belts where it becomes minimum (between 25^0-35^0 latitudes). It further increases poleward. The zones of high and low relative humidity shift northward and southward with northward and southward migration of the sun respectively. Seasonal distribution of relative humidity is largely controlled by latitudes. Maximum relative humidity is found during summer season between 30^0N and 30^0S latitudes while high latitudes record relative humidity more than average value during winters. There is maximum relative humidity in the morning whereas lowest value is recorded in the evening. Fig. 8.4 denotes zonal distribution of relative humidity.

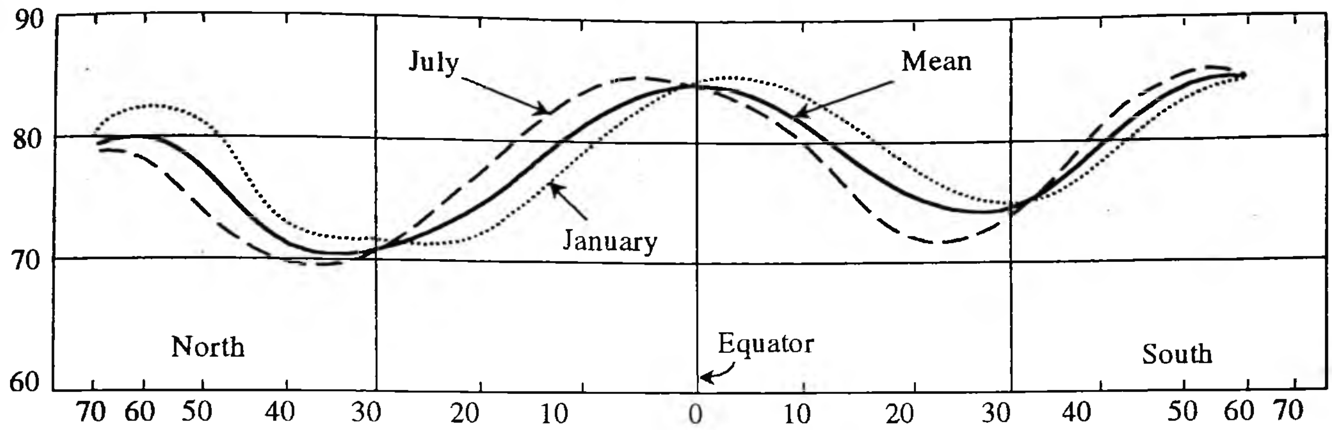


Fig. 8.4 : Zonal distribution of relative humidity.

5. Mixing Ratio

The ratio of weight (mass) of water vapour to the weight of per unit volume of dry air is called mixing ratio while the concentration of maximum amount of water vapour in a dry air of certain volume and mass (weight) is called **sataturation mixing ratio.** There is direct positive relationship between air temperature and mixing ratio *i.e.* if air temperature increases the mixing ratio also increases and vice versa. This is why cold air mass has low mixing ratio while warm air mass carries high mixing ratio. Mixing ratio is expressed in gram per kilogram weight of dry air (g/kg). If we look into the definitions of **specific humidity** and mixing ratio, there is very little difference between these two measures of humidity. This difference is only in terms of dry or moist air. In other words, the **specific humidity** is defined as a ratio of weight of water vapour to the weight of unit moist air, while **mixing ratio** represents the ratio of weight of water vapour to the weight of unit dry air.

$$\text{Mixing ratio (W)} = \frac{Mv}{Md}$$

where Mv = mass of water vapour

Md = mass of dry air

8.7 EVAPORATION

The process or mechanism of conversion of water into gaseous state *i.e.* water vapour by the use of heat energy is called evaporaion. More simply, the process of transformation of liquid (water) into gaseous form is called **evaporation.** On the other hand, the process of transformation of solid (ice) directly into gaseous form (water vapour) by the use of heat energy is called **sublimation.** As mentioned in section 8.2 the heat energy required to transform water into water vapour through evaporation is called **latent heat of vapourization** (latent means hidden) which is 540 to 607 cal/gram whereas the heat energy spent in transforming ice into water vapour is called **latent heat of sublimation** which is 680 cal/gram. If the latent heat of vapourization is removed from water vapour, the vapour returns to liquid state (this may happen when condensation takes place above freezing point). Similarly, if the latent heat of sublimation is removed from water vapour, the vapour returns to solid state (ice) when condensation occurs below freezing point. On an average, about 600 calories of heat are required (to be spent) to convert one gram of water into water vapour, while 680 calories of heat are required to convert one gram of ice into water vapour. This spent heat energy, which is associated with water vapour, is called latent heat (hidden heat).

Rate of Evaporation

There are spatio-temporal variations in the rate and amount of evaporation due to a host of factors as follows :

(1) **Vapour pressure of water surface,** which determines the rate of evaporation, depends on the temperature of the water surface. There is direct positive relationship between water surface temperature and surface vapour pressure (absolute humidity). It is the difference between the temperature of water surface and air temperature which motivates the process of evaporation. The higher the water surface temperature than the air temperature, the higher the rate of evaporation. It is evident that evaporation is directly proportional to the water surface temperature (*i.e.* the temperature of evaporating surface, evaporating surface is water surface, as the water molecules are set in motion and are released from the water surface due to temperature to become in gaseous state, vapour).

(2) **Vapour pressure of the air,** representing the pressure exerted by water vapour of a given parcel of air, is negatively correlated with the rate of evaporation. In other words, the greater the vapour pressure of a parcel of air, the lower the rate of evaporation and vice versa. It is the difference between the vapour pressure of evaporating surface (water surface) and air vapour pressure, which is directly related to the rate of evaporation. The greater the difference as referred to above, the higher the rate of evaporation. It may be further elaborated, if the overlying air is dry (little moisture in it) resulting into low atmospheric vapour pressure, the evaporation will take place more rapidly. As the atmospheric vapour increases (due to increase in air moisture) the rate of evaporation decreases. It may also be inferred that the rate of evaporation varies with relative humidity *e.g.* the higher the relative humidity, the lower the rate of evaporation because almost saturated air cannot retain more moisture and vice versa. This is why evaporation is greater during dry summer season than during wet summer season, greater at mid-day than at night, and greater during summer than during winter.

(3) **Wind velocity** is directly positively related to the rate of evaporation *e.g.* greater the wind velocity, higher the rate of evaporation and slower the wind velocity, lower the rate of evaporation. It may be further explained as follows—if the wind speed is high, the moist air moves away from the evaporating surface (water surface) and is replaced by relatively dry air, with the result the vapour pressure of the overlying air becomes much less than the vapour pressure of the water surface (there is large difference between the air vapour pressure and water surface pressure). This situation allows higher rate of evaporation because of the turbulence set up in the air. Conversely, if the air is almost static over water surface, it gets saturated quickly and hence the rate of evaporation is retarded. In more simple term, the higher the wind velocity, the greater the rate of evaporation and vice versa.

(4) **Salinity** of water bodies (salt content in different water bodies) is inversely related to the rate of evaporation *i.e.* the higher the salt content in water, the lower (retarded) the rate of evaporation, and lower the salinity, the higher the rate (accelerated rate) of evaporation. This is why the rate of evaporation from fresh water bodies (lakes, ponds, tanks, rivers etc.) having very low salinity is 5 per cent higher than the rate of evaporation from more saline sea surfaces. Since there is spatial variation in salinity in different parts of the oceans and seas world over, so is the spatial variation in the rate of evaporation over oceans and seas.

It may be summarized that if there is high temperature (*i.e.* more heat is available), very low relative humidity (*i.e.* absolute humidity is far less than moisture retaining capacity of the air) *i.e.* dry air (less moist), high wind speed, larger water surface, less saline water, the rate of evaporation will be very high, say maximum evaporation.

The spatial distribution of evaporation is thus largely controlled by the combination of temperature, potential evaporation, availability of water bodies and evapotranspiration. As temperature decreases from the equator poleward the evaporation also decreases from the equator towards the poles but the rates of evaporation vary over land and water surfaces. It may be pointed out that the potential evaporation (evaporating power) is much higher over land surfaces than over ocean surfaces because of relatively less moist air over land surface but the actual evaporation is far less over land surfaces than over ocean surfaces because in comparison to oceans, the availability of water over land surfaces is far less. Since the land surfaces in the equatorial regions are mostly covered with dense evergreen rainforests and hence the potential evaporation is low because of more moisture coming from evapotranspiration from plant cover. So, there is not much difference in the potential evaporation over land and ocean surfaces in the equatorial regions. It may be concluded that air temperature is the most dominant control factor of the rate of evaporation. This is why evaporation decreases poleward. Following G.T. Trewartha, about 60 percent of the total evaporation over the globe takes place in the tropical zone extending from 20^{0}N to 20^{0}S latitudes, while 80 per cent of the world total evaporation occurs in the zone located between 35^{0}N and 35^{0}S latitudes. It is evident from table 8.4 that mean evaporation is slightly higher in the southern hemisphere than in the northern hemisphere because of overdominance of water in the southern hemisphere.

Table 8.4 Spatial distribution of actual evaporation in inches. Based on Wust.

	Latitudes in degree					
	Northern Hemisphere					
	60-50	50-40	40-30	30-20	20-10	10-0
Continents	14.2	13.0	15.0	19.7	31.1	45.3
Oceans	15.7	27.6	37.8	45.3	47.2	39.4
Mean	15.0	20.1	28.0	35.8	42.9	40.6
	Southern Hemisphere					
Continents	7.9	19.7	20.1	16.1	35.4	48.0
Oceans	9.1	22.8	35.0	44.1	47.2	44.9
Mean	8.8	22.8	35.5	39.0	44.5	45.7

The spatial distribution of evaporation at global level including both land and ocean surfaces reveals the following characteristic features :

(1) The potential evaporation is higher on land surfaces than over the ocean surfaces because of limited water bodies over the land areas.

(2) Actual evaporation is far higher over the ocean surfaces (because of 70 per cent area of the globe occuplied by oceans and seas) than over the land surfaces (continets). Evaporation rates are greater over oceans than over the continents.

(3) Mean annual evaporation decreases from the equator poleward. Evaporation is far greater over the equator than over the poles.

(4) The greatest rate of evaporation occurs in the western north Atlantic Ocean off the east coast of the United States of America.

8.8 EVAPOTRANSPIRATION

The loss of water from the leaves of plants directly and the soils holding the plants indirectly is called **transpiration**. It may be mentioned that plants take water and nutrients from soils through the process of **root osmosis**. This is why the loss of water from the soils which have vegetation is considered as indirect loss of water under the process of transpiration. In more simple term, the loss of water from plants on the earth's land surface is called **transpiration** which is controlled by the opening and closing of stomata of living plants. The opening and closing of stomata responsible for transpiration is in turn controlled by relative humidity, amount of water present in the plant leaves, wind speed, concentration of water in plant holding soils etc. The ultimate transpiration from plants is controlled by a host of factors as elaborated just above plus vapour pressure in the cells of plant leaves and air vapour pressure. It may be mentioned that plants leave vapour pressure is always greater than air vapour pressure and hence there is continuous transpiration during photoperiod (day light period) of a day, mostly during summer season. It is important to mention that the data of loss of water from land not having surface water, loss of water through evaporation from water bodies of land surfaces, and loss of water from living plants through transpiration and loss of water from ocean surfaces through evaporation are required to study and analyse terrestrial water balances but it is not possible to measure the loss of water from plants through transpiration exclusively and hence a composite term of **evapotranspiration** is used to estimate loss of water from land surfaces through evaporation and transpiration because it is very difficult to separately measure the amount of water evaporated from the soils, evaporated from intercepted moisture (it may be rembered that certain portion of falling rains is intercepted by plant canopy and remains on the leaves surfaces, this intercepted water is called intercepted moisture of interception storage, as shown in fig. 8.2, a portion of which is evaporated, while the remaining portion reaches the ground surface as **aerial streamlets** through twigs, branches and stems of plants) and transpiration. It may be summarized that **evapotranspiration** process includes the processes of loss of water from the surfaces of plant leaves as intercepted moisture through evaporation, loss of water from soils through evaporation and loss of water from plant leaves through transpiration, Evaportranspiration, thus, is controlled by a host of factors *e.g.* (1) intensity of solar radiation, say quantity of available heat energy received from the sun, (2) air temperature, (3) length of daylight *i.e.* length of photoperiod of a day (photoperiod of a day denotes that part of a day during which solar radiation is received on the earth's surface), (4) wind speed, (5) vegetation type and vegetation density, (6) soil moisture conditions i.e the amount of water retained in the soils in terms of (i) **saturated stage or condition**, when all the voids and pore spaces within the soils are filled with water, (ii) **field capacity stage or condition** when 50 per cent of the total voids and pore spaces are filled with water and remaining 50 per cent voids are occpuied by air, and (iii) **wilting stage or condition**, when soil water is lost through continued evaporation, uptake of water by plant roots through the process of root osmosis etc., (7) precipitation types (*e.g.* dew, fog, rainfall, snowfall etc.) etc.

As stated above it is not possible to measure evapotranspiration directly in the field because a host of controlling factors, referred to above, affect evapotranspiration and it is difficult to measure all such parameters and hence it is estimated on the basis of a few methods *e.g.* (1) theoretical methods, (2) empirical methods etc.

Potential evapotranspiration (PE) is an index of thermal efficiency and water loss because it represents the amount of transfer of both moisture and heat to the atmosphere from soils and vegetation (evaporation of liquid or solid water-ice, and transpiration from living plant leaves) and thus is a function of energy received from the sun. It may be pointed out that evapotranspiration is calculated (and not directly measured) from the mean monthly temperature (in ^{0}C) with corrections for day length (photoperiod *i.e.* 12 hours, when sun light is available). The PE (potential evapotranspiration) for a 30-day month (a day having only the length of sunshine *i.e.* 12 hours) is calculated as follows:

$$\text{PE (in cm)} = 1.6\,(10t / I)^a$$

where PE = potential evapotranspiration

I = the sun light for 12 months of $(t/5)^{1.514}$

a = a further complex function of I

t = temperature in ^{0}C

Thornthwaite (1948) used evapotrnspiration to calculate thermal efficiency index which is simply the potential evapotranspiration expressed in centimeters, to determine boundaries of different world climatic types.

8.9 CONDENSATION

The transformation of gaseous form of water (i.e water vapour) into solid form (ice) and liquid form (water) is called condensation. In other words, the process of change of water vapour into liquid form is called **condensation.** It is evident that condensation is opposite to evaporation. The process and mechanism of condensation depends on the amount of relative humidity present in the air. The air having 100 percent relative humidity is called **saturated air.** An air may become saturated in two ways *e.g.* either (i) the absolute humidity at a given temperature is raised to equal the humidity retaining capacity of the air or (ii) the temperature of the air is reduced to such an extent (*i.e.* the air is cooled) that the humidity capacity becomes equal to its absolute humidity. For example, the humidity capacity and absolute humidity of an air with 60°F (about 16°C) temperature are 5.7 grains and 4. grains per cubic foot respectively (relative humidity being 72 percent, table 8.1), if the air is cooled to 50°F (10°C) temperature, the humidity capacity decreases to 4.1 grains which is equal to absolute humidity of 4 grains per cubic foot, thus the air becomes saturated as relative humidity becomes 100 per cent, and hence condensation begins. The temperature at which an air becomes saturated is called **dew point.** It may be pointed out that condensation will begin only when the air is supersaturated *i.e.*, if the relative humidity exceeds 100 per cent, and this can be achieved only when the air is further cooled. If dew point is above freezing pont (30°F or 0°C), condensation will occur in liquid form (*e.g.*, dew, fog, rainfall etc.) but if dew point is below freezing point, condensation occurs in solid form (*e.g.*, frost, ice, snow, hailstorm etc.). The temperature at which condensation occurs (always below freezing point *i.e.* below 0°C) is called **frost point** or **frost point temperature.**

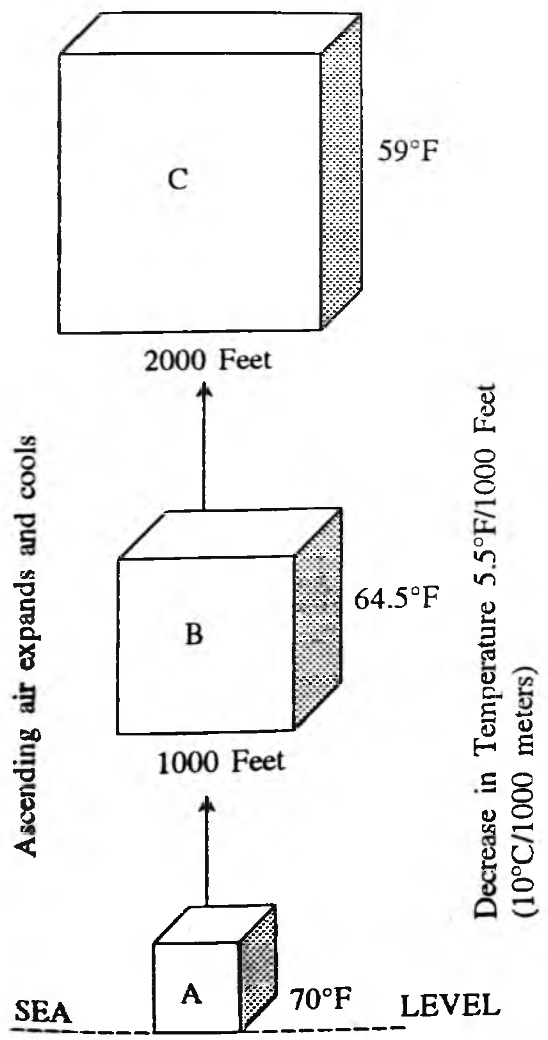


Fig. 8.5 : Expansion and cooling of air due to lifting and adiabatic change of temperature.

It is apparent that condensation depends on (1) the percentage of relative humidity of the air, and (2) the degree of cooling of the air. The air becomes cool when it rises either due to thermal heating and consequent volume expansion or is forced by topographic barrier to ascend, while it gets heated when it descends. Thus, the ascending air may bring moist weather while descending air causes dry condition. Much cooling of air is required in hot arid regions before dew point is reached. On the other hand, very little cooling causes condensation in humid regions. It is also to be remembered that heat energy is absorbed during the process of evaporation but it is released during condensation. The heat energy released after condensation is called **latent heat of condensation.** As described in section 8.3 the latent heat released after condensation of water vapour in liquid form is called latent heat of condensation while the released heat after the condensation of vapour into solid form (*i.e.* ice) is called **latent heat of sublimation.** This released heat (latent heat of condensation) is added to the atmosphere and hence retards the cooling of ascending air. The cooling of air is accomplished through different mechanisms (processes) which are discussed in the following section of 8.10.

8.10 COOLING OF AIR AND ADIABATIC CHANGE OF TEMPERATURE

The cooling of air by loss of heat is prerequisite condition for condensation process. As mentioned in section 8.5 the moisture holding capacity of a given parcel of air at given temperature increases with increasing temperature or decreases with decreasing temperature. On the other hand, relative humidity (section 8.6) is inversely related to temperature i.e. relative humidity decreases with increasing temperature (because moisture holding capacity increases) or increases with decreasing temperature (because moisture holding capacity decreases) because the relative humidity is the function of absolute humidity and moisture holding capacity of a given parcel of air at given temperature at a point of time. If the air is not saturated (*i.e.* if the absolute humidity and moisture holding capacity of the air are not equal or if the relative humidity is not hundred per cent), it must lose heat by ascending so that it is cooled, so that moisture holding capacity is reduced to such an extent that the moisture retaining capacity equals the amount of absolute humidity and the air becomes saturated, so that condensation may occur.

The required cooling of air for condensation is accomplished through two processes (mechanisms) of **diabatic process** and **adiabatic process**.

1. Diabatic Process

Diabatic or non-adiabatic change of temperature and cooling of air involves the process of cooling of air without the change of the amount of water vapour (either subtraction or addition) and volume of the air (the volume of air remains constant). Thus, diabatic cooling of the air involves loss of heat through radiation, conduction or mixing of a given parcel of air with colder air. Thus, the diabatic cooling processes can be grouped into three types e.g (1) **radiation cooling**, (2) **contact cooling**, and (3) **advection cooling**.

(1) **Radiation cooling** : The loss of heat through direct radiation from the layer of moist air is called radiation cooling which is exceedingly a slow process. It may be mentioned that this diabatic process cannot exclusively cause condensation but may help condensation if other factors controlling condensation are favourable. Radiation cooling cannot cause precipitation but may produce fog, dew, frost or thin light clouds.

(2) **Contact cooling** : The loss of heat from an air layer having relatively higher temperature to relatively colder air layer through the process of conduction of transfer of heat is called **contact or conduction cooling**. It is to be remembered that air is poor conductor of heat and hence this diabatic process of cooling is also very slow process of transfer of heat. Moreover, the rate of transfer of heat from warmer air to colder air depends on the degree of difference of temperatures between two air layers. The higher the difference of temperature, the higher the rate of conduction and hence cooling and vice versa.

(3) **Advection cooling** : The loss of heat from an air mass due to horizontal movement of air and consequent mixing of two air masses of varying temperatures is called advectional diabatic cooling. If a warm and moist air having high vapour pressure (near saturation level) reaches a cold moist air having high vapour pressure (near saturation level) and lies over it, there is mixing of two air layers and ultimately the warm moist air is cooled and condensation takes place.

It may be concluded that the diabatic process of cooling of air does not involve changes in the moisture content of the air and changes in its volume due to expansion. This is a very slow process of cooling and involves thin layer section of the atmosphere and hence causes condensation to limited extent resulting into the formation of dew, fog (when condensation occures above freezing-dew point) and frost (when condensation takes place below freezing point). Sometime thin clouds can also be formed but these cannot yield much precipitation, rather light shower or drizzle in limited area may occur.

2. Adiabatic Process

Adiabatic process of cooling of air (and also warming of air, infact change of temperature) involves loss of heat from the air due to expansation of air (increase in volume, warming occurs due to contraction of air) caused by (i) mechanical lifting or (ii) dynamic lifting, or (iii) by cyclonic (frontal) lifting. The adiabatic processes of cooling of air are the only processes of effective condensation and substantial precipitation. The adiabatic processes involving cooling of air through increase in volume due to expansion of air are explained as follows :

Temperature decreases with increasing altitude at the rate of 6.5°C per 1000 meters or 3.6°F per 1000 feet. The rate of vertical decrease of temperature is called **normal lapse rate** or **standard lapse rate** which is calculated 'from the difference between the average surface temperature (15°C) and the average temperature at the tropopause (-59°C at 11 kilometers). A definite parcel of ascending air with given volume and temperature expands due to decrease in pressure and thus cools (loses heat). For example, an air with the volume of one cubic foot and pressure of 1016 mb at sea level if rises to the height of 17,500 feet, its volume is doubled because of expansion. On the other hand, a descending air contracts and thus its volume decreases but its temperature increases at the rate of 10°C per 1000 meters. It is apparent that there is change in temperature of air due to ascent or descent but without addition or subtraction of heat. Such type of change of temperature of air due contraction or expansation is called **adiabatic change of temperature.** The rate of change of temperature of ascending air (decrease of temperature or cooling of air at the rate of 10°C per 1000 meters before condensation level is reached) or desending air (increase of temperature at the rate of 10°C per thousand meters) is called **adiabatic lapse rate**. Standard lapse rate 'is measured value. Since it measures the temperature of the environment, it is called **environmental lapse rate.'**

Fig. 8.5 depicts the mechanism of cooling of a parcel of ascending air due to expansion of volume (adiabatic change of temperature). Adiabatic change of temperatures is of two types *e.g.* (i) **dry adiabatic change,** and (ii) **moist adiabatic change.** The temperature of unsaturated air decreases with increasing altitude at the rate of 5.5°F per 1000 feet or 10°C per 1000 meters. On the other hand, if a parcel of air descends, its temperature increases downward at the rate of 10°C per 1000 meters. This type of change of temperature of unsaturated ascending or descending air is called **dry adiabatic rate.** The rate of decrease of temperature of a parcel of ascending air beyond condensation level is lowered due to addition of latent heat of condensation to the surrounding atmosphere. This is a called **moist adiabatic rate** wherein temperature of an ascending air beyond condensation level decreases (and hence the air cools) at the rate of 3°F per 1000 feet or 6°C per 1000 meters. The moist adiabatic rate is also called **retarded adiabatic rate.**

As mentioned above the ascent of a parcel of air in the process of adiabatic cooling may be effected either by thermal convection, or by mechanical lifting caused by physical barrier (*e.g.* hills and mountains), or by cyclonic (frontal) lifting. It may be mentioned that for effective condensation to cause substantial precipitation the vertical movement of air and its consequent expansion due to decrease in density and pressure is a necessary condition. In a more simple term, a rising moist warm air expands, becomes less dense, loses temperature and hence cools, relative humidity increases and ultimately condensation occurs after saturation level (dew point) is reached. The upward movement of a parcel of air requires the mechanism which may effect the ascent of air. Such mechanism is called **lifting mechanism** and falls into three categories *e.g.* (1) mechanical lifting, (2) dynamic lifting, and (3) frontal or cyclonic lifting. The **mechanical lifting,** also called as **physical barrier lifting** or **orographic lifting,** is caused by orographic barriers wherein a horizontally moving air encounters hills or mountains and is forced to rise along the windward slope of the hills. The **dynamic** or **convectional lifting** is caused due to warming of surface air due to insolation heating. The warm air expands in volume and becomes light due to decrease in density and hence rises upward and is cooled. The **frontal** or **cyclonic lifting** is caused due to meeting of two thermally contrasted air masses and consequent formation of cyclonic front. The warm air mass being lighter is pushed upward by dense cold air mass and hence upward warm air cools due to its contact with underlying cold air mass.

8.11 CONDENSATION NUCLEI

The necessary conditions for condensation to occur include (1) saturation of air (hundred per cent relative humidity), and (2) surfaces on which condensation may occur (*e.g.* hygroscopic nuclei). The mechanism of cooling and saturation of air has been described in previous sections 8.9 and 8.10. The hygroscopic nuclei include solid objects like dust particles, salt particles, and smoke. (1) The **salt particles** are provided by sea spray and comprise sodium chloride and magnesium chloride, (2) **dust particles** include flyash emitted from factories, dusts from volcanic eruptions, sands and dry soil particles blown by wind, and (3) **smokes** and **soots.** Besides, sulphur dioxides released from the combustion, nitric oxides, ammonium sulphate, carbon iodide etc. also form nuclei for condensation. It may be pointed out that these condensation nuclei are called hygroscopic nuclei because these particles have affinity to water. Salt particles are most significant condensation nuclei because these have more affinity to water as electrically charged ions of salt particles attract more water molecules which are deposited around the particles during condensation process. On the other hand, terrestrial (of land) dust particles attract less water molecules and hence are less hygroscopic but may become effective hygroscopic nuclei when they are in large number and the air is supersaturated.

It is significant to mention that the air is never pure in nature because it is mixed with numerous impurities of natural as well as anthropogenic sources and therefore they (impurities) provide constant supply of hygroscopic nuclei. Consequently, condensation is a continuous process but it is not necessary that condensation will always produce precipitation on the ground surface because if the condensation is slow and weak, the resultant forms of condensation may be evaporated in the transit. It has been estimated that the atmospheric air contains about 1000 impurities per cubic centimeter volume of air over the land surfaces (over the continents) while the concentration of atmospheric impurities in the air over the ocean surfaces is much less (only 200 impurities per cubic meters of air volume). The continuous deposit of water molecules around hygroscopic nuclei through condensation results in the formation of water droplets for precipitation. The water droplets formed around larger hygroscopic nuclei are called **cloud droplets.** The aggregation of large number of cloud droplets forms clouds. These cloud droplets are so microscopic in size that they remain suspended in the air. Rainfall does not occur unless these cloud droplets become so large due to coalescence that the air becomes unable to hold them. This is why, sometimes the sky is overcast by thick clouds but there is no rainfall. The diameter of a raindrop is 5 mm and one raindrop contains about 8,000,000 cloud droplets. Raindrops fall down at the velocity 200 times greater than cloud droplets.

8.12 FORMS OF CONDENSATION

As mentioned above condensation of water vapour around hygroscopic nuclei results ultimately in the formation of water droplets. The forms of condensation vary considerably depending on a host of factors, namely the nature of moist air (*i.e.* the quantity of moisture-vapour in the air and level of saturation, whether the parcel of air is undersaturated, saturated or oversaturated depending on the percentage of relative humidity), rate and mode of cooling of ascending air (*e.g.* radiation cooling, contact cooling, or advection cooling), temperature of air, nature and rate of movement of air, turbulence in the air, nature and amount of hygroscopic nuclei, place of condensation etc.

Condensation occurs both (1) near the ground surface, and (2) up in the air above the ground surface.

1. Condensation Near the Ground Surface

The condensation of vapour of supersaturated air near the ground surface may be effected by radiation cooling, or contact cooling or advection cooling (the mechanisms of cooling of air have already been discussed in section 8.10). The ground level condensation occurs in several forms depending on local environmental conditions, of which climatically important are dew, frost, rime, mist, fog etc.

(1) **Dew :** refers to direct deposition of water vapour without hygroscopic nuclei on the surfaces of objects on the ground (like vegetation to mention) after condensation of moist air caused by

radiation and contact cooling of air lying above the ground surface. The necessary conditions for dew formation include high relative humidity, almost calm air with low wind velocity, suitable radiating surface, effective nocturnal (night time) radiation resulting into sufficient loss of heat from ground surface, clear skies so that nocturnal radiation (terrestrial outgoing longwave radiation during night) is not retarded etc. If a particular day receives rainfall during photoperiod, the night becomes cloudless (clear skies), and wind speed is very low (calm air), the loss of heat from the ground surface by nocturnal radiation makes it cool. Since there is sufficient moisture in the overlying air, it gets cooled because of its contact with underlying cool ground surface, the air is saturated and ultimately condensation occurs and water vapour is deposited on the leaves of vegetation and other objects to form dew. It may be mentioned that dew formation occurs when condensation takes place above freezing point of the saturated air. The temperature at which the condensation occurs in liquid form is called **dew point.** Conversely, cloudy sky (cloud covers obstruct outgoing longwave terrestrial radiation and hence keep the ground surface warm), windy weather (high wind speed causes mixing of air and taboos the air to reach saturation and condensation level-dew point), less moisture in the air etc. disfavour the formation of dew. This is why dew formation is more frequent during rainy season and winter season.

(2) **Frost** : is defined as transformation of gaseous form of water (water vapour) directly into solid form (the process being called sublimation) at the ground surface, in the soils and in the air layer just lying over the ground surface due to condensation occurring below freezing point. Frost is generally divided into two types, namely (i) ground frost, and (ii) air frost. **Ground frost** occurs when the cooling of ground surface and the air lying over it is not very much effective, consequently only thin layer of air in direct contact with the ground surface is cooled and reaches condensation level (dew point) below freezing point (less than 0^0C temperature) and hence the moisture in the soils is frozen. **Air frost,** on the other hand, occurs, when the entire air layer overlying the ground surface is cooled to such an extent that it reaches its dew point (condensation level) below freezing point and the moisture is frozen. When the vapour is directly transformed into ice (by the process of sublimation) which is deposited on roofs, grasses, pavements etc., it is called **hoar frost** wherein the ice crystals having silvery white colour look like jewels and are very attractive. When thin ice sheets as a result of frost formation are deposited on roads, the resultant frost is called **black ice** or **glazed frost.** When the drizzles or very light rains occur below O^0C temperature on the ground surface, they are frozen before reaching the ground surface and hence these are called as **freezing drizzle** and **freezing rain.** These are also called as **crachin.** Such frost generally causes deposition of thin ice over leaves and twigs of plants, telephone poles and wires etc. The frosts caused by cooling of ground surface and overlying air due to radiational loss of heat are also called **radiation frost.** Frosts are economically hazards as these damage orchards and such crops which have fibrous roots like potato, peas, oil seeds etc.

(3) **Rime** : 'is an opaque coating of tiny, white, granular ice particle, caused by rapid freezing of super-cooled water droplets on impact with an object' (Webster's Encyclopedic Unabridged Dictionary, p. 1658) below freezing point (below O^0C). Rime is deposited mainly on the edges and points of objects.

(4) **Mists and fogs** : are formed when condensation occurs above freezing point in the air lying just over the ground surface around tiny hygroscopic nuclei. Infact, mists and fogs are the form of suspended water droplets in the air which reduce visibility. The difference between mist and 'fog is related to the size of suspended water droplets. Mist is the suspension of microscopic water droplets that reduces visibility at the earth's surface. It forms fairly a thin grayish veil that covers the landscape. In contrast, fog is the suspension of very small water droplets in the air that reduces visibility to less than one kilometer' (J. E. Oliver and J.J. Hidore, 2003). The other difference between mist and fog is related to the weather conditions. For example, in fog there is damp and raw weather but in mist it is not so damp and raw. Since the size of water droplets in fogs is fariy larger than the droplets in mist and hence fog

droplets are visible but the mist water droplets are not visible. Mist is generally formed on wet surface in the evening and is evaporated with sunrise while fog develops in the night and continues late in the morning period. Some time it continues throughout the day, as happened in the Ganga plain during the winters of 2002-03, 2003-04 in North India. It may be mentioned that a mist becomes fog when it is intensified and visibility is further reduced. Mists and fogs are formed due to radiation, conduction and mixing of warm and cold air masses near the ground surface. Fogs will be further elaborated in the succeeding chapter 9.

2. Condensation Above the Ground Surface

The condensation of saturated air above the ground surface caused by adiabatic cooling of ascending moist air results in the formation of **clouds** which are defined as aggregates of innumerable tiny water droplets, ice particles or mixture of both in the air above the ground surface. Clouds are formed due to condensation of water vapour around the hygroscopic nuclei caused by cooling due to lifting of moist air and consequent expansion of volume, generally known as adiabatic cooling (see section 8.10 of this chapter). Meteorologically clouds are very significant because all forms of precipitation occurs from them. Clouds also play major roles in the heat budget of the earth and the atmosphere as they reflect, absorb, and diffuse some portion of incoming shortwave solar radiation and absorb some portion of outgoing long wave terrestrial (ground) radiation and re-radiate it back to the earth's surface. The clouds will be discussed in detail in the succeeding 9th chapter of this book.

3. Other Forms of Condensation

(1) **Snowfall :** The fall of larger snowflakes from the clouds on the ground surface is called snowfall. In fact, snowfall is 'perecipitation of white and opaque grains of ice'. The snowfall occurs when the freezing level is so close to the ground surface (less than 300m from the surface) that aggregations of ice crystals reach the ground without being melted in a solid form of precipitation as snow.

(2) **Sleet** refers to a mixture of snow and rain but in American terminology sleet means falling of small pellets of transparent or translucent ice having a diameter of 5 mm or less.

(3) **Hail** consists of large pellets or spheres of ice. In fact, hail is a form of solid precipitation wherein small balls or pieces of ice, known as hailstones, having a diameter of 5 to 50mm fall downward known as hailstorms. Hails are very destructive and dreaded form of solid precipitation because they destroy agricultural crops and claim human and animal lives.

(4) **Drizzle :** The fall of numerous uniform minute droplets of water having diameter of less than 0.5 mm is called drizzle. Drizzles fall continuously from low stratus cloud but the total amount of water received on the ground surface is significantly low.

8.13 STABILITY AND INSTABILITY OF THE ATMOSPHERE

Different forms of precipitation (dew, fog, rainfall, frost, snowfall, hailstorm etc.) depend on suitability and instability of the atmosphere. The air without vertical movement is called **stable air** while **unstable air** undergoes vertical movement (both upward and downward). An airmass ascends and becomes unstable when it becomes warmer than the surrounding airmass while descending airmass becomes stable. The stability and instability depend on the relationships between **'normal lapse rate'** and **'adiabatic change of temperature'**. Adiabatic rate (see section 8.10) is always constant whereas normal lapse rate of air temperature changes. When the normal lapse rate is higher than dry adiabatic rate, the air being warmer rises and becomes unstable. On the other hand, when the normal lapse rate of temperature is lower than dry adiabatic rate, the air being cold descends and becomes stable.

Stability : When dry adiabatic lapse rate of an ascending dry air is higher than the normal lapse rate and if it is not saturated and does not attain dew point it becomes colder than surrounding air at certain height with the result it becomes heavier and descends. This process causes stability of atmospheric circulation due to which vertical circulation of air is resisted. For example, at ground surface if the temperature of a parcel of air is 40°C, the dry adiabatic lapse rate and normal (environmental) lapse rate are 10°C per 1000 m and 6.5°C per 1000 m respectively, then at the height of one kilometre (or 1000 m) from the ground surface the temperature of the ascending air would be 30°C (40° - 10° = 30°C) while the temperature of surrounding air at that height would be 33.5°C (40°-6.5° = 33.5°C). Thus, the ascending air being colder than surrounding air would descend and atmospheric stability is caused. Such air (descending) is called to be in **stable equilibrium.** Some times, the normal lapse rate in a certain layer of the atmosphere is about 4.6°C per 1000 meters. In such conditions if the normal lapse rate is less than wet adiabatic lapse rate even at condensation point, further vertical motion of air is stopped and thus such air is said to be **absolutely stable** and such atmospheric condition is called **absolute stability.**

Instability : When normal lapse rate is greater than dry adiabatic lapse rate of ascending parcel of air, the rising air continues to rise upward and expand and thus becomes **unstable** and is in **unstable equilibrium.** In other words, atmospheric instability is caused when the rate of cooling of rising air (dry adiabatic lapse rate) is lower than the normal lapse rate. For example, if the temperature of a certain parcel of air at ground surface is 40°C, the dry adiabatic and normal lapse rates are 10°C and 11°C per 1000 m respectively, then the temperature of ascending air at the height of 1000m (one kilometer) would be 30°C (40°-10° = 30°) while the temperature of the atmosphere at that height would be 29°C (40°-11°C = 29°C). Thus, the rising air being warmer (30°C) than the surrounding air (29°C) continues to rise and expand to cause atmospheric instability. If the wet adiabatic lapse rate is also less than normal lapse rate, the rising air further continues to rise upward. Such state of continued upward movement of air is called **absolute instability.** When the ascending parcel of air reaches such height that its temperature equals the temperature of surrounding air, its further upward movement is stopped. Such air is said to be in the state of **neutral equilibrium.**

Mechanical Instability : Some times, there are abnormal conditions when normal lapse rate is exceptionally very high (15° to 35°C per 1000 metres). In such condition the upper layers of the atmosphere become exceptionally cold and denser than the underlying layers, with the result cold and denser upper layers automatically descend. Such situation is called mechanical instability which helps in the formation of tornadoes.

Conditional Instability : When a parcel of air is forced to move upward, it cools at dry adiabatic lapse rate (10°C per 1000 m or 5.5°F per 1000 feet) whereas normal lapse rate is 6.5°C per 1000 m. After rising to certain height the air becomes saturated and latent heat of condensation is added to the rising air so the rising air cools at wet adiabatic lapse rate (5°C per 1000 m) whereas the normal lapse rate (6.5°C per 1000 m) is greater than it. Consequently, the air becomes warmer than the surrounding air and hence rises upward automatically. This is called conditional instability because the air is initially forced to move upward but rises automatically due to its own properties after condensation point is reached. For example, if a parcel of air with 35°C temperature is initially forced to rise upto the height of 1000 m, its temperature decreases to 25°C (35°C-10°C, dry adiabatic rate = 25°C) whereas the temperature of surrounding layers of air at the height of 1000 m would be 28.5°C (35°C-6.5°C, normal lapse rate) and thus the rising air becomes colder by 3.5°C than the surrounding air. If the rising air gets saturated at this temperature (25°C), the latent heat of condensation returns back to the rising air and hence it cools at the wet adiabatic lapse rate (5°C per 1000 m). Thus, the rising air becomes warmer and unstable. Conditional instability may occur only when the normal lapse rate ranges between dry adiabatic and wet adiabatic lapse rates. In other words, conditional instability occurs when normal lapse rate is greater than dry adiabatic lapse rate but less than wet adiabatic lapse rate.

The above mentioned stability and instability conditions of the atmosphere may be briefly summarized as follows :

1. The column of air is in **stable equilibrium,** when dry adiabatic lapse rate of an ascending air is higher than the prevailing normal lapse rate (environmental lapse rate) *i.e.* when el.< dra.;

2. The column of the air is in **absolute stable condition** when environmental lapse rate (prevailing lapse rate) is less than wet (moist) adiabatic rate even at condensation point *i.e.* el < ma.
3. The column of the air is in **unstable equilibrium** condition when environmental lapse rate is greater than dry adiabatic lapse rate *i.e.* el.> dra.
4. The column of the air is in **neutral equilibrium** condition when environmental lapse rate and dry adiabatic lapse rate are equal *i.e.* el. = dra.
5. The column of the air is in **conditional unstable** state when the environmental lapse rate is greater than the moist (or saturation or wet) adiabatic rate *i.e.* el> ma.

where el = environmental (normal or prevailing) lapse rate (6.5^0C/1000 metrs)

dra = dry adiabatic lapse rate (10^0C/1000m)

ma = moist (or saturation or wet) adiabatic lapse rate (5^0C/1000m)

Potential Instability : Some time extensive and thick air mass undergoes differential rate of adiabatic changes of its temperature because of variation in moisture condition of its upper and lower parts. For example, if the upper part of the air mass is dry while its lower part is moist and is bodily lifted upward either by mountain barriers or cyclonic front, the rate of decrease of temperature becomes different in its upper and lower parts, *i.e.* the upper part of the rising airmass cools at dry adiabatic rate while the lower part cools at moist adiabatic rate, the lower part, after certain ascent, is saturated, and latent heat of condensation is added to the air which retards the rate of cooling. This differential cooling of different parts of ascending air mass causes anomaly in temperature distribution in the airmass which changes the stable condition of air mass into unstable condition which is called **potential instability** or **convective instability**.

8.14 ATMOSPHERIC STABILITY AND WEATHER

The conditions of atmospheric stability and instability control day to day weather conditions in terms of dry or moist weather. As is apparent from the aforesaid discussions on different types of atmospheric stable (equilibrium) and unstable (inequilibrium) conditions, the atmospheric stability disfavours vertical movement in the air and hence resists saturation of air and condensation rather causes dry weather. On the other hand, instability of the atmosphere causes wet weather. This requires further explanation.

The stability of the atmosphere is caused mainly by inversion of temperature wherein warm air overlies cold air, and by mechanicl process wherein air descends *e.g.* under anticyclonic condition. The stability of the atmosphere stops vertical movement of air and hence does not allow mixing of air and moisture. In the absence of vertical movement of air *i.e.* no ascent, the air is not saturated and hence condensation does not occur and there is no cloud formation. Some time, the stable air is forced-uplifted by orographic (mountain) obstruction resulting into saturation of air and formation of thin clouds producing light drizzle and overcast sky. It may be pointed out that if a day is characterized by overcast sky but light drizzle, one should infer that the stable air has been forced to ascend. Atmospheric stability due to inversion of temperature also causes dense fogs if the overlying warm air is moist and underlying cold air is dry. Since there is no vertical mixing between the overlying warm air and underlying cold air, most of the pollutants mainly emitted from anthropogenic sources (from automobiles, combustion of fossil fuels in the factories, domestic uses of firewood etc.) are concentrated in the lower layer which causes health hazards of various sorts.

On the other hand, atmospheric instability favours vertical movement of air which is cooled on expansaion and ascent and is ultimately supersaturated resulting into condensation and cloud formation. The clouds so formed are thick and cumulonimbus which yield heavy downpour. It is apparent that the formation of cumulonimbus clouds and heavy showers therefrom are indicators of atmospheric instability. It may be concluded that movement of air and day to day changes in temperature and forced uplift or downlift of air are important factors which determine the stability or instability of the atmosphere which in turn determines whether the day to day weather will be dry or wet respectively. The surface radiational heating causes steep lapse rate of temperature which causes ascent of the air and makes the air unstable, while surface cooling due to radiation loss of heat causes low lapse rate which favours descent of air and makes it stable. The forced ascent of air by frontal convergence also causes instability.

8.15 IMPORTANT DEFINITIONS

Absolute humidity : The total weight of moisture content (water vapour) per volume of air at definite temperature and point of time is called absolute humidity, generally expressed in gram per cubic meter volume.

Adiabatic lapse rate : The rate of change of temperature of ascending or descending air is called adiabatic lapse rate which is 10^0C per 1000 meters before dew point (condensation level) and 5^0C per 1000 meters after dew point.

Adiabatic process : Adiabatic process refers to change of temperature of an ascending air (due to expansion of volume) or descending air (due to contraction of volume), the former (expansion) causes cooling of air while the latter (contraction) causes warming of air (at the rate of 10^0C per 1000 meters).

Convective instability : The change of stable condition of air into unstable condition due to cooling of upper and lower parts of thick airmass (having upper moist layer and lower dry layer) at different rates is called **potential instability** or convective instability of the atmosphere, which requires lifting of airmass either by mountain barrier or by cyclonic frontal activity.

Condensation : The process of conversion of water vapour into liquid (water) and solid form (ice, snow, frost) is called condensation. Alternatively, the transformation of gaseous form of water and ice (water vapour) into liquid (water) and solid forms (ice) is called condensation.

Dew : Dew refers to direct deposition of water vapour in the form of water without hygroscopic nuclei on the surfaces of objects on the ground (*e.g.* vegetation) after condensation of moist air caused by radiation and contact cooling of air lying over the ground surface.

Dew point : The temperature, at which the given air is saturated *i.e.* the humidity holding capacity and absolute humidity of a given volume of air at given temperature and point of time become equal is called dew point.

Diabatic process : Diabatic process is the change of temperature and cooling of air without vertical movement of air and without change of the amount of water vapour (either addition or subtraction) and volume of the air. The diabatic process of coloing of air involves loss of heat through radiation, conduction or mixing of a given parcel of air with colder air.

Dry adiabatic rate : The increase of temperature of a descending air or decrease of temperature of an ascending air at the rate of 10^0C per1000 meters of altitude before dew point is reached is called dry adiabatic rate or dry adiabatic lapse rate.

Environmental lapse rate : The decrease of temperature of air at the average rate or 6.5^0C per 1000 meters of altitude is called **normal lapse rate** or environmental lapse rate.

Evaporation : The process of transformation of liquid (water) into gaseous form (water vapour) is called evaporation.

Evapotranspiration : The processes of loss of water from soils through evaporation, loss of water from the surfaces of plant leaves through evaporation and loss of water from plant leaves through transpiration are collectively called as evapotranspiration.

Frost : Frost is defined as transformation of gaseous form of water (water vapour) directly into solid form through the process of sublimation at the ground surface, in the soils, and in the air layer just lying over the ground surface due to condensation occurring below freezing point.

Frost point : The temperature at which condensation occurs (always below freezing point *i.e.* below 0°C) is called frost point or **frost point temperature.**

Freezing rain : The drizzles or light rains occurring below 0°C temperature and being frozen before reaching the ground surface are called freezing drizzles or freezing rains.

Glazed frost : The thin ice sheets as a result of frost formation deposited on roads are called **black ice** or glazed frost.

Hail : Hail is a form of solid precipitation consisting of large pellets or spheres of ice balls having a diameter of 5 to 50 mm known as hailstones, the fall of which on the ground surface is **called hailstorm.**

Hoar frost : The direct transformation of water vapour into ice and its deposition on roofs, grasses, pavements etc. is called hoar frost wherein the ice crystals having silvery white colour look like jewels and are very attractive.

Humidity capacity : The moisture retaining capacity or simply humidity capacity refers to the capacity of a parcel of air having certain volume at certain temperature and point of time to retain or hold maximum amount of moisture content. It is directly proportional to air temperature.

Hydrological cycle : The hydrological cycle refers to a model of exchange of water over the surface of the earth from the oceans via atmosphere, continents, and back to the oceans.

Latent heat : The heat energy spent during the evaporation of water and its conversion into water vapour is called latent heat (hidden in the water vapour).

Latent heat of condensation : The release of heat energy after condensation of water vapour into liquid or solid form is called latent heat of condensation.

Latent heat of fusion : The amount of heat required (79-80 cal.) to transform one gram of ice into water is called latent heat of fusion.

Latent heat of sublimation : The amount of heat required (680 cal) to transform one gram of ice directly in to gaseous phase (water vapour) is called latent heat of sublimation.

Latent heat of vapourization : The amount of heat required (540-607 cal) to transform one gram of water into gaseous phase (water vapour) is called latent heat of vapourization.

Moist adiabatic rate : The decrease of temperature of an ascending air at the rate of 5°C per 1000 meters of height after condensation of moist air is called moist adiabatic rate or simply **retarded adiabatic rate** or **saturation adiabatic rate.**

Mixing ratio : The ratio of weight (mass) of water vapour to the weight of per unit volume of dry air is called mixing ratio while the concentration of maximum amount of water vapour in a dry air of certain volume and mass (weight) is called saturation mixing ratio.

Neutral equilibrium : When the ascending parcel of air reaches such height that its temperature equals the temperature of surrounding air, its further upward movement is stopped. Such air is said to be in the state of neutral equilibrium.

Potential evapotranspiration : Potential evapotranspiration is an index of thermal efficiency and water loss because it represents the amount of transfer of both moisture and heat to the atmosphere from soils and vegetation and thus is a function of energy received from the sun.

Relative humidity : Relative humidity is defined as a ratio of the amount of water vapour actually present in the air having definite volume and temperature (*i.e.* absolute humidity) to the maximum amount the air can hold (humidity capacity) at that volume and temperature.

Rime : 'Rime is an opaque coating of tiny, white, granular ice particles, caused by rapid freezing of super cooled water droplets on impact with an object.'

Saturated air : The parcel of air with definite volume at given temperature at given moment of time having moisture content equal to its humiity capacity is called saturated air.

Saturation deficit : The difference between the moisture retaining capacity (humidity capacity) and actual humidity (absolute humidity) of a given volume of an air at given temperature and moment of time is called saturation deficit.

Sleet : Sleet refers to a mixture of snow and rain but in American terminology sleet means falling of small pellets of transparent or translucent ice having a diameter of 5 mm or less.

Specific humidity : Specific humidity is defined as the mas of water vapour in grams contained in one kilogram of moist air. 'In fact, specific humidity is a ratio of water vapour to the weight of moist air.'

Stable equilibrium : A column of air is said to be in stable equilibrium when dry adiabatic lapse rate of an ascending air is higher than the prevailing normal (environmental) lapse rate.

Sublimation : The process of transformation of solid (ice) directly into gaseous form (water vapour) by the use of heat energy is called sublimation.

Transpiration : The loss of water from living plants on land surfaces is called transpiration.

Vapour pressure : Vapour pressure refers to the pressure exerted by water vapour of a given parcel of air. In fact, vapour pressure represents the part of the total atmospheric pressure contributed by the amount of water vapour present in the atmosphere.

9

FOGS, CLOUDS AND PRECIPITATION

9.1 FORMS OF CONDENSATION

The transformation of gaseous form of water (water vapour) into solid form, when the dew point is below freezing point, and liquid form, when dew point is above freezing point (*i.e.* above 0^0C temperature of the air), is called condensation. It is, thus, evident that condensation is opposite to evaporation where the heat energy (latent heat) is released to the atmosphere as latent heat of condensation in the former, while heat energy is used in the latter. The process and mechanism of condensation depends on the percentage of relative humidity of the air. The air having cent per cent relative humidity is called **saturated air**. An air may become saturated in two ways *e.g.* either the absolute humidity of a given volume of air at a given temperature is raised to equal the humidity retaining capacity of that air or the temperature of that air is reduced to such an extent (*i.e.* the air is cooled) that the humidity capacity becomes equal to its absolute humidity. The temperature at which an air becomes saturated and condensation begins is called its **dew point**. It may be pointed out that condensation will begin only when the air is supersaturated *i.e.* if the relative humidity exceeds 100 per cent, and this can be achieved only when the air is further cooled by adiabatic rate of cooling. If dew point is above freezing point (above 0^0C), condensation will occur in liquid form (*e.g.*. dew, fog, rainfall etc.) but if dew point is below freezing point, condensation occurs in solid form (*e.g.* frost, snow, ice, hailstorm etc.)

The various forms of condensation near the ground surface and above the ground surface include dew, frost, rime, mist and fog, clouds, snowfall, sleet, hail, drizzles, rainfall etc. The minor forms of condensation other than major forms (*e.g.* fogs, clouds and rainfall) have been briefly explained in the preceding 8th chapter. This chapter includes the detailed discussion on fogs, clouds and precipitation mainly rainfall in the following sections.

It may be mentioned that at the first glance fogs and clouds appear to be similar at least in their appearance and structure to general public but to a climatologist and meteorologist these two weather phenomena are quite different as regards visibility, the place and mechanism of their formation. As mentioned in the preceding chapter the formation of both (fogs and clouds) requires cooling of air and consequent attainment of saturation level and dew point for condensation. The cooling of air in the formation of fogs is accomplished through radiation and advection cooling while for cloud formation adiabatic cooling (discussed in chapter 8 of this book) caused by vertical lifting of air and consequent increase in volume of ascending air due to expansion is required. Fogs are formed near the ground surface in the night and morning period while clouds are formed above the ground at reasonable height and at any time of a day (both night and photoperiod).

9.2 FOGS : MEANING AND CHARACTERISTICS

Fog is special type of thin cloud consisting of microscopically small water droplets which are kept in suspension in the air near the ground surface and reduces horizontal visibility. According to Byers fog is defined 'as almost microscopically small water drops suspended in the atmosphere and reducing the horizontal visibility to less than one kilometer.' It may be pointed out that coulds are formed due to ascent, expansion and cooling of air while fogs are formed due to radiation, conduction and mixing of warm and cold air masses near the earth's surface.

Fog is formed when the moist air (with relative humidity above 97 per cent) becomes saturated, reaches its dew point and further cools (but above freezing point) so that water vapour is condensed around dust particles, smokes etc. to form tiny water droplets which being very light are suspended in the air. These microscopically tiny water droplets form smoky clouds which fly with the winds. Invisibility increases as the fog becomes dense and there is darkness when the fog becomes extremely dense. A light fog, called as **mist**, is that when visibility is restricted to 2 kilometres. Fog is generally associated with inversion of temperature and occurs in the morning hours but some times also continues till noon. Fog occurs during winters in subtropical regions but it occurs in all seasons in the regions beyond 35^0 latitudes. Generally, fog looks whitish in colour but over large cities and industrial areas it looks dirty yellow or gray because of mixing of smoke, dust and fly ash.

Somky fog over the cities and industrial areas is generally called as **smog** or **urban smog**. Smog is generally formed when fog is mixed with smoke. When smog is mixed with air pollutants such as sulphur dioxide (SO_2), oxides of nitrogen (NOx) and ozone (O_3), it becomes poisonous and deadly health hazard to human beings. Sulphur dioxide is the main culprit in the formation of smog. It readily combines with atmospheric oxygen (O_2) and reacts with water films on suspended particulate matter (SPM) to produce sulphuric acid (H_2SO_4). This sulphuric acid after combining with smog makes it poisonous. Nitrous Oxide (N_2O) forms nitric acid (HNO_3) which also makes smog poisonous. Ozone after reacting with hydrocarbon compounds forms some toxic compounds such as ethylene which is a common pollutant in urban smog. It maybe pointed out that these air pollutants (sulphur dioxide, nitrogen oxides, ozone etc.) are trapped in a shallow layer over the cities caused by inversion of temperature (warmer air over cooler air) and thus are mixed with fog over the cities and industrial areas. The resultant fog having poisonous air pollutants is called urban smog and is highly undesirable weather phenomenon for human society.

The incidents of deadly urban smogs of December 1930 in Meuse Valley of Belgium, of October 26, 1948 at Donora in Pennsylvania (USA) and of 1952 in London tell the ordeal of air pollution causing poisonous smogs. The poisonous smog of December 1930 of Meuse Valley of Belgium was caused due to trapping of huge volume of sulphur dioxide emitted from coke ovens, steel mills, blast furnaces, zinc smelters and sulphuric acid plants into a stagnant cold air layer, the result of inversion of temperature. This poisonous fog caused respiratory trouble in human beings, consequently 600 people fell ill and 63 people died. The five-day health disaster of Donora, Pennsylvania (USA) was preceded by the formation of thick fog due to strong inversion of temperature on October 26, 1948. The next day fog thickened and combined with sulphide fumes and soot spewed from mills and became a poisonous urban smog which claimed 20 human lives and 43 per cent of the total population of Donora became ill. A thick polluted fog, urban smog, was formed in December 1952 over London which claimed 4000 human lives mostly through respiratory diseases.

9.2.1 CLASSIFICATION OF FOGS

Fogs have been classified variously by different scientists on different bases *e.g.* physical processes of fog formation, evaporation and cooling mechanism, applied aspect such as practical applications in weather forecasting etc. The important schemes of classification of fogs include those of H.C. Willett (1928), H.R. Byres (1944), H.J. Chritchfield, G. T. Trewartha, George etc. which are mentioned as follows:

1. H.C. Willett's Classification

H.C. Willett presented his scheme of fog classification in 1928 on the basis of physical processes of the formation of fogs. He classified fogs into two broad categories as follows :

(A) Airmass fogs

(B) Frontal fogs

It may be mentioned that Willett's two-tier classification was further elaborated in subsequent classifications of fogs.

2. H.R. Byers' Classification

Boyers modified and elaborated the classification of fogs of Willett and presented his scheme in the year 1944. It may be mentioned that Byers subdivided Willett's airmass fogs into two broad subcategories *e.g.* advective types of fogs and radiation types of fogs on the basis of methods of cooling of moist air which have been further subdivided into 6 types besides two special types of fogs *e.g.* advection-radiation fogs, and upslope fogs as given below:

(A) Airmass fogs

(1) Advective types :

(a) fogs due to transport of warm air over a cold surface

(i) land and sea breeze fogs

(ii) sea fogs

(iii) tropical fogs

(b) fogs due to transport of cold air over a warm surface

(iv) steam fog or arctic sea smoke

(2) Radiation types :

(a) ground fogs

(b) high inversion fogs

(3) Aadvection-radiation fogs

(4) upslope fogs

(B) Frontal fogs

(1) prefrontal fog or warm frontal fog

(2) post-frontal or cold frontal fog

(3) front passage fog

3. Critchfield's Classification

H.J. Critchfield classified fogs in two broad categories on the basis of processes of evaporation and cooling, which are the principal processes that cause saturation of moist air to form fogs of various types. These two broad categories have been further subdivided into 7 subtypes as follows :

(1) **Fogs resulting from evaporation**

(a) steam fog

(b) frontal fog

(2) **Fogs resulting from cooling**

(a) ground or radiation fog

(b) advection fog

(c) upslope fog

(d) mixing fog

(e) barometric fog

4. G.T. Trewartha's Classification

The scheme of classification of fogs of G.T. Trewartha is also based on Willett's scheme. Trewartha's classification of fogs is, in fact, a modified and simplified scheme of Willett.

(A) **Intra-airmass fogs**

(1) **Radiation fogs**

(a) ground radiation fog (due to simple radiation and conduction cooling of relatively moist air lying over a chilled land surface).

(b) high inversion fog (due to inversion of temperature at the height of 400 to 2000 feet above mean sea level)

(2) **Advection-radiation fogs**

(due to transport of warm moist air over cold surfaces but the loss of heat is due to radiation)

(a) sea fog (when warm moist air maves over relatively colder sea surfaces)

(b) land fog (when moist warm air moves over the colder surfaces of land during winters)

(c) inland fog (when warm moist air moves over colder surfaces of inland water bodies)

(d) moist tropical air mass fog (when warm moist tropical air mass is transported poleward over a cooler surface mainly in middle latitudes)

(B) **Frontal fogs**

1. **warm frontal fogs**

   (due to forced ascent of warm moist air caused by convergence of two contrasting airmasses—warm and cold)

2. **Cold frontal fogs**

   (due to saturation of cold surface layer of air by rainfall from the overrunning warm air aloft)

5. George's Classification

George presented a simplified scheme of fog classification on the basis of applicability of fogs in weather forecasting but he also considered the significance of physical processes which are responsible for the formation of fogs while classifying them. He identified 5 principal types of fogs as follows :

1. prefrontal fog or warm front fog
2. post-frontal fog or cold front fog
3. advection fog
4. radiation fog
5. radiation-advection fog

6. Classification Based on Visibility

Fogs are classified into four main types on the basis of intensity and visibility as follows :

1. light fog (visibility upto 1100 meters)
2. moderate fog (visibility 1100m-550m)
3. dense fog (visibility 550m-300m)
4. intense dense fog (less than 300m)

7. Classification Based on Characteristic Features

The fogs having unique characteristic features are identified by different names. Thus, on the basis of uniqueness in appearance fogs are named as follows.

1. **general fog** (*i.e.* common fog)
2. **smog or urban smog** (mainly over the polluted urban and industrial areas, these become poisonous and deadly when mixed with sulphur dioxide, the smog over London is called **pea-soup fog**)
3. **smaze** (when fog is mixed with smoke and haze)
4. **frost-smoke** (such fogs comprise numerous ice crystals and super cooled water droplets, such fog is locally known as **pogonip** in the mountains of the USA)
5. **cheyenne fog** (upslope fog in the valleys of S.E. Wyoming State of the USA is named as **cheyenne**)

8. Classification Based on Fog Forming Processes

(1) **Cooling processes**

(a) radiation fog

(b) advection fog

(i) land fog

(ii) sea fog

(iii) advection-radiation fog

(c) valley fog

(d) upslope fog

(2) **Evaporation process**

(a) frontal fog

(i) warm front fog

(ii) cold front fog

(b) precipitation fog

(c) steam fog

(3) **Anthropogenic activities**

(a) smog or urban smog

(b) smaze fog

9.2.2 ORIGIN AND CHARACTERISTIC FEATURES OF FOGS

1. Radiation fog

Radiation fog is formed when warm and moist air lies over cold ground surface. Due to this situation overlying warm and moist air cools and thus dew point is reached, with the result condensation of water vapour around hygroscopic nuclei (dust particles and smokes) forms numerous tiny water droplets and thus fog is originated. The occurrence of radiation fog requires certain conditions *e.g.* long and cool winter nights, cloudless sky, sufficient amount of moisture in the air, very weak air motion (light wind having speed of 3 to 5 km per hour) and ground inversion of temperature. Fog is formed at the ground surface during nights and thickens upward. It disappears in the morning with the sunrise because the water droplets are evaporated due to rise in air temperature. Radiation inversion occurs only on land surface. Radiation fog is more common over large cities and surrounding areas because of abundance of hygroscopic nuclei. When fog is combined with sulphur dioxide it becomes poisonous and causes human deaths. Such fog is called **urban smog.** Some times, fogs also occur at higher elevation due to upper air inversion of temperature. Such fog is called **high inversion fog.**

The disappearance of fogs is called '**lift**' or '**burn off**' because the evaporation of microscopic tiny water droplets first begins at the ground surface because solar rays first warm up the ground surface. The evaporation procedes upward untill the entire fog layer disappears. This is called radiation fog because the cooling of air is accomplished through loss of heat by radiation from the ground surface.

2. Advectional Radiation Fog

The fog formed due to mixing of warm moist air and cold air due to arrival of warm and moist air over cold ground surface is called advectional radiation fog. There are certain necessary conditions for the origin of advection radiation fog. *e.g.* (i) horizontal movement of air, (ii) greater contrast between air temperature and the temperature of ground surface, (iii) moist air or say high relative humidity in the air, (iv) stable stratification in the atmosphere etc. The warm and moist air when blows over cold surface (either land surface or sea surface) is cooled from below so that dew point is reached and condensation of water vapour occurs around hygroscopic nuclei and thus miscroscopic water droplets are formed to create fogs. Advection fogs are generally originated during winters on land surfaces and during summers on sea surfaces because lands are relatively colder than seas and oceans during winters. Dense advectional fogs are also formed where cold and warm ocean currents converge. For example, dense fogs are formed near Newfoundland due to convergence of cool Labrador and warm Gulf Stream ocean currents. Similarly, dense fogs are formed near Japanese coast due to convergence of cool Kurile and warm Kuroshio currents. The fogs occurring over sea surfaces are called **sea fogs** which are generally formed near the coastal areas frequented by cold ocean currents. For example, cool California current (along the Californian coast), cool Peru current (along the Peruvian coast), cool Benguela current (along the western coast of South Africa) and cool Western Australian current cause sea fogs. The sea breezes transport sea fogs inland upto the distance of 400 km.

3. Steam Fog

Steam fogs are, in fact, advectional fogs which are formed when cold air moves from land over oceanic surface and there is evaporation of large quantity of moisture from water surface to saturate the overlying cold air. It is interesting to note that in such situation overlying cold air is warmed from below and thus water vapour due to evaporation of warm water surface rises upward and condenses after meeting cold air above to form fog. The vapour particles above the water surface look as if steam is coming up from the water. This is why such fogs are called steam fogs. They are also called **evaporation fogs.** Dense and extensive steam fogs produced in the Arctic regions during winter season, are called **arctic sea smoke.**

4. Upslope fog

Upslope or hill fogs originate when continental warm and moist air rises upslope along the hillslopes because the rising air is saturated due to cooling and condensation of moisture around hygroscopic nueclei and forms fogs which cover the lower segments of hillslopes. It may be mentioned that such fogs are formed due to adiabatic expansion and cooling of moist air. Such fogs are very common on the hillslopes in temperate regions. They may occur in any season. The necessary conditions required for the formation of upslope fogs include enough cool and moist air, vertical movement of air, radiational and adiabatic cooling, and high relative humidity. As the cool and moist air ascends along the slopes of hills and mountains, it expands and cools enough at the dry adiabatic rate and reaches saturation level (dew point) soon. It may be mentioned that since the moist air is initially cool and hence requires little ascent to become saturated. Such type of fog in the mountainous areas looks like thin cloud. Such fogs are very common along the eastern slopes of the Rockies where moist air coming from over the Gulf of Mexico produces such fogs in the Great Plains of the USA. In southeastern Wyoming State of the USA upslope fogs are known as **cheyenne fog.**

5. Tropical Airmass Fog

Tropical airmas fogs are produced over the sea surfaces in the middle latitudes when the tropical moist airmass moves poleward. The cooling of the air occurs in the transit as the warm moist air moves from warmer areas to the colder areas. Such fogs are very common in the Gulf of Alaska, Aleutian islands, eastern parts of the North Atlantic bordering western European coastal areas. The tropical airmass fogs cover large and extensive areas because they are associated with extensive tropical airmass. Such fogs are also accompanied by mist and drizzle. The tropical airmass fogs are also formed over land areas during winter season, for example, in north central USA where the tropical airmass is drawn northward over snow covered surface during winter season. The tropical warm air masses are drawn by winter cyclones in the area mentioned above.

6. Frontal Fogs

The fogs produced along the warm and cold fronts of temperate cyclones are formed due to cooling of overlying warm and moist air by underlying cool air. It may be mentioned that fronts are formed when two contrasting airmasses (warm and cold airmasses) converge along a line. Warm air being lighter is pushed upward by heavier cold air and hence overlying warm air is chilled from below due to underlying cold air resulting into the saturation of warm air and its condensation to form fogs. Such fogs are formed in middle latitude temperate regions. In fact, the saturation and condensation of overlying warm and moist air causes rainfall which saturates the underlying cold surface air and after the passage of cyclones and sky becoming clear of clouds fogs are produced. Such fogs are formed in north India during winter after the precipitation occurring from western disturbances. Such fogs become extensive and more persistent. These fogs when mixed with anthropogenic pollutants, become very thick and dense and persist for weeks together, for example the extensive and dense fogs in the winters of north India during 2002-2003 and 2003-04 became so persistent that they continued upto 3rd week of January. They became so dense and severe that the trees shed their leaves and presented deserted and tattered appearance. Frontal fogs are further classified into two subtypes *e.g.* (i) pre-frontal or warm front fogs, and (ii) post-frontal or cold front fogs.

9.2.3 WORLD DISTRIBUTION OF FOGS

After the aforesaid discussion of origin and characteristic features of several types of fogs it is clear that fogs are formed in certain places and at definite time period where favourable conditions for the fog producing processes are more frequent.

This is why fogs vary in both time and space *i.e.* there is spatial and temporal variation in the world distribution of fogs.

If the world distribution of fogs is considered in spatial context, it becomes apparent that they are more widespread and frequent over oceans. The sea fogs are generally advectioanl in origin because relatively warm air coming from over the land surfaces produces fog over relatively colder oceanic surface. Foggy areas are positively related to cool ocean currents mainly when they meet warm ocean currents. The eastern portions of oceans and western continental margins are characterized by frequent fogs because these areas are influenced by cool ocean currents (*e.g.* California current, Western Australia current, Peru current, Beneguela current, Canary current etc.). Frontal fogs are produced in middle and high latitudes areas due to convergence of cold polar airmass and warm westerlies mainly over the eastern North Atlantic Ocean and western coasts of north-west Europe and over the eastern north Pacific Ocean near Aleutian Islands and Alaska coast. Radiation fogs are produced in low latitudes on continental areas during winter season. Dense fogs are formed where cold and warm ocean currents converge *e.g.* near Newfoundland and Grand Bank (due to convergence of cold Labrador current and warm Gulfstream) and near Japanese coasts (due to convergence of cold Kurile current and warm Kuroshio current). Advection fogs are most widespread and frequent world over.

North America : The foggiest places of North America include north-east coastal areas from the State of Maine of the USA to Newfoundland and Grand Banks where advectional dense fogs are produced due to convergence of warm Gulfstreams and cold Labrador current. The warm and moist air coming from over the warm water of the Gulfstreams is cooled and saturated over cold water of Labrador current and after condensation dense fog is produced. The other foggy areas of North America include (1) **Aleautian islands and Alaska coastal areas** (fogs formed due to advectional cooling of warm air coming from over the warm North Pacific Drift after coming in contact with cold air of cool Bering current) where fogs are produced during summer season from March to September; (2) **Californian coastal areas, where** advectional fogs are produced due to cooling of warm air coming from over the Pacific Ocean after its contact with cold upwellig water along the California coasts, fogs are generally produced during summer season from March to September; (3) **Eastern slopes of the Rocky mountains,** in the western Great Plains and eastern slopy areas of the Rockies extending from Texas to Wyoming (USA) upslope fogs are produced due to adiabatic cooling of warm air coming from over the Gulf of Mexico, the State of Wyoming is most frequented by upslope fogs where these are known as **Cheyenne fog** on the basis of Cheyenne located in Wyoming; (4) **Applachian valleys,** where advection—radiation fogs are produced when warm air coming from over the Gulf of Mexico is cooled and saturated; (5) **Great Lakes,** where radiation, steam, and frontal fogs are produced; (6) other foggy areas include Atlantic and Gulf coastal areas, valley zones of the Ohio, the Missouri and the Mississippi rivers mainly lower valleys, upper Mississippi valleys, west coasts of Canada, Great Plains of the USA etc.

Europe : The western coastal areas *i.e.* the north-western Europe and islands are more frequented by fogs of multiple origin. The warm air coming from over the warm North Atlantic Drift produces advectional fogs in the coastal areas of the north-western Europe after its cooling and saturation by relatively colder ocean surfaces. The western Europe is also characterized by tropical airmass fogs, and frontal fogs associated with warm and cold fronts of temperate cyclones. The other foggy areas include British Isles, Baltic Sea area, Mediterranean Sea and interior eastern Europe. The industrial areas of Europe are frequented by poisonous urban smogs due to mixing of industrial and urban pollutants mainly sulphur dioxide with normal fogs. The most adversely affected areas by urban smogs are London areas, Rhur valley, Saar Basin, Meuse Valley etc.

The incidents of deadly urban smogs of December 1930 in the Meuse Valley of Belgium, and of 1952 in London tell the ordeal of poisonous urban smogs caused by air pollution effected by human activities. The poisonous smog of December 1930 of the Meuse Valley was produced due to trapping of huge volume of sulphur dioxide emitted from coke ovens, steel mills, blast furnaces, zinc smelters and sulphuric acid plants into stagnant cold air layer, the result of inversion of temperature. The poisonous fog caused respiratory trouble in human beings, consequently 600 people fell ill and 63 people died. A thick polluted fog, urban smog, was formed in December 1952 over London which claimed 4000 human lives mostly through respiratory diseases.

Asia : The eastern coastal areas of Asian continent and island groups like those of Japan, Philippines, etc. are more frequented by summer fogs. The east coasts of Japan are characterized by dense advection fogs due to convergence of cold Kurile current and warm Kuroshio current. Infact, a long coastal and oceanic stretch extending from Bering Sea upto East China Sea is affected by summer fogs. Steam fogs are originated during winter season. Advection-radiation fogs are produced in Japan due to cooling and condensation of warm moist air coming from over the warm Japan current. North India mainly the Ganga Plains are frequented by light to dense fogs of frontal type, inversion type and radiation cooling type. The winter rains are succeeded by the formation of dense fogs which sometime continue from December to January. The fogs are intensified due to mixing of pollutants with normal fogs and are dissipated only after rainfall occurs. The hazardous fogs of 2002-03 and 2003-04 continued from December 20 to January 25 over the Ganga Plains including Punjaba, Haryana, Delhi and Uttar Pradesh.

South America : The Peruvian and Chilean coasts are considered to be the foggiest area of the world, where most of the fogs originate over cold Peru current and spread out eastward to cover the coastal areas of Peru and Chile. The western portion of South Atlantic Ocean and the coastal areas of Argentina are frequented by advection-radiation fogs due to convergence of warm Brazil current and cold Falkland current. Sea fogs are also formed along the coasts of Patagonia, Tierra del Fugo and Falkland islands. The valleys of the western coastal plains are characterized by radiation ground fogs.

9.2.4 EFFECTS OF FOGS

Fogs effectively hinder sea navigation, land and air transport systems. Dense fogs cause severe accidents on high-speed highways involving collision of trucks, buses, cars etc. Landing and take-off of aircrafts are delayed by dense fogs causing economic loss to airlines and inconvenience to stranded passengers. Dense fogs are navigational hazards in the seas as ships and huge supertankers carrying oil some times collide resulting into spilling of huge quantity of oil causing enormous **oil slicks** on sea water which cause **ecological disaster.** Vehicular traffic comes to grinding halt in the event of dense fogs. Some times, fogs are so dense and visibility is so reduced that walking by human beings becomes impossible. When fogs are polluted through sulphur coming out of the chimneys of the mills, they become poisonous and health hazards. For example, killer poisonous smog was formed due to mixing of dense fog with smokes and sulfide fumes coming out from the chimneys in the Donora Valley of Pennsylvania (USA) on 26 October, 1948. This toxic fog (smog) caused 20 human deaths and 43 per cent inhabitants fell ill due to cough and respiratory problem. Similar poisonous fog was produced due to mixing of sulphur dioxide coming out of the factories of zinc smelters and sulphuric acid in the Meuse Valley of Belgium in the month of December, 1930. This killer fog claimed 63 human lives due to obstruction in respiratory system. The poisonous fogs of December, 1952 claimed 4000 human lives in London.

Some times, fogs are also economically beneficial to human society. For example, they protect tea and coffee plants from scorching sunlight on the hillslopes. Mocha coffee on the Yemen hills (Arabia) is highly benefitted from fogs.

Long-continued dense fogs become very injurious to plants as the foliage is severely damaged and plants including tall trees become bare for months together and some of them cannot sustain the severity of dense fogs of long duration and ultimately they die. Such situation was created due to persistence of dense fog from December 20 to January 25 during 2002-03 and 2003-04 in the Ganga Plains of Uttar Pradesh.

9.2.5 NATURAL AND MAN-INDUCED DISPERSAL OF FOGS

Fogs are dissipated by both natural and anthropogenic processes in variety of ways. The natural processes of fog dissipation include cooling of fogy air layer, heating of foggy layer, vertical mixing of air etc. When the foggy air moves over very cold surface say snow-covered surface, it is excessively cooled from below and fog disappears as if by magic. Such dissipitation of fogs occurs in the summer of high latitudes when the temperature of the surface reaches 0^0C or below it. The descending foggy air is heated by dry adiabatic rate and the moisture contents in the foggy air are evaporated and fogs are dissipitated. Conversely, persistent fogs are dissipated after condensation and precipitation. The evaporation of moisture contents in foggy air by direct solar radiation is also responsible for dispersal of fogs. This is why normal fogs during winter season in the Ganga Plains start dissipating with sunrise in the morning. Sometime, the fog is intensified after sunrise due to more evaporation from moist surfaces and resultant condensation but it is dissipated as the sun rises overhead.

The **man-induced mechanisms** of fog dispersal include seeding of dry ice, emission of liquid propane, mechanical mixing of foggy air with dry and warm air, seeding of foggy air with silver iodide, carbon, calcium chloride spray, drying of foggy air with hygroscopic chemicals, heating of air etc. It may be mentioned that different methods are used to drive out cold and warm fogs. The efforts to disperse fogs are generally made to dissipate fogs from air ports to clear the sky for safe take off and landing of aircrafts. Dissipation of cold fogs is carried out with the seeding of dry ice, silver iodide with foggy air with the help of air craft dropping from above. The direct emission of liquid propane from the ground surface with the help of dispensers is also practiced to drive out cold fogs from over the air ports. It may be mentioned that warm fogs are thick, dense and more persistent and hence their dissipation by mechanical methods is more difficult than the dissipation of cold fogs. Among the prevailing practices to disperse warm fogs, the mechanical mixing of foggy air with dry warm air, drying of foggy air by heating from below with the help of specially designed burners, drying of foggy air by hygroscopic chemicals etc. have proved more effective but the cost involved is very high and sometimes becomes uneconomical. The artificial methods of dissipation of fogs are generally used at the airports of the USA, East European countries mainly in Russia, France, Germany, England etc.

9.3 CLOUDS

Clouds are defined as aggregates of innumerable tiny water droplets, ice particles or mixture of both in the air generally above the ground surface. Clouds are formed due to condensation of water vapour around hygroscopic nuclei caused by cooling due to lifting of air generally known as adiabatic cooling. Meteorologically, clouds are very significant because all forms of precipitation occur from them. It may be mentioned that not all clouds yield precipitation but no precipitation is possible without cloud. Clouds play major role in the heat budget of the earth and the atmosphere as they reflect, absorb and diffuse some part of incoming shortwave solar radiation and absorb some part of outgoing longwave terrestrial radiation and then re-radiate it back to the earth's surface.

9.3.1 CLASSIFICATION OF CLOUDS

There is wide range of variations in clouds in terms of height, shape, colour and transmission or reflection of light. Baptist Lamarck is considered to be pioneer in the field of classification of clouds but Luke Howard, an English pharmacist and naturalist is given full credit to present a sound scheme of classification of clouds into main and secondary types in the year 1803. His classification was so well designed that it is still in use. With the increase of more and more knowledge about cloud characteristics, efforts were made to present comprehensive system of cloud classification. Consequently, International Meteorological Committee presented a system for naming and identifying different cloud types in the year 1895. The first International Cloud Atlas was presented in the following year *i.e.* in 1896. The World Meteorological Organisation (WMO) now publishes International Cloud Atlas. The characteristic features of classification of clouds as presented by Howard and WMO are given below.

1. Luke Howard's Classification

Luke Howard classified the clouds into three major forms (types) and assigned them Latin names as follows :

(1) **Stratus clouds** (derived from Latin word 'stratum' meaning thereby 'layer') are stratified or layered.

(2) **Cumulus clouds** (the word cumulus is a Latin word meaning thereby 'pile') are characterized by flat base and rounded tops, mound or tower shape like cauliflower.

(3) **Cirrus clouds** (derived from Latin word 'cirrus' meaning there by 'hair') are white in colour and look fibrous and feather like in appearance. These are curly or fibrous clouds.

2. Classification by W.M.O.

It may be mentioned that cloud varieties are so large that it becomes difficult to group them into certain limited categories but inspite of this difficulty the World Meteorological Organisation has classified clouds on the basis of (1) their genesis and characteristic features, and (2) on the basis of altitude of their occurrences. In the first part of cloud classification contained in the International Cloud Atlas the WMO classified the clouds into genera (basic types, 10), species (26) and varieties (3). On the basis of altitude clouds have been classified into high, medium, and low clouds as follows :

(A) **High clouds** (height, 3-8 km over the poles, 5-13 in temperate regions, 5-18 km in tropical regions)

(1) Cirrus clouds

(2) Cirro-cumulus clouds

(3) Cirro-stratus clouds

(B) **Middle clouds** (height 2-4 km over the poles, 2-7 km in the temperate regions, 2-8 km in the tropical regions)

(4) alto-stratus clouds

(5) alto-cumulus clouds

(6) nimbo-stratus clouds

(C) **Low clouds** (height, ground surface to 2.5 kilometers)

(7) strato-cumulus clouds

(8) stratus clouds

(9) cumulus clouds

(10) cumulo-nimbus clouds

The names have been derived from Latin word where cirro (cirrus) means high clouds, alto means middle clouds, nimbo (nimbus) means rain clouds, strato (stratus) means stratified clouds, cumulus means detached clouds etc.

3. Characteristic Features of Clouds

The main characteristic features of 10 basic types (genera) of clouds regarding their structure, altitude of their occurrence and appearance are given below :

(1) **Cirrus clouds (Ci)**—The high altitude detached clouds having fibrous (hair like) or silky appearance are called cirrus clouds. They are composed of tiny ice crystals and are transparent and white in colour but have brilliant colours at sunset and sunrise. These clouds are indicative of dry weather. These are found at the altitude of 3-8 km over the poles, 5-13 km in temperate regions, and 5-18 km in tropical regions.

(2) **Cirro-cumulus clouds (Cr)** are white coloured clouds having cirriform layer or patches of small white flakes or small globules which are arranged in distinct groups, or wavelike form. They are high altitude clouds. They generally appear as ripples similar to sand ripples in the desert. These are not common type of clouds.

(3) **Cirro-stratus clouds (Cs)** are high altitude clouds and are generally white in colour and spread in the sky like milky thin sheets. In fact, cirro-stratus is a thin white veil of cirrus cloud. They are composed of tiny ice crystalls which refract the lights of the sun and moon and thus halos are formed around them (around sun and moon). They are so transparent that the sun and moon are visible through them. These form halo around the moon in the night.

(4) Alto-stratus clouds (As) are thin sheets of gray or blue colour having fibrous or uniform appearance. When they become thick sheets the sun and the moon are obscured and they appear as bright spots behind the cloud. They do not form halo around the sun and the moon. They cover the sky partly or totally or are smoothly distributed over the entire sky. They yield widespread continued precipitation either in the form of drizzle or snow.

(5) Alto-cumulus clouds (Ac) are characterized by wavy layers of globular form. They form fairly regular patterns of lines, groups or waves. In fact, they are individual masses of clouds which are fitted closely together in geometrical patterns. High globular groups of alto-cumulus are some times called as **sheep clouds** or **wool pack clouds.** They appear white or gray in colour.

(6) Nimbo-stratus clouds (Ns) are low clouds of dark colour very close to the ground surface. They are so compact and thick (hundreds of meters) that there is complete darkness and there is copious precipitation. Nimbo is from Latin word 'nimbus' meaning thereby rainstorm. They are associated with rain, snow and sleet but are not accompanied by lightning, thunder or hailstorm.

(7) Strato-cumulus clouds (Sc) are of grey or whitish colour. They are found in rounded patches between the height of 2500m to 3000m. They are composed of globular masses or rolls which are generally arranged in lines, waves of groups. They are generally associated with fair or clear weather but occasional rain or snow is not ruled out.

(8) Stratus clouds (St) are dense, lowlying fog-like clouds of dark grey colour but are seldom close to the ground surface. They are composed of several uniform layers. When these clouds are associated with rains or snow, they are called nimbostratus clouds as referred to above.

(9) Cumulus clouds (Cu) are very dense, widespread and dome-shaped and have flat bases. They are white woolpack cloud masses and are associated with fair weather but some times they become thunder clouds.

(10) Cumulo-nimbus clouds (Cb) are thunder-storm clouds. They show great vertical development and produce heavy rains, snow or hailstorm accompanied by lightning, thunder and gusty winds. They appear like mountains or huge towers and assume the shape of anvil or vast plume. Some time precipitation occurring from cumulus clouds in summer is evaporated before reaching the ground surface. Such rain is called **virga.**

The species of clouds as described by WMO are presented in table 9.1.

Table 9.1 : Cloud Species and Their Characteristics

1. **Arcus** : arc shaped, dark and threatening, lower part of cumulonimbus cloud, mainly of line-squal type.
2. **Cavus** : bald, refers to the absence of sprouting (cauliflower) structure as well as cirriform appendages in the upper part of a cumulonimbus cloud.
3. **Capillatus** : hairy, fibrous or straited structure of upper part of cumulonimbus.
4. **Castellamus** : turreted, heap shaped towers, resembling miniature cumulus protruding from clouds in the middle and upper troposphere, especially altocumulus.
5. **Congestus** : congested, heaped, sprouting, towering structures in the upper portion of developing cumulus.
6. **Fractus** : fractured, torn; ragged fragments of clouds, notably stratus, cumulus, and nimbostratus.
7. **Humilis** : humble, small, flat; used to characterize nondeveloping cumulus clouds.
8. **Incus** : anvil shaped; cirriform mass of cloud in the upper part of developed cumulonimbus clouds.
9. **Intortus** : twisted, entangled; used to describe a type of cirrus clouds.

10. **Mamma** : shaped like udders; protuberances hanging down from the undersurface of a cloud; most pronounced in connection with thundery cumulonimbus clouds.
11. **Pileus** : cap or hood-shaped; accessory cloud of small horizontal extent above, or attached to, the upper part of a cumulus cloud, particularly during its developing phase.
12. **Spissatus** : spiss, compact; describes cirrcus that is sufficiently dense to appear grayish when viewed in direction toward the sun.
13. **Tuba** : tube-shaped; typical of clouds associated with tornadoes, water spouts etc.
14. **Unchinus** : hooked, typical of streaky cirrus drifting in strong winds in the upper troposphere.
15. **Velum** : flap, an accessory cloud of considerable horizonal extent, sometimes connecting the upper parts of several cumulus clouds.
16. **Virga** : twig; trails or streaks of precipitation, hanging from the undersurface of a cloud but not reaching the ground.

Source : Reproduced from World Meteorological Organization, as produced in J.E. Oliver and J.J. Hidore, 2003.

9.4 PRECIPITATION

Precipitation refers to fall of atmospheric moisture either in liquid form (such as water through rainfall) or in solid form (such as snowfall) after cooling and condensatin of ascending moist air after dew point is reached. Precipitation is also defined as deposition of atmospheric moisture either in liquid or solid form. The adiabatic cooling of moist air caused by either mechanical lifting (orographic obstruction and lifting) or by dynamic lifting (as a result of radiation heating and resultant convection and turbulence; and as a result of frontal activity) causes condensation and precipitation.

9.4.1 FORMS OF PRECIPITATION

The precipitation of atmospheric moisture occurs in a number of ways depending upon (1) the temperature of dew point at which the air is saturated and condensation begins, (2) the altitude and types of clouds, (3) the atmospheric conditions through which the cloud droplets pass through mainly in terms of temperature, (4) the process of adiabatic cooling *i.e.* the cooling either caused by mechanical lifting of moist air and consequent expansion of air leading to decrease in temperature, increase in relative humidity and ultimately condensation of moisture or by dynamic lifting of moist air (either by radiation or by frontal activity). If the condensation occurs at the temperature above freezing point (*i.e.* above 0^0C), the precipitation takes place in liquid state namely rainfall, on the other hand if condensation occurs below freezing point (*i.e.* below 0^0C), the precipitation takes place in solid state such as snowfall. The types of precipitation include rain, drizzle, freezing rain or freezing drizzle, snow, snowpellets, snow flakes, snow grains, ice pellets, hail etc. It may be mentioned that generally fog, dew and mist are not considered as forms or types of precipitation but some scientists plead for their inclusion under the category of precipitation.

Rain is the most widespread and important form of precipitation. It occurs when there is sufficient moisture in the air and condensation occurs above freezing point (*i.e.* above 0^0C). Rain is, infact, liquid water, in the form of raindrops with diameter of more than 5 mm. It is important to point out that one rain drop contains as many as 8,000,000 cloud droplets. Rain drops fall at the velocity of 200 times greater than cloud droplets. When rain drops become very large and fall down at greater speed (more than 30 kilometers per hour), they are split in the transit but give heavy downpour. Sometimes precipitation occurs at higher altitude from cumulus clouds in the form of rain but the trails or streaks of such rain coming from the under surface of clouds is evaporated in the transit before reaching the ground. Such rain is called **virga**.

Drizzle is defined as the fall of numerous uniform tiny droplets of water having diameter of less than 0.5 mm. Drizzles fall continuously from low stratus clouds but the total amount of water received at the ground surface is significantly low. Sometimes drizzles are combined with fog and hence reduce visibility. The drizzle intensity is generally one mm per hour.

Snow is formed when condensation occurs below freezing point (less than 0^0C). The fall of snow flakes is called snow-fall. Snowflakes are formed when air temperature is greater than-5^0C but less than 0^0C. In fact, snowfall is 'precipitation of white and opaque grains of ice'. The snowfall occurs when the freezing level is so close to the ground surface (less than 300 m from the ground surface) that aggregations of ice crystals reach the ground without being melted in solid form of precipitation as snow.

Snow pellets having white and opaque grains of ice of spherical shape are formed when condensation takes place around freezing point. The diameter of snow pellets ranges between 2mm to 5mm. The grains involved in the formation of snow pellets are so brittle that they break in pieces after being pelted by the ground surface. Snow pellets are also considered as soft variety of hails.

Graupel, a form of precipitation in solid form, is comprised of ice grains of white colour and is opaque for light. The diameter of graupel, also called as snow grain, is less than one mm.

Ice pellets are, unlike graupel or snow grains, transparent or translucent grains of ice which are formed when condensation takes place below freezing point. The diameter of ice pellets is upto 5 mm and the shape of the pellets is highly irregular depending upon the conditions of condensation. Ice pellets are, infact, frozen raindrops. Sometimes they are also formed when snowflakes are melted and refrozen.

Hail consists of large pellets or spheres (balls) of ice. In fact, hail is a form of solid precipitation wherein small balls or pieces of ice, known as hailstones, having a diameter of 5mm to 50mm fall downward known as hailstorms. Hails are very destructive and dreaded form of solid precipitation because they destroy agricultural crops and claim human and animal lives.

Sleet refers to mixture of snow and rain but in American terminology sleet means falling of small pellets of transparent or translucent ice having a diameter of 5mm or less.

Freezing rains or freezing drizzles are formed when the drizzles or very light rains occur below 0^0C temperature, they are frozen before reaching the ground surface and hence they are called freezing rains or freezing drizzles. They are also called as **crachins.**

Rime is an opaque coating of tiny, white, granular ice particles, caused by rapid freezing of supercooled water droplets on impact with an object (Webster Dictionary) below freezing point. Rime is deposited mainly on the edges and points of objects. Rime is in fact deposit of opaque, white, and rough textured ice crystals. The form after accumulation of rime looks like cauliflower shaped heap.

9.4.2 PROCESSES OF PRECIPITATION

The main mechanisms or processes of precipitation are related to adiabatic cooling of moist air (see section 8,10 in the preceding chapter 8), condensation of moist air (see section 8,11 in the preceding chapter 8), formation of cloud droplets and their growth to form water droplets and ultimately their fall on the ground surface in different forms as elaborated in the previous subsection 9.4.1. The processes of precipitation are elaborated as follows.

The presence of warm, moist and unstable air and sufficient number of hygroscopic nuclei are prerequisite conditions for precipitation to occur. The warm and moist air after being lifted upward is cooled at the dry adiatabtic rate of 10^0C per 1000m height and becomes saturated and clouds are formed after condensation of water vapour around hygroscopic nuclei (salt and dust particles) but still there may not be precipitation in liquid form, *i.e.* rainfall unless the air is supersaturated. The process of condensation begins only when the relative humidity of ascending air becomes 100 per cent and air is further cooled through dry adiabatic lapse rate but first condensation occurs around larger hygroscopic nuclei only. Such droplets are called **cloud droplets.** The aggregation of large number of cloud droplets forms clouds.

These cloud droplets are so microscopic in size that they remain suspended in the air. Precipitation does not occur unless these cloud droplets become so large due to coalescence by impact of collision due to gravitational attraction that the air becomes unable to hold them. This is why, some times the sky is overcast by thick clouds but there is no rainfall. If by chance these cloud droplets fall downward they are evaporated before they reach the ground surface as **virga**. Rainfall occurs only when cloud droplets change to raindrops. There are two possible processes of change of cloud droplets into raindrops.

(1) If warm and moist air ascends to such a height that condensation begins below freezing point, then both, water droplets and ice droplets, are formed. The water droplets are evaporated because of difference of vapour pressure between them and ice droplets and there is condensation of evaporated water around ice crystals which go on increasing in size. If they become sufficiently large in size, they cannot be held in suspension by the air and consequently they begin to fall down. If the temperature above the ground is high they fall in the form of raindrops.

(2) The suspended cloud droplets in the clouds are of different sizes. These cloud droplets collide among themselves at varying rates due to difference in their sizes and thus form large droplets. In the process several cloud droplets are coalesced to from raindrops. When they become so large in size that ascending air becomes unable to hold them, they fall down as rainfall.

The diameter of raindrop is upto 5mm and one raindrop contains about 8,000,000 cloud droplets. Rain drops fall down at the velocity 200 times greater than cloud droplets. When raindrops become very large and fall down at greater speed (more than 30 kilometres per hour), they are split in the transit but give heavy downpour. When the air ascends slowly, the process of condensation is also very slow and hence small raindrops are formed and the resultant rainfall is drizzle but if the air ascends huriedly with greater speed, very large raindrops are formed and resultant rainfall is heavy downpour. When condensation occurs below freezing point, the resultant precipitation is in solid form and is called snowfall.

The **colloidal stability** and **instability** of different clouds also control and determine precipitation. There are certain clouds wherein the water droplets do not coalesce rather remain independent and hence they are suspended in the clouds and are held by them. This is called coloidal stability of clouds, which does not allow precipitation to occur. On the other hand, when ever water droplets are attracted and collide against each other, they ultimately coalesce and are aggregated and hence grow in size. Such large water droplets, referred to as raindrops, cannot be held up within the clouds. This condition is called colloidal instability of clouds. In such condition, water droplets fall down as raindrops and precipitation occurs. The following theories explain the processes or mechanisms of precipitation.

9.4.3 THEORIES OF PRECIPITATION

Various theories of precipitation and rainfall have been put forth from time to time but the riddle of raindrop formation still remains unresolved. Very generalized two processes and mechanisms of raindrop formation have been outlined above. The early theories related to the formation of raindrops and their growth may be briefly summarized in the following manner.

(i) The raindrops are differently electrically charged and thus they are coalesced by electrical attraction and grow in large size. This theory is opposed on the ground that the distances between raindrops are so large and difference between electrical charges is so small that coalescence of raindrops due to this mechanism is not possible. In other words, the coalescence and growth of raindrops due to differential electrical charges are not possible.

(ii) The large rain drops capture small rain drops and thus become further large in size but the observations have revealed that there is regular pattern in the size and distribution of drops in the clouds. In other words, generally most of the drops are more or less uniform in size as their diameters range between 20 to 30 micrometres and only a few drops are larger than 80 micrometres.

(iii) There is variation in saturation vapour pressure with varying temperatures. In such condition the atmospheric turbulence brings warm and cold cloud droplets in close conjunction, with the result there is supersaturation of air with reference to the surface of the cold cloud droplets and undersaturation of air with reference to the surface of warm cloud droplets and growth of cold droplets at the expense of warm droplets. This situation causes evaporation of warm droplets. This theory is opposed on the ground that the difference of temperature of cloud droplets is not so great that this differential mechanism may operate.

(iv) Raindrops grow around very large condensation (hygroscopic) nuclei but it is argued that no doubt the process of condensation around exceptionally large hygroscopic nuclei is very rapid but their further growth cannot be explained on this mere ground of size of cloud droplets.

It appears from the above discussion on ideal situation for the formation of large enough water/ice droplets to fall down as precipitation (rainfall) that it depends on the **size and weight of water droplets** and droplet size is a critical factor in the occurrence of precipitation. The second important factor in the development of precipitation is the **speed of fall of water droplets.** The fall speed of water droplets in turn depends on the balance between the weight of water droplets and resistance (resisting force) of air to hold the water droplets or to retard the fall speed. In other words, there are two forces *e.g.* driving force (fall speed of water droplets) and resisting force (resistance offered by the air). The fall speed is determined by the gravitational force of the earth which increases with increase of size and weight of falling objects (*i.e.* water droplets). In a situation when the resisting force of the air and the force of gravity are balanced, the resultant velocity is called terminal velocity. In more simple term, **terminal velocity** refers to balance between the force of gravity and the force offered by the resistance of the air. If the speed of falling body (here water droplets) is equal to the terminal velocity, the forces remain in balance and water droplets fall down at constant speed but when the terminal velocity is greater than the updraught velocity (updraught is a variant spelling of updraft and both are pronounced in the same manner; updraught velocity is infact upward velocity *i.e.* resistance of the air), the water droplets fall down as raindrops and reach the ground surface as the air is unable to hold them. It may be remembered that the size and weight of falling body (here water droplets) is directly proportional to terminal velocity *i.e.* larger the size and heavier the falling body, the greater would be terminal velocity and vice versa.

Another important factor involved in the occurrence of precipitation is the **rate of condensation.** The greater the speed/rate of condensation, the quicker would be precipitation.

The theories of precipitation and rainfall are grouped in two main categories on the basis of processes of formation and growth of raindrops, namely rapid growth of raindrops due to growth of ice crystals at the cost of water droplets. (1) **cloud instability theory of Bergeron-Fiendeison** (also known as **Bergeron-Fiendeisen Process** or simply **ice crystal theory**), and (2) rapid growth of raindrops due to coalescence of small water droplets by sweeping actions of falling drops, and (3) **collision theory,** or **collision coalescence theory,** or simply **collision-coalescence process.**

(1) Cloud Instability Theory of Bergeron (Ice Crystal Theory of Bergeron)

Tor Bergeron, an eminent Norwegian meteorologist, postulated his theory of precipitation, known as '**cloud instability theory**' or '**ice crystal theory**' in 1933. The core of the theory is based on the concept of mechanism of the growth of raindrops. According to him water droplets and ice crystals are found together in unstable clouds when temperature is below freezing point. The theory is based on commonly accepted fact that "the relative humidity of air is greater with respect to an ice surface than with respect to water surface". With the fall of air temperature below 0^0C the atmospheric vapour pressure decreases more rapidly over ice surface than over water surface with the result saturation vapour pressure becomes greater over water surface than over ice surface when the air temperature ranges between -5^0C and -25^0C and the difference between saturation vapour pressure over water and ice surfaces exceeds 0.2 mb. In such condition, when air temperature ranges between -5^0C and -25^0C, water droplets become supersaturated. If ice crystals and super cooled water droplets exist together in a cloud, then the water droplets are evaporated and resultant vapour is deposited on the ice crystals.

It may be pointed out that the formation of ice particles requires freezing nuclei (*e.g.* fine soil particles, meteoric dust etc.) in the same manner as the formation of water droplets requires the presence of hygroscopic nuclei. Slowly and slowly ice crystals grow in size as the deposition of vapour derived through evaporation of super-cooled water droplets on their surfaces continues. Ice crystals then aggregate due to their mutual collision and thus they form large snow flakes. The aggregation of ice crystals is more prevalent when air temperature ranges between 0^0C and -5^0C. When the ice crystals become large (snow flakes) and their falling velocity exceeds the velocity of rising air currents, they fall downward. When the falling ice crystals pass through a thick layer of air with temperature more than 0^0C, they are changed into raindrops and thus begins rainfall.

(2) Collision-Coalescence Theory

Though the Bergeron process of the origin of precipitation and rainfall satisfied most of the observed facts but it could not explain the mechanism of rainfall in the tropical areas where cumulus clouds over the oceans give copious rains when they are only 2000 m thick and the air temperature at their top is 5^0C or even more. It is thus evident that ice crystals do not help in the formation and growth of raindrops of large size

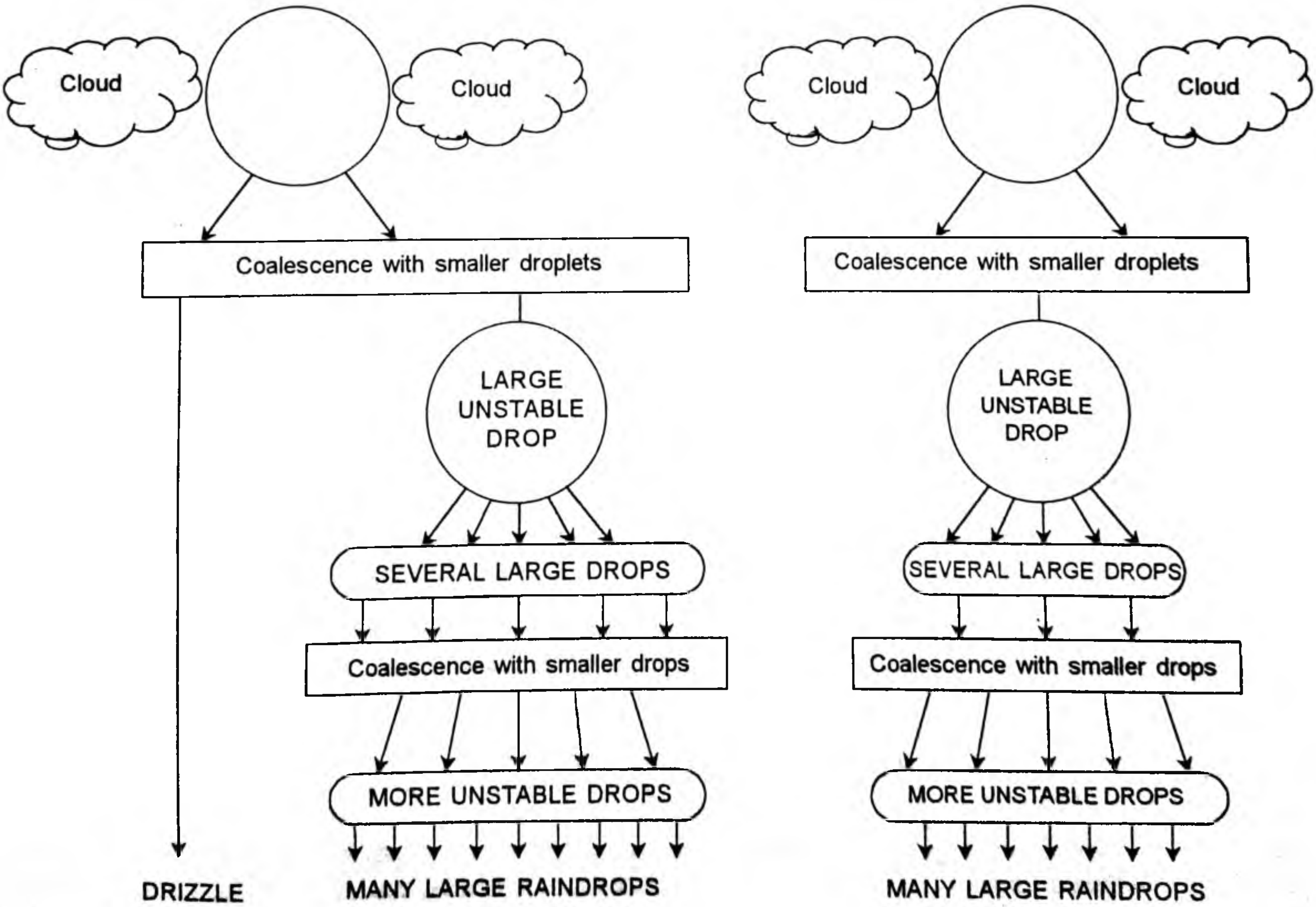


Fig. 9.1 : Illustration of Bergeron -Fiendeison Process of precipitation or ice crystal theory of Bergeron-Fiendeison.

in warm clouds. Thus, collision theory involving collision, coalescence and sweeping for the formation and growth of raindrops was postulated by several meteorologists. According to some meteorologists atmospheric turbulence causes collision of cloud droplets. Due to collision they coalesce and grow in size. This concept suffers from two shortcomings *e.g.* (i) collision may cause splitting and scattering of cloud droplets rather than their aggregation due to coalescence, and (ii) there is little and often no precipitation from highly turbulent clouds. Langmuir suggested modifications in the **'general coalescence theory'** in order to plug its loopholes as mentioned above. According to him the terminal velocities of falling drops are directly related to their diameters. In other words, larger drops fall ith greater velocity than smaller drops. Thus, larg drops absorb smaller droplets. Smaller droplets are also swept by larger droplets. All these lead to increase in the size of larger droplets which become raindrops which fall as rains because they cannot be held in suspension by rising air currents.

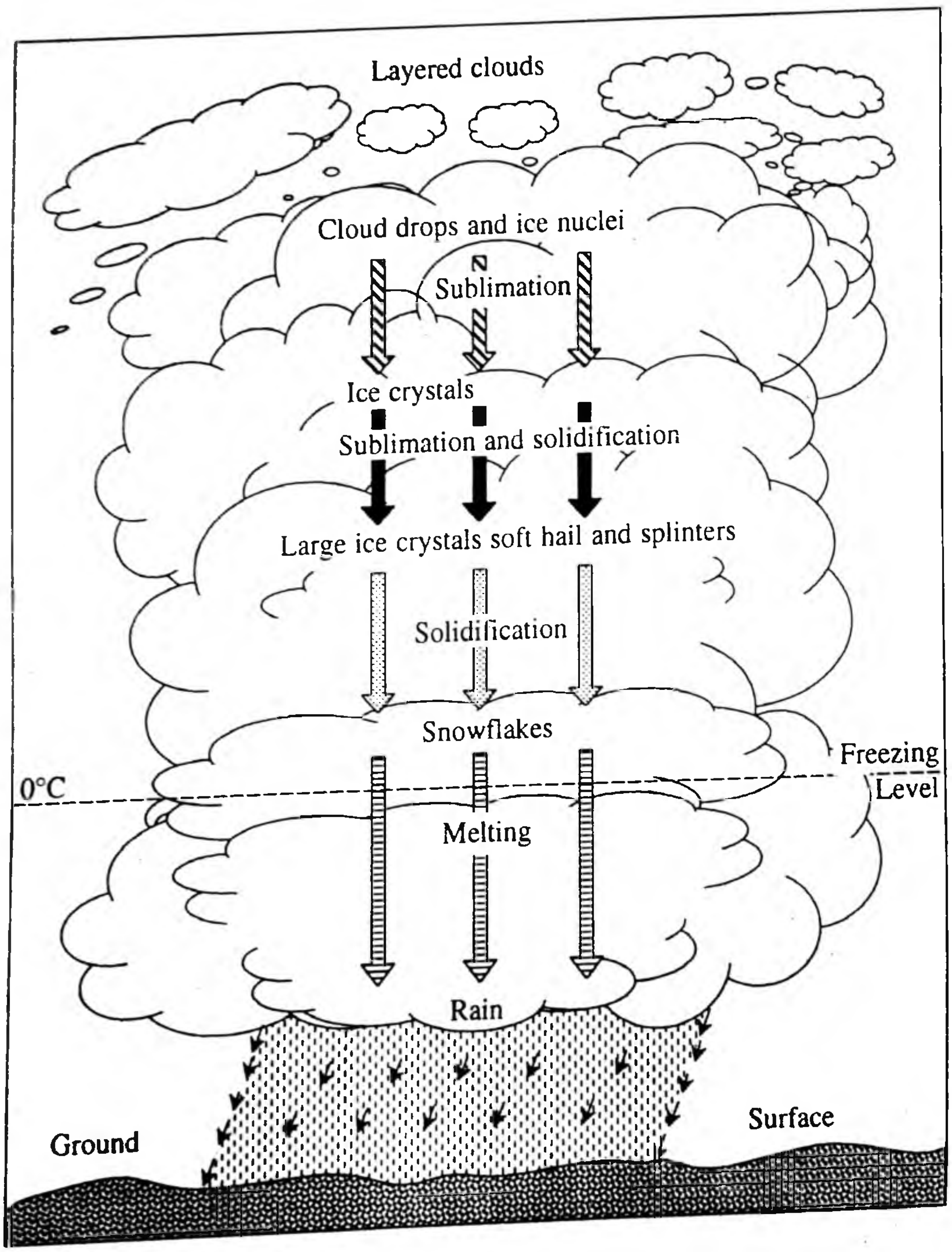


Fig. 9.2 : Illustration of Bergeron-Fiendeison process of precipitation.

9.4.4 TYPES OF PRECIPITATION (RAINFALL)

Rain is the most common form of precipitation which takes place when condensation occurs in liquid form above freezing point (*i.e.* above 0^0C). For precipitation it is necessary that moist air must ascend, cool, saturate (relative humidity 100 per cent), and condense. Adiabatic cooling due to upward movement of air, consequent expansion of volume and cooling is by far the most important mechanism of condensation and related precipitation including rainfall. It is apparent that constant supply of moisture and upward movement of moist air are prerequisite conditions for cloud formation and rainfall. Thus, precipitation and rainfall are classified on the basis of conditions and mechanisms of upward movement (lifting) of moist air. There are two main mechanisms of upward movement of *e.g.* (1) **mechanical uplifting**, and (2) **dynamic uplifting**, which further falls under two subcategories *e.g.* (a) **convectional uplifting**, and (b) **frontal uplifting of air.** The mechanical and frontal uplifting of air is also called **forced uplifting.** Mountain barrier, when located transverse to horizontally moving air, obstructs the wind and forces it to rise upward along its slope. This is called **orographic forced uplifting** of air. The frontal uplifting of air involves pushing of warm air upward by colder air lying below. Convectional uplifting of air involves radiation heating of ground surface leading to warming of surface air and consequent expansion of air and its ascent, the process is called convection mechanism.

It is, thus, evident from the above discussion that there are three ways in which moist air is forced to move upward and cools according to adiabatic rates *e.g.* (1) **radiation uplift** or **convection uplift,** due to heating of ground surface the air being heated expands and rises upward in the form of convection currents, the mechanism is known as thermal convection, (2) **orographic uplift,** forced ascent of air over orographic barrier because of its obstruction, and (3) **frontal uplift,** forced uplift of air associated with cyclonic activities. It may be pointed out that it is not necessary that all these three factors always act independentally and separately in relation to the ascent of air. Sometimes, more than one factors are operative. In such situation, the form of precipitation and rainfall is determined on the basis of most dominant factor. Thus, precipitation and rainfall are classified into the following three types :

(1) **convectional rainfall,** occurring due to thermal convection currents caused due to insolational heating of ground surface.

(2) **orographic rainfall,** occuring due to ascent of air forced by mountain barrier, and

(3) **cyclonic or frontal rainfall,** occurring due to upward movement of air caused by convergence of extensive air masses.

1. Covectional Rainfall

The principal motivating force behind the ascent of warm and moist air is thermal convection caused by heating of the ground surface through insolation. Two conditions are necessary to cause convectional precipitation and rainfall *e.g.* (i) abundant supply of moisture through evaporation to the air so that relative humidity becomes high, and (ii) intense heating of ground surface through incoming shortwave electromagnetic solar radiation (say, insolation heating). The mechanism of convectional rainfall may be explained in the following manner.

The ground surface is intensely heated due to enormous amount of heat received through solar radiation during daytime (photoperiod), with the result the air coming in contact with warm ground surface also gets heated, becomes warm, expands, and ultimately rises upward. The ascending warm and moist air cools according to **dry adiabatic lapse rate** (decrease of temperature at the rate of 10^0C per 1000 meters). The cooling of ascending air increases its relative humidity. The moist air becomes saturated soon (relative humidity becomes 100 per cent) and further ascent of air beyond saturation level (supersaturation) causes condensation and cloud formation (cumulo-nimbus clouds) and thus rainfall starts. The air still continues to rise and in the process further cools but at **moist adiabatic lapse rate** or **retarded adiabatic rate** (decrease of temperature at the rate of 5^0C per 1000 meters) due to addition of **latent heat of condensation** to the ascending air released after condensation of atmospheric vapour. When the ascending air reaches such height where its temperature matches with the temperature of surrounding air, the process of condensation is more activated and hence cumulo-nimbus clouds are formed and there begins instantaneous heavy rainfall (fig. 9.3).

Since the ascending moist air (convectively motivated) cools soon after rising to very little height, causing immediate saturation and condensation, the convectional rainfall occurs in the form of heavy downpour. It is also apparent from the above description that convectional rainfall is a **warm weather phenomenon** and is associated with lightning and cloud thunder. Convectional rainfall mainly occurs in equatorial regions of low latitudes where daily heating of ground surface upto noon causes convection currents. Consequently, the sky becomes overcast by 2-3 P.M. daily causing pitch darkness and heavy rains and the sky becomes clear by 4 P.M. Thus, the convectional rainfall in the equatorial region is a daily regular feature.

Convectional rainfall also occurs in the tropical, subtropical and temperate regions in summer months and in the warmer parts of the day. The following are characteristic features of convectional rainfall.

(i) It occurs daily in the afternoon in the equatorial regions.

(ii) It is of very short duration but occurs in the form of heavy showers (heavy downpour).

(iii) It occurs through thick dark and extensive cumulo-nimbus clouds.

(iv) It is accompanied by cloud thunder and lightning.

(v) Though much of the rainfall becomes runoff and is drained off in the form of surface runoff and overland flow to the streams but still there is sufficient moisture in the soils due to daily rainfall in the equatorial regions. Outside equatorial regions convective rainfall is of little significance to crop growth because most of rainwater is drained to the streams through surface runoff which causes severe rill and gully erosion resulting into enormous loss of loose soils.

(vi) Convective rainfall supports luxurious evergreen rain forests in the equatorial regions.

(vii) Convective rainfall in the temperate regions is not in the form of heavy showers rather it is slow and of longer duration so that most of rainwater infiltrates into soils. Here rains are always in summers.

(viii) Convective rainfall in hot deserts is not regular but is irregular and sudden.

2. Orographic Rainfall

Orographic rainfall occurs due to ascent of air forced by mountain barriers. The mountain barriers lying across the direction of air flow force the moisture laden air to rise along the mountain slope and thus lifted air mass cools according to dry adiabatic lapse rate (decrease of temperature at the rate of 10°C per 1000 metres), which increases the relative humidity of the air. The ascending air becomes saturated after reaching certain height and condensation begins around hygroscopic nuclei. The addition of latent heat of condensation to the air causes it to move further upward and cool at moist adiabatic lapse rate (decrease of temperature with increasing height at the rate of 5°C per 1000 metres). Thus, ascending air continues to yield precipitation with increasing height. It is apparent that mountain barriers produce **trigger effect** for the moist air to ascend, cool and become unstable. The slope of the mountain facing the wind is called **windward slope** or **onward slope** and receives maximum precipitation while the opposite slope is called **leeward slope** or **rainshadow region** because the ascending air after crossing over the mountain barrier descends along the leeward slope and thus is warmed at dry adiabatic lapse rate (increase in temperature with decreasing height at the rate of 10°C per 1000 metres). Consequently, the humidity capacity of the descending air increases resulting into substantial decrease in relative humidity. Secondly, the moisture present in the air is already precipitated on the windward slope and thus there is very little precipitation on the leeward slope. Most of the world precipitation occurs through orographic rainfall.

The following conditions are necessary for the occurrence of orographic rainfall.

(i) There should be mountain barier across the wind direction, so that the moist air is forced on obstruction to move upward. If the mountain barriers are parallel to the wind direction, the air is not obstructed and no rainfall occurs. For example, Aravallis ranges running in southwest-northeast direction are parallel to the Arabian Sea Branch of south-west Indian monsoon and hence Rajasthan receives very low amount of rainfall.

(ii) If the mountains are very close and parallel to the sea coasts, they become effective barriers because the moisture laden winds coming from over the oceans are obstructed and forced to ascend and soon become saturated. For example, Coast Range mountains situated on the western margins of North America are parallel to the Pacific coast. Similarly, the situation of the Western Ghats in India presents ideal conditions for orographic rainfall.

(iii) The height of mountains also affects the form and amount of orographic rainfall. If the mountains are very close to the sea coast, even low height can be effective barrier and can yield sufficient rainfall because the moist air becomes saturated at very low height. On the other hand, the inland mountains should be of higher height because the air after covering long distances loses much of its moisture content.

(iv) There should be sufficient amount of moisture content in the air.

The following are the characteristic features of orographic rainfall :

(a) The windward slope, also called as **rain slope**, receives maximum amount of rainfall whereas leeward side of the mountain gets very low rainfall. For example, Mangalore located on the western slope (windward slope) of the Western Ghats receives mean annual rainfall of above 2000 mm whereas Bangalore situated in the rain shadow region gets only 500 mm of mean annual rainfall. The southern slopes of the Himalayas receive mean annual rainfall of more than 2000 mm whereas the northern slope receives only 50 mm of mean annual rainfall. Similarly, the western slopes of the Coast Ranges of North America receive more than 2000 mm of mean annual rainfall while the eastern slopes fall in rainshadow region.

(b) There is maximum rainfall near the mountain slopes and it decreases away from the foothills. For example, the cities and towns located at the southern slopes of the Himalayas receive more rainfall *e.g.* Simla 1520 mm, Nainital 2000 mm and Drazeeling 3150 mm whereas the places away from the Himalayan foothills receive relatively low rainfall *e.g.* Patna 1000 mm, Allahabad 1050 mm and Delhi 650 mm.

(c) If the mountains are of moderate height, the maximum rainfall does not occur at their tops rather it occurs on the other side.

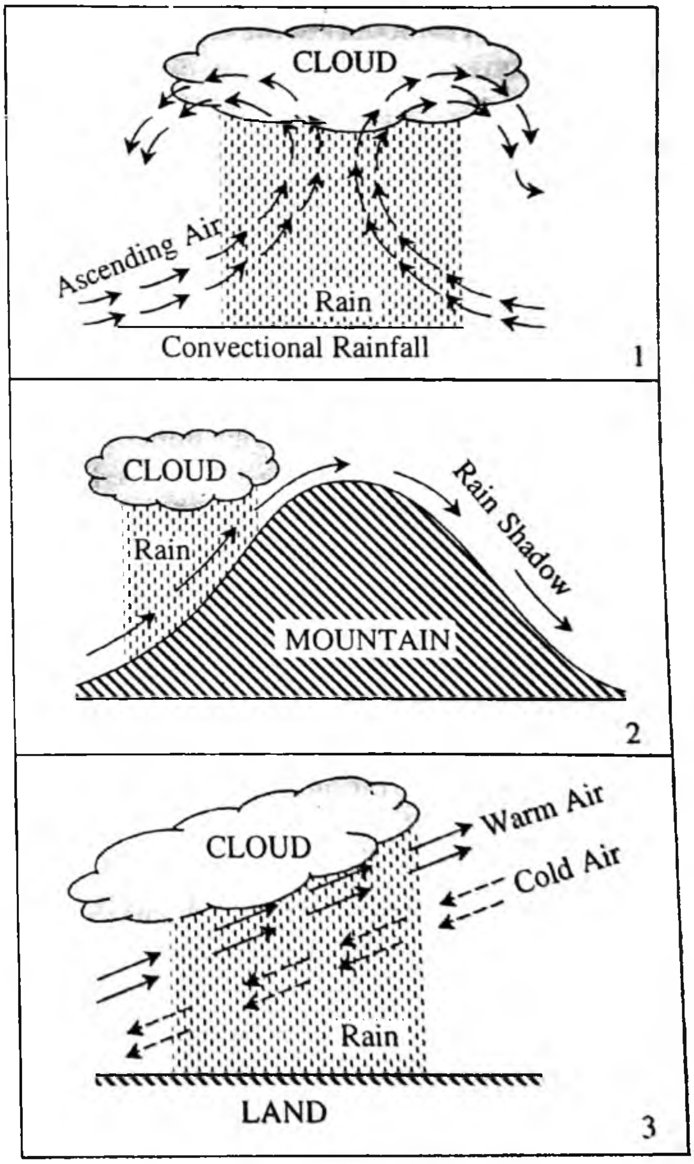


Fig. 9.3 : Types of rainfall : (1) convectional rainfall, (2) orographic rainfall, and (3) cyclonic or frontal rainfall.

(d) The windward slopes of the mountains at the time of rainfall are characterized by cumulus clouds while leeward slopes have stratus clouds.

(e) The amount of rainfall increases with increasing height along the windward slopes of the mountains upto a certain height beyond which the amount of rainfall decreases with increasing height because of marked decrease in the moisture content of the air. This situation is called **inversion of rainfall.** The height of the mountains beyond which the amount of rainfall decreases upward is called **maximum rainfall line** which varies spatially depending on the location of mountain, their distance from the sea, moisture content in the air, mountain slope, season etc. Maximum rainfall line is at 24,000 feet (7,000m) at the equator, at 12,000 feet (3,600 m) in the Himalayas, at 21,000 feet (6,300m) in the Alps, at 18,000 feet (5400m) during summer and at 12,000 feet (3,600m) during winter in the Pyrenees mountains etc.

(f) Orgraphic rainfall may occur in any season. Unlike other types of rainfall it is more widespread and of long duration.

(g) It may be pointed out that orographic rainfall is induced not only because of lifting of moist air due to mountain barrier but convective and cyclonic mechanisms also help in the process of orographic rainfall. For example, in warm regions valleys are heated during daytime (photoperiod) and hence winds are also heated and ascend along the hillslopes in the form of convection currents and yield rainfall after being saturated. Some times, forward moving cyclones are also forced to ascend along the hillslope due to obstructions offered by mountain barriers.

3. Cyclonic or Frontal Rainfall

Cyclonic or frontal rainfall occurs due to ascending of moist air and adiabatic cooling caused by convergence of two extensive air masses. The mechanism of cyclonic precipitation is of two types on the basis of two types of cyclones viz. temperate cyclones and tropical cyclones. Rainfall associated with temperate cyclones occurs when two extensive air masses of entirely different physical properties (warm and cold air masses) converge. When two contrasting air masses (cold polar air mass and warm westerly air mass) coming from opposite directions converge along a line, a front is formed. The warm wind is lifted upward along this front whereas cold air being heavier settles downward. Such cyclonic fronts are created in temperate regions where cold polar winds and warm westerlies converge. The warm air lying over cold air is cooled and gets saturated and condensation begins around hygroscopic nuclei. It may be pointed out that lifting of warm air along cyclonic front is not vertical like convective currents rather it is oblique. Since the lifting of warm air along the warm front of temperate cyclone is slow and gradual and hence the process of condensation is also slow and gradual, with the result precipitation occurs in the form of drizzles but continues for longer duration. Thus, the precipitation associated with warm front is widespread and of long duration. On the other hand, the precipitation associated with cold fronts is always in the form of thunder showers but is of very short duration. Sometimes, the precipitation occurs in the form of snowfall and hailstorms. This is because of the fact that lifting of warm air along cold front occurs quickly as cold air pushes warm air upward with great force. Most of the rains of temperate regions are received through cyclones.

Since the temperate cyclones consist of cells and hence weather conditions and associated precipitation in warm front, warm sector, cold front and cold sector differ significantly as described below :

(i) When the temperate cyclone coming from the western direction draws nearer to the observation point, wind velocity slows down considerably, air pressure decreases and the sun and the moon are encircled by halo which is infact the reflection of thin veneers of cirrus and cirrostratus clouds in the west. Temperature suddenly increases when the cyclone comes very close to the observation point, wind direction changes from easterly to south-easterly, the cloud cover thickens and the sky becomes overcast with dark, thick and low clouds.

(ii) **Warm frontal precipitation** : Clouds become very thick and dark with the arrival of warm front of the cyclone and heavy showers begin with nimbostratus clouds. Since the warm air rises slowly along the front, and hence the precipitation is slow, gradual but of long duration. The warm frontal precipitation largely depends on the amount of the moisture and instability of the rising warm air. If the air is full of moisture and is unstable, there is sufficient precipitation, the sky is overcast and the sun is not visible for several hours.

(iii) **Warm sector** : The warm sector comes over the observation point after the passage of warm front and there is sudden change in the pre-existing weather conditions. The wind direction becomes southerly. The sky becomes cloudless and clear. There is sudden rise in air temperature and increase in the specific humidity of the air but air pressure decreases remarkably. Though weather becomes clear but there may be some occasional drizzles. In all, the weather is clear and pleasant.

(iv) **Cold front** : Temperature registers marked decrease with the arrival of cold front. Cold increases considerably. The cold air pushes the warm air upward and there is change in wind direction from southerly to south-westely and westerly. Sky is again covered with clouds which soon start precipitation.

(v) **Cold frontal precipitation** : Sky becomes overcast with cumulonimbus clouds which yield heavy showers. Since the warm air is forcibly lifted upward hurriedly, the cold frontal precipitation is in the form of heavy downpour with cloud thunder and lightning but the precipitation is of short duration and less widespread because the cold sector is very close.

(iv) **Cold sector** : Weather again changes remarkably with the passage of cold front and arrival of cold sector. Sky becomes cloudless and hence clear. There is sharp fall in air temperature and considerable rise in air pressure but decrease in specific humidity. Wind direction changes from 45^0 to 180^0 and thus it becomes true westerly. After the occlusion of cyclone the weather conditions of pre-cyclone period again set in.

Tropical cyclonic precipitation : In tropical regions two extensive air masses of similar physical properties converge to form tropical cyclones wherein lifting of air is almost vertical and is very often associated with convection. It may be pointed out that convergence mechanism provides initial trigger effect to the upward movement of convectively unstable air which if full of moisture becomes saturated and yields heavy showers characterized by lightning and thunder. Tropical cyclones, regionally called as typhoons, hurricanes, tornadoes etc. yield heavy downpour in China, Japan, South-East Asia, Bangladesh, India, USA etc.

9.4.5 GLOBAL DISTRIBUTION OF PRECIPITATION

There is a wide range of spatial and temporal variation in the distribution of precipitation over the globe, *e.g.* the equatorial region records the highest mean annual rainfall which is more or less evenly distributed throughout the year, the tropical and subtropical hot deserts receive the lowest mean annual rainfall, the monsoon climatic regions receive more than 80 per cent of mean annual rainfall during four wet months of summer season (June to September), the monsoon lands also record the highest rainfall in the world (at Cherrapunji and Mawsyram, 1087 cm and 1141 cm respectively, in India), the polar areas receive precipitation in solid form etc.

Mean annual rainfall for the whole globe is 970 mm but this mean annual distribution is highly variable and unevenly distributed. Some places receive less than 100 mm of mean annual rainfall (for example, tropical hot deserts like Sahara, Thar, Acatama, Kalahari, Australian desert, Sonoran desert of North America etc.) while some places receive more than 10,000 mm of annual rainfall (*e.g.* Cherrapunji and Mawsyram of India). Not only this, there is much temporal variation of annual rainfall in a particular area (*e.g.* Bahia Felix of Chile has 325 rainy days, while Arica of the same country has only one rainy day per year, Iquique located near Arica could not receive any amount of measurable precipitation for 14 years in continuation from 1899 to 1913). 'It may seem strange that one of the areas with least frequent rainfall is in the same country as one of the rainiest places in the world' (J.E. Oliver and J.J. Hidore, 2003). If some regions have high mean annual rainfall with almost equal monthly averages (*e.g.* equatorial regions) while in some regions most of the annual amount of rainfall is received during a few months of the year while most of the months either remain dry or receive little rainfall. For example, 10870 mm of annual rainfall at Cherrapunji in India is received only in 159 rainy days. The equatorial regions receive rainfall throughout the year but other areas are characterized by seasonal rainfall. For example, more than 80 per cent of mean annual rainfall is received during 4 wet summer monsoon months in India. On the other hand, the Mediterranean regions receive most of their annual rainfall during winter months while summer season remains dry.

It appears that precipitation is controlled by a variety of factors and different combinations of these factors determine the spatial and temporal variations in the distribution over the globe, so, it is desirable to discuss those important factors which control the world distribution of rainfall before attempting regional/zonal and seasonal distribution of precipitation.

1. Controls of Precipitation Distribution

The spatial and temporal distribution of precipitation over the globe is controlled by a host of factors *e.g.* moisture content in the air, moisture retaining capacity of the air and rate and amount of evaporation (both are the functions of temperature and water surface), the general air circulation pattern in terms of convergent circulation or divergent circulation, the origin and movement of airmass, topographic conditions in terms of relief barriers, distance from the source of moisture, differential heating of land and sea surfaces etc. The influences of these factors on world distribution of precipitation need brief explanation.

(1) **Moisture content of the air** is supposed to be positively correlated with rainfall (both type and amount) while atmospheric humidity is closely related with air temperature through the process of evaporation. The atmospheric moisture depends on evaporation of water or ice through the input of heat energy. Thus, precipitation is also, though indirectly, related to evaporation. The regions having high temperature and abundance of surface water, and of course wide open oceanic surfaces for evaporation, receive higher amount of annual rainfall. Equatorial regions are typical examples of such situation. Subtropical regions are also characterized by above conditions but the western parts of the continents receive least rainfall because there are anticyclonic conditions due to descent of air and resultant aridity.

The direct positive relationship between moisture content in the air and amount of precipitation resulting therefrom has been refuted by a few scientists. They contend that it is not the amount of moisture in the air alone which controls rainfall distribution. 'The presence of water vapour is a necessary but not sufficient condition for precipitation. There is no direct relationship between the amount of atmospheric water vapour over an area and the resulting precipitation. To illustrate this, a comparison can be made between conditions over El Paso, Texas (USA), and St. Paul, Minnesota (USA). The average moisture content above these cities is about the same and yet the mean annual precipitation is more than three times greater at St. Paul, (J.E. Oliver and J.J. Hidore, 2003).

(2) **The convergent or divergent air circulation** determines the ascent or descent of air and its adiabatic cooling or heating which in turn determines the amount of precipitation. The convergence of two contrasting airmasses creates frontal activity where warm airmass is pushed upward by underlying cold airmass resulting into uplifting of warm and moist airmass. The overlying warm and moist air is cooled and precipitation occurs after condensation. Such frontal zone of convergence is responsible for precipitation in middle latitudinal zones mainly in the northern hemisphere through temperate cyclones. The other significant convergence zone is intertropical convergence (ITC) where tropical moist air masses converge and force moist air to ascend and yield precipitation. The warm and moist tropical winds (trade winds) are also uplifted by orographic barriers in the coastal areas. On the other hand, divergent circulation allows descent of air from above and creates anticyclonic condition and atmospheric stability resulting into dry weather. Such situation develops in the subtropical high pressure area (20^0-30^0). This is why most of the hot deserts of the world are found in this zone.

(3) **Topographic conditions** present both favourable and unfavourable conditions for precipitation. If the mountain barriers parallel the coastal lands and there is onshore moist air (relief barriers transverse to wind direction), the moist air is forced by the mountains to ascend and cool adiabatically ultimately yielding percipation, the

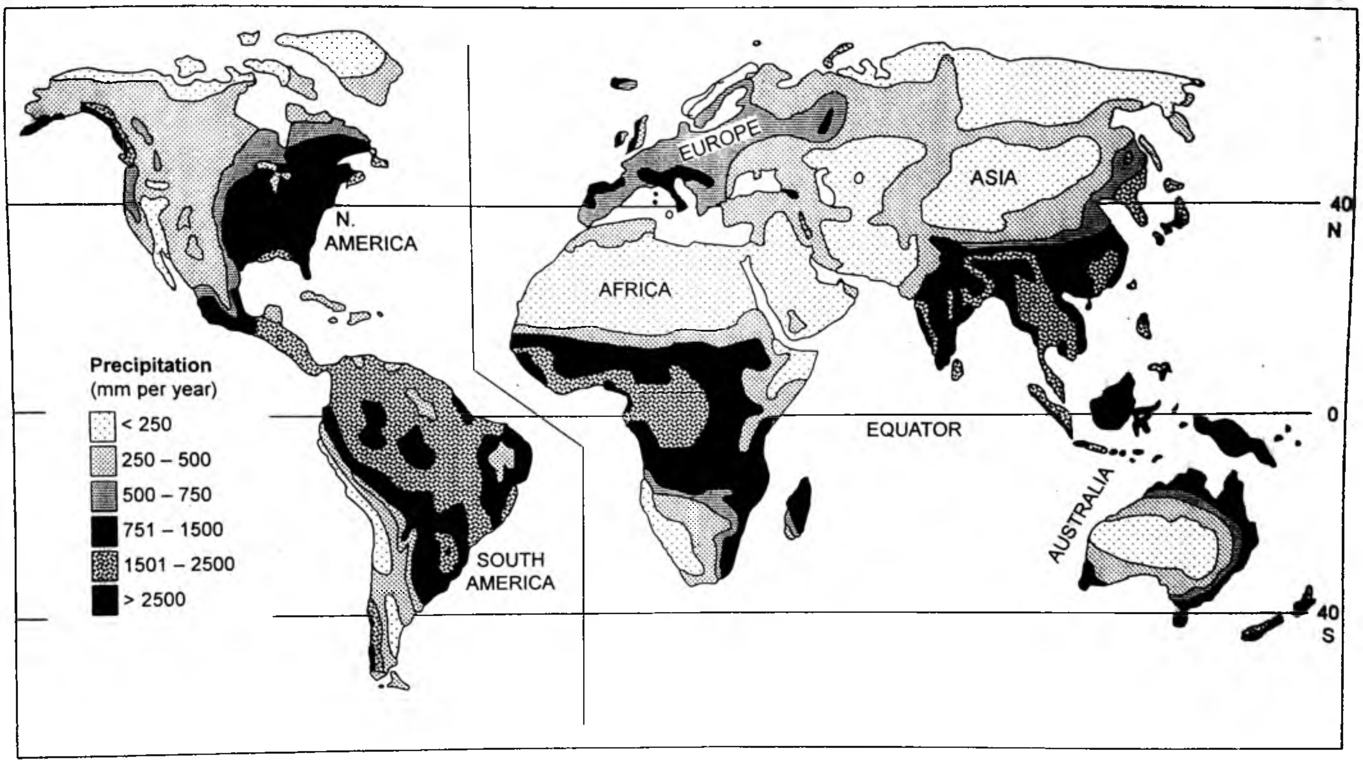


Fig. 9.4 : World distribution of rainfall.

amount of which depends on the moisture content of the air. Such conditions are available along the west coasts of India (where north-south stretching western Ghats obstruct moisture laden south-west monsoon winds coming from over the Arabian Sea and these winds after little ascent along the western slopes of the Western Ghats give copious rainfall), along the west coastal areas of North America where Coast Ranges obstruct the moisture laden winds coming from over the Pacific Ocean and force them to ascend, cool and yield heavy precipitation, etc. The effects of mountain on precipitation have been discussed in the section 9.4.4 (2).

(4) **Distance from the source of moisture** determines the amount of precipitation in different areas. As the distance from the source of moisture (mainly oceans) increases, the moisture content and hence the amount of precipitation decreases. For example, trade winds give more precipitation in the eastern parts of the continents and the amount decreases westward because the westward moving winds lose moisture. The monsoon winds in India give more rainfall in the coastal areas than in the interior regions. The continental deserts located in the interior of the continents are arid because they are far away from oceanic source of moisture (it is to be remembered that atmospheric moisture in the form of water vapour is supplied through evaporation of water surfaces). The amount of precipitation decreases eastward from the west coastal plains of North America in response to increasing distance from the source of moisture of the Pacific Ocean. Here mountain (barrier) effect is equally important. The Coast Ranges receive more than 2000mm of annual rainfall while the zone situated between the Sierra Nevada—Cascade Range, and the Rockies extending from the border of Mexico to the Canadian border with the USA receives less than 250 mm of annual rainfall because of its location in the rainshadow region and ofcourse at greater distance from the Pacific Oceanic source of atmospheric moisture. Similar pattern is found along the western coastal plains of India and in the areas located further eastward. The west slopes, which are very close and parallel to the Arabian Sea coast, of the Western Ghats receive mean annual rainfall of more than 2000 mm but as the distance from the coast increases eastward, rainfall amount decreases, for example, the regions to the east of the Western Ghats falling in Karnatka receive about 500mm of annual rainfall. The amount of annual rainfall decreases from Kolkata (1582 mm) in West Bengal (near to the source of moisture of the Bay of Bengal) westward *i.e.* 1000 mm at Patna, 1050 mm at Allahabad, 650 mm at Delhi etc.

2. Zonal Distribution of Rainfall

It is true that the cooling of ascending air is a prerequisite condition for the occurrence of rainfall. The air is lifted through thermal convective mechanism, convergence of two extensive air masses and obstruction of mountain barriers. If the relative importance of these three factors in different areas of the world is taken into account, it appears that air is generally lifted due to convergence of two extensive air masses in most parts of the world. Convergence of air masses is directly related with air temperature and air pressure. There are two major convergence zones of air masses *i.e.*, trade winds converge along the equatorial low pressure belt and westerlies and polar winds converge along high latitude low pressure (60^0-65^0 latitudes in both the hemispheres). On the other hand, winds descend near subtropical high pressure belt (30^0-35^0 latitudes in both the hemispheres) and diverge in opposite directions and form anticyclones which introduce dry weather. Since the convergence of air masses is in zonal form and hence rainfall distribution is also found in zonal pattern. Besides, moisture content, mountain barriers and land and water (continents and oceans) also influence world distribution of rainfall. Since air moisture depends upon temperature and horizontal distribution of temperature is found in zonal patterns and hence rainfall distribution is also characterized by zonal pattern. Based on above considerations, 6 major zones of rainfall distribution are identified on the earth's surface.

(1) **Equatorial zones of maximum rainfall :** This zone extends upto 10^0 latitudes on either side of the equator and falls within intertropical convergence characterized by warm and moist air masses. The mean annual rainfall ranges between

1750 mm and 2000 mm. Most of the rains are received through convectional rainfall accompanied by lightning and cloud thunder. There is daily rainfall in the afternoon. The rainfall intensity is very high as it occurs in the form of heavy showers. The clouds are cleared within short period and sky becomes cloudless in the late evening.

(2) Trade wind rainfall zone extends between 10^0-20^0 latitudes in both the hemispheres and is characterized by north-east and south-east trade winds. These winds yield rainfall in the eastern parts of the continents because they come from over the oceans and hence pick up sufficient moisture but as they move westward in the continents they become dry and thus the western parts of the continents become extremely dry and deserts. The monsoon regions located in this zone receive much rainfall. Summers receive most of the mean annual rainfall.

(3) Subtropical zone of minimum rainfall extends between 20^0 and 30^0 latitudes in both the hemispheres, where descending air from above induces high pressure and winds diverge in opposite directions at the ground surface, with the result anticyclones are formed. This condition is not conductive for rainfall and hence dry conditions prevail over large areas. Mean annual rainfall is 900 mm. It may be pointed out that all the tropical hot deserts are located in this zone where mean annual rainfall is below 250mm. The average annual rainfall becomes, for the whole zone, higher (900mm) than the average value for the deserts because the eastern parts of the continents receive more rainfall from relatively moist trade winds which come from over the oceans. Most of annual rainfall occurs during summer months while winter season is dry.

(4) Mediterranean rainfall zone extends between 30^0-40^0 latitudes in both the hemispheres where rainfall occurs through westerlies and cyclones during winter season while summers remain dry because this zone comes under the influence of trade winds due to northward shifting of wind and pressure belt during northern summer (summer solstice). Mean annual rainfall is 1000mm.

(5) Mid-latitudinal zone of high rainfall extends between 40^0-50^0 latitudes in both the hemispheres where rainfall occurs through westerlies and temperate cyclones. Mean annual rainfall ranges between 1000 mm and 1250 mm. The western parts of the continents receive more rainfall. It decreases from the western coastal areas inland. Southern hemisphere records more rainfall than northern hemisphere because of the dominance of oceans in the former. Winter season receives maximum precipitation through temperate cyclones. The precipitation is of long duration but occurs in the form of light showers.

(6) Polar zone of low precipitation : Precipitation decreases from 60^0 latitude poleward in both the hemispheres. Mean annual precipitation becomes only 250mm beyond 75^0 latitude. Most of the precipitation occurs in the form of snowfall.

Patterson has divided the globe into 15 rainfall zones wherein the northern and southern hemispheres account for 7 zones each and the remaining zone is on either side of the equator. These rainfall zones have been identified mainly on the basis of seasonal behaviour of rainfall.

	latitudes
(i) Rains throughout the year	7^0N to 7^0S
(ii) Summer rains, winter dry	7^0-16^0
(iii) Light summer rains	16^0-20^0
(iv) All seasons dry, minimum rains	20^0-30^0
(v) Light winter rains	30^0-35^0
(vi) Summer dry, winter rains	35^0-45^0
(vii) All seasons rains, maximum in summers	40^0-70^0
(viii) All seasons scanty precipitation, mostly snowfall	70^0-90^0

3. Rainfall Regime (Seasonal Distribution)

Precipitation or rainfall regime refers to seasonal behaviour and variation of rainfall. Haurwitz and Austin have identified 6 rainfall regimes.

(1) Equatorial rainfall regime is characterized by rainfall in all seasons but there are two maxima in March (vernal equinox) and September (autumnal equinox). Thermal convection air currents generated by intense insolational heating of the ground surface account for most of the rains. Besides, convergence of trade winds also causes cyclonic rains. This zone extends between 10^0N and 10^0S latitudes. At the outer limit of this zone there is only one rainfall maximum. The rainfall is accompanied by lightning and thunder and occurs in the form of heavy showers but is of short duration.

(2) Tropical rainfall regime has one rainfall maximum and one minimum in a year. In the northern hemisphere the eastern parts of the continents receive maximum and minimum rainfall in the months of July and December respectively whereas the western parts of the continents get maximum rainfall in December and minimum in July.

(3) Monsoon rainfall regime is characterized by maximum rainfall in July and August (northern hemisphere). Thus, there is summer maximum and winter minimum. Summer rainfall is received through south-west and south wet monsoon winds associated with tropical atmospheric disturbances (cyclones). Most of the rains are orographic and cyclonic in origin.

(4) Mediterranean rainfall regime receives maximum rainfall during winter season because the zone of this regime comes under the domain of prevailing westerlies during winters due to shifting of pressure and winds belts. Summer is a dry season.

(5) Continental rainfall regime is characterized by maximum precipitation in summers when convective mechanism due to insolational heating of the ground surface is maximum. Winters are dry because of the prevalence of anticyclonic conditions. This regime is found in the interior of the continents.

(6) Maritime rainfall regime : Temperate areas record maximum precipitation in winter over the oceans and adjoining coastal areas due to maximum cyclonic activity. This regime is found along the western margins of the continents in middle latitudes.

9.5 MAN-INDUCED PRECIPITATION

Man-induced precipitation refers to artificial nucleation of ice crystals in supercooled clouds through the introduction of dry ice, silver iodide (in the form of iodide powder or in the form of smoke), finely ground salt, solid carbon dioxide, iodine compounds etc. to augment condensation process to yield precipitation. The technique of man-induced percipitation involves **cloud seeding** by the above mentioned materials. The cloud seeding comes under the programme of weather modification by man for various purposes *e.g.* for hailstorm suppression, dissipation of fog, reduction of velocity and force of tropical cyclones (mainly in the USA), suppression of lightning, augmentation of precipitation etc. wherein the latter is the most optimistic purpose. The above mentioned materials are sent upward in the suppercooled clouds by aeroplanes, explosive rockets, baloons, burners (to seed smoke) etc.

The ideal conditions for cloud seeding require the presence of suppercooled clouds with great thickness (*i.e.* precipitable and seedable clouds with vertical thickness of 1500m or more) and moist weather. It may be mentioned that cloud seeding may increase precipitation or sometime may also decrease precipitation, *e.g.* if cumulus clouds in maritime environment are seeded with cloud seeding materials, as mentioned above, additional nuclei are formed which lead to crowding of nuclei and increase in tiny droplets. This causes reduction in precipitation because tiny droplets cannot fall down unless they are aggregated and become too large to be held by the air. The orographic clouds (the clouds formed due to ascent of moist air forced by mountains and resultant saturation of the air) are considered most productive seedable clouds to yield precipitation. Experiments on cloud seeding in Tasmania have revealed that seeding of stratiform clouds with suitable seeding materials increased precipitation while seeding of cumulus clouds reduced precipitation.

The crystallization of supper cooled droplets through the application of solid carbon dioxide and certain compounds of iodine has proved productive in stimulating clouds and inducing precipitation. 'A few hundred grams of solid carbon dioxide or a few grams of iodine compound are enough to crystallize a cubic kilometer of supper cooled cloud of water drops' (E. Fedorov, 1983). It may be mentioned that V.J. Schaefer and E. Langmuir (the American scientists) were the first to use dry ice to seed the cloud to induce precipitation in the year 1946. Later on silver iodide was found suitable seedable material by B. Vonnegut in the year 1949.

The cloud seeding and intended induced precipitation is also plagued by certain problems *e.g.* (1) the assessment of productiveness of cloud seeding to stimulate rainfall is not without error, (2) the expenditure involved in the artificial cloud seeding is very high while the result is not so encouraging, (3) the effectiveness of cloud seeding has not been properly demonstrated by practical experience, (4) the environmentalists raise objections to such anthropogenic weather modification programmes as these may interfere with natural atmospheric and environmental processes etc.

9.6 IMPORTANT DEFINITIONS

Cheyenne fog : Upslope fogs in the south-eastern Wyoming of the USA are called Cheyenne fogs because it is a place.

Cloud droplets : Cloud droplets refer to the deposition of moisture after condensation around large hygroscopic nuclei.

Cloud seeding : Cloud seeding is artificial means of injection of seedable materials (*e.g.* iodine compounds, solid carbon dioxide, dry ice, iodide etc.) in the suppercooled precipitable clouds to induce precipitation by man.

Dew point : The temperature at which the given air is saturated *i.e.* the humidity holding capacity and absolute humidity of a given volume of air at given temperature and point of time become equal, is called dew point.

Drizzle : Drizzle is defined as the fall of numerous tiny water droplets having diameter of less than 0.5mm.

Freezing rains : Freezing rains or freezing drizzles are formed when the drizzles or very light rains occur below 0^0C temperature, they are frozen before reaching the ground surface and hence are called freezing rains or freezing drizzles. They are also called as **crachins**.

Hail : Hail consists of large pellets or spheres (balls) of ice. Hail is a form of solid precipitation wherein small balls or pieces of ice, known as hailstones, having a diameter of 5mm to 50 mm fall downward known as hailstorms.

Inversion of rainfall : The decrease of rainfall with increasing height along a mountain slope because of marked reduction in moisture content upward is called inversion of rainfall.

Leeward slope : The opposite side slope of the hills or mountains through which the wind descends and is warmed adiabatically resulting into very low rainfall is called leeward slope and rainshadow region.

Man-induced precipitation : Man-induced precipitation refers to artificial nucleation of ice crystals in suppercooled clouds through the injection of dry ice, silver iodide, finely ground salt, solid carbon dioxide, iodine compounds etc. to augment. condensation process to yield precipitation.

Pea-soup : The urban smog over London city is locally called pea-soup.

Pogonip : The fogs comprising numerous ice crystals and supercooled water droplets are locally known as pogonip in the mountains of the USA.

Rainfall regime : Rainfall regime refers to seasonal distribution and variation of rainfall.

Rime : Rime 'is an opaque coating of tiny, white, granular ice particles, caused by rapid freezing of supercooled water droplets on impact with an object.'

Saturated air : The air having cent per cent relative humidity is called saturated air. In othder words, a saturated air is that of which absolute humidity and moisture retaining capacity are equal.

Sleet : Sleet refers to mixture of snow and rain but in American terminology sleet means falling of small pellets of transparent or translucent ice having a diameter of 5mm or less.

Virga : Virga refers to such type of precipitation which after occurring from cumulus clouds in summer is evaporated before reaching the ground surface.

Windward slope : The slope of the mountain facing the wind is called windward or onward slope and receives maximum precipitation.

10

AIR MASSES

10.1 MEANING AND DEVELOPMENT OF CONCEPT

The concept of air mass owes its inception during World War I when V. Bjerknes and his son J. Bjerknes, the Norwegian scientists, studied the importance of large-scale atmospheric circulation involving both horizontal and vertical components and thus identified large and extensive body of air having more or less homogeneity of temperature and humidity both horizontally and vertically. Such large air body was named as air mass by them. Later on, T. Bergeron, J. Bjerknes and Solberg recognised the role of air mass in meteorology mainly for weather forecasting. The concept of airmass was further developed on the basis of meteorological data obtained during military operations in the decade 1940s. The further development of air mass concept lead to its close relationship with synoptic climatology, which 'may be defined as the study of climates in relation to atmospheric circulations; it emphasizes the relationships among air circulation, weather types, and climatic regional differences' (J.E. Oliver and J.J. Hidore, 2003).

The term and concept of air mass have been defined by a few persons as follows. According to Barry and Chorley (1968) 'an airmass may be defined as a large body of air whose physical properties, especially temperature, moisture content, and lapse rate (of temperature), are more or less uniform horizontally for hundreds of kilometers'. It appears from this definition that vertical characteristics of air mass have not been included. According to A.N. Strahler and A.H. Strahler (1978) 'a body of air in which the upward gradients of temperature and moisture are fairly uniform over a large area is known as an air mass.' This definition suffers from the shortcoming of exclusion of physical characteristics in horizontal component of the air mass. Alternatively, 'air mass is a large, horizontal, homogeneous body of air that may cover thousands of square kilometers and extend upward for thousands of meters. Its uniformity is principally one of temperature and humidity' (Oliver and Hidore, 2003). It is evident from the aforesaid three definitions that horizontal homogeneity in relation to temperature and humidity has been included in the first definition while vertical homogeneity has been included in the second definition. Now, question arises, as to why there should be vertical and horizontal homogeneity in an air mass. The answer is simple, the horizontal extent of air mass is so large that horizontal homogeneity is not possible because the air mass spreads over heterogeneous topographic areas. In other words, 'an airmass may be so extensive that it may cover a large portion of a continent and it may be so thick in vertical dimension that it may vertically extend through the troposphere'. 'It may be pointed out that since a single air mass is so large that it may cover hundreds of thousands to millions of square kilometers of the earth's surface, and hence horizontal homogeneity of an air mass in terms of its physical properties may not be practically possible because the nature and degree of uniformity of air mass properties depend upon (1) the topographic characteristics, (2) the properties of the source area and direction of its movement, (3) changes introduced in the air mass during its journey away from the source area, and (4) the age of air mass' (Savindra Singh, 2004, p 481). All of these vary considerably over the earth's surface and hence complete horizontal homogeneity in terms of temperature and humidity is not possible. Similarly, the temperature and moisture content also change with altitude. So horizontal and vertical homogeneity should be taken in general sense and not in specific sense.

10.2 CHARACTERISTICS OF AIR MASS

The basic characteristic features of air mass which control the weather conditions of the area affected (visited) by a particular air mass include (1) vertical distribution of temperature in an air mass, and (2) moisture content of the air. It may be pointed out that the nature of vertical distribution of temperature in air mass denotes the stability or instability of air mass while the content of moisture determines the nature and degree of condensation which in turn determines whether the weather would be moist, semi-moist or dry. The significance of air mass lies in the fact that it plays major role in the transfer of energy in the atmosphere through its movement from its source region.

The thermal nature of an air mass is determined on the basis of temperature. An air mass is designated as cold air mass when its temperature is less than the temperature of the underlying surface while an air mass is termed warm air mass when its temperature is higher than the underlying ground surface. The boundary between two different air masses, when they converge, is called front. The physical properties of an air mass is determined on the basis of the characteristic feature of the ground surface through which it travels. An air mass also affects and modifies temperature and moisture conditions of the areas visited by it and in term it is also modified by the local conditions of the visited areas. The degree of air mass modification depends upon the distance covered by the air mass after its movement from the source region. Air mass characteristics are also helpful in weather forecasting.

10.3 SOURCE REGIONS

The extensive areas over which air masses originate or form are called source regions whose nature and properties largely determine the temperature and moisture characteristics of air masses. An air mass originates when atmospheric conditions remain stable and uniform over an extensive area for fairly long period so that the air lying over that area attains the temperature and moisture characteristics of the ground surface. Once formed, an air mass is seldom stationary over the source region, rather it moves to other areas.

An ideal source region of air mass must possess the following essential conditions. (i) There must be extensive and homogeneous earth's surface so that it may possess uniform temperature and moisture conditions. The source region should be either land surface or ocean surface because irregular topography and surface comprised of both land and water cannot have uniform temperature and moisture conditions. (ii) There should not be convergence of air, rather there should be divergence of air flow so that the air may stay over the region for longer period of time and thus the air may attain the physical properties of the region. It is, thus, apparent that anticyclonic areas characterised by high barometric pressure and low pressure gradients are most ideal regions for the development of air masses. (iii) Atmospheric conditions should be stable for considerable long period of time so that the air may attain the characteristics of the surface.

The air mass source regions are divided into two categories *e.g.* (1) **primary source regions**, and (2) **secondary source regions**. The primary source regions are extensive where air mass lies for fairly long period. Such source regions are tropical warm sea surfaces and hot desert land surfaces, and Arctic cold region. The secondary source regions are characterized by extensive uniform surfaces where the air mass does not stay for longer period, rather the air mass moves away after its origin. In other words, the secondary source regions are those where air masses are transformed (modified) and attain unique characteristic features. It may be mentioned that air mass source region cannot be convergence zone of air, rather it should be divergent zone.

There are 6 major (primary) source regions of air masses on the earth's surface *e.g.* (1) polar oceanic areas (North Atlantic Ocean between Canada and Northern Europe, and North Pacific Ocean between Siberia and Canada-during winter season), (2) polar and arctic continental areas (snow-converted areas of Eurasia and North America, and Arctic region during winter season), (3) tropical oceanic areas (anticyclonic areas-throughout the year), (4) tropical continental areas (North Africa-Sahara, Asia, Mississippi Valley zone of the USA-most developed in summers), (5) equatorial regions (zone located between trade winds-active throughout the year), and (6) monsoon lands of S.E. Asia.

Source regions are also classified on the basis of (A) nature of surface into (1) continental source region and (2) maritime (oceanic) source region, and (B) on the basis of latitudes into (1) equatorial source region, (2) tropical source region, (3) polar source region, and (4) arctic source region.

10.4 MODIFICATIONS OF AIR MASSES

The air mass after being originated in the source region moves away and carry most of the initial physical properties which include (1) lapse rate of temperature (*i.e.* vertical distribution of temperature, (2) mean temperature, (3) moisture content in the air, (4) wind velocity etc. As regards horizontal component of the air mass, there is more or less uniformity in terms of their physical properties but there are variations in vertical component of the air mass. As the air mass moves away from the source region it affects the weather conditions of the area visited by the air mass but the air mass is also modified in terms of its physical properties as mentioned above by the physical properties of the visited area. The modifications in the physical properties of air mass are effected by (1) the temperature of ground surface of the visited area which determines warming (if the temperature of the ground surface is higher than the overlying visitor air mass) or cooling (if the temperature of the ground surface is less than overlying air mass) of air mass from below, (2) the degree of radiational heating (from solar radiation) and cooling (loss of heat through terrestrial radiation) of the ground surface, (3) addition of moisture through increased evaporation or loss of moisture due to condensation and precipitation, (4) the vertical air circulation pattern, whether subsidence of air from above or upward movement (uplifting of air either due to radiation heating or mechanical uplifting-forced uplift) etc. It is evident that the modifications of air masses are of two types, namely (1) **thermodynamic modifications** by heating or cooling of air mass from below, changes in moisture content either by increased or decreased evaporation, increase in moisture content from precipitation of overlying moist air, and (2) **mechanical modifications** caused by uplift or subsidence of air, turbulent mixing, divergence or convergence of air circulation etc.

1. Thermodynamic Modifications

Thermodynamic modification of an air mass involves its heating or cooling from below while passing through different surfaces away from the source region. Heating of an air mass causes decrease in the vertical stability of the atmosphere. After being originated the air masses move out of their source regions to other regions and in the process they modify the weather conditions of the areas travelled by them and in turn they also get modified by the surface conditions over which they move. The thermodynamic modifications of air masses, besides heating or cooling from below, also include evaporation of water into the air from below or into intermediate layer by precipitation from moist air aloft.

The modification of air masses depends on 4 factors *e.g.* (i) initial characteristics of air mass in terms of temperature and moisture content, (ii) nature of land or water surface over which a particular air mass moves, (iii) path followed by the air mass from the source region to the affected area, and (iv) time taken by the air mass to reach a particular destination.

An air mass while moving over the surface whose temperature is greater than the lower layer of the moving air mass, is heated from below and becomes unstable due to resultant steepened lapse rate and upward movement of air. This mechanism causes condensation, cloud formation and precipitation if the moving air mass contains sufficient amount of moisture content. On the other hand, if the moving air mass is warmer than the surface over which it travels, it is cooled from below resulting into atmospheric stability which restricts upward movement of the air and thus there is no chance for condensation, cloud formation and precipitation. It is, thus, obvious that cold polar air masses while moving from their source regions to relatively warmer surfaces become unstable because they are warmed from below. On the other hand, warm tropical air masses, when move out of their source areas and reach colder surfaces, are cooled from below, causing atmospheric stability and dry weather.

A **warm air mass** (w) is that whose temperature is greater than the surface temperature of the region visited while if the air mass is colder than the surface temperature it is called **cold air mass** (k). It is apparent that the warmness or coldness of an air mass is determined by the temperature of the underlying surface. Air mass also undergoes thermodynamic modification when evaporation is added to it from outside.

2. Mechanical Modifications

Mechanical or **dynamic modification** of air mass involves vertical (upward-uplift and downward-subsidence) and advectional movement of air and resultant changes in the air mass. An air mass is termed stable air mass when air descends while an air mass becomes unstable when upward movement of air is operative. Such **mechanical modifications** in an air mass are introduced due to cyclonic and anticyclonic conditions. Besides, mechanical modifications are also introduced due to (i) turbulent mixing caused by eddies or convection, (ii) divergence and convergence of air masses and their effects on lapse rate of temperature, (iii) subsidence of air and lateral expansion on the ground surface (anticyclonic conditions), (iv) lifting of air and convergence of air at the ground surface (cyclonic conditions), and (v) advection.

Based on thermodynamic and mechanical (dynamic) modifications air masses are divided into (i) cold air mass and (ii) warm air mass, each of which is further divided into (a) stable air mass, and (b) unstable air mass.

10.5 CLASSIFICATION OF AIR MASSES

Any classification of air masses must consider the fact that all of their weather characteristics (mainly temperature, humidity and lapse rate) are properly represented and incorporated. Thus, the weather conditions of air masses at their source regions and thermodynamic and mechanical modifications introduced in them during their journey away from their respective source regions must be taken into consideration while classifying them into definite categories. There are two approaches to the classification of air masses *e.g.* (1) geographical classification, and (2) thermodynamic classification.

1. Geographical Classification

The geographical classification of air masses is based on the characteristic features of the source regions. Basically air masses are classified into (1) warm air mass, and (2) cold air mass on the basis of temperature of the source regions. Trewartha has classified air masses on the basis of their geographical locations into two broad categories viz. (i) Polar air mass (P), which originates in polar areas. Arctic air masses are also included in this category, (ii) Tropical air mass (T), which originates in tropical areas. Equatorial air masses are also included in this category. These two air masses have been further divided into two types on the basis of the nature of the surface of the source regions (whether continental or oceanic areas) *e.g.* (a) continental air masses (indicated by a small latter c), and (b) maritime air masses (indicated by a small letter m). It may be pointed out that a continental air mass gets modified and is transformed into maritime type while passing through ocean surface but maritime air mass is seldom transformed into continental type while passing through land surface. Based on above facts air masses are classified into the following four principal types according to their geographical locations.

(1) Continental polar air mass (cP)

(2) Maritime polar air mass (mP)

(3) Continental tropical air mass (cT)

(4) Maritime tropical air mass (mT)

2. Thermodynamic Classification

Based on thermodynamic and mechanical (dynamic) modifications air masses are divided into (1) cold air mass, and (2) warm air mass, each of which is further divided into (i) stable air mass, and (ii) unstable air mass.

(1) **Cold air masses** originate in the polar and arctic regions. They are characterized by the following properties in their source regions :

(i) Temperature is very low because of loss of heat through outgoing longwave terrestrial radiation.

(ii) Specific humidity is extremely low.

(iii) Stability increases and normal lapse rate of temperature is low.

Cold air masses after moving out from their source regions and reaching other areas have the following properties :

(i) The temperature of the areas where cold air masses reach starts decreasing.

(ii) The air mass is warmed from below and thus normal lapse rate increases and the air becomes unstable. This mechanism causes convective currents.

(iii) If the cold air mass lies over warm ocean surface, then its specific humidity increases and cumulo-nimbus clouds are formed.

(iv) The usual visibility in the air mass is maintained.

(v) Precipitation occurs only when the air mass lies over warm ocean surface but if it lies over warm continent, there is clear weather.

(vi) If the cold air mass lies partly over warm ocean surface and partly over adjoining cold land surface, then cyclonic conditions are induced.

Cold air masses are further divided into (a) continental cold air mass, and (b) maritime cold air mass.

(2) **Warm air mass** is that whose temperature is greater than the surface temperature of the areas over which it moves. Such air mass is cooled from below and thus its lower layer becomes stable due to which its vertical movement stops. Warm air masses generally originate in the subtropical regions characterized by anticyclonic conditions. They are further divided into (a) continental warm air mass, and (b) maritime warm air mass.

3. Composite Classification

Based on thermodynamic and mechanical (dynamic) modifications and some other considerations air masses are divided into 16 types as follows :

(A) Continental Polar Air Masses (cP)

(1) Continental Polar Cold Stable Air Mass (cPKs)

(2) Continental Polar Cold Unstable Air Mass (cPKu)

(3) Continental Polar Warm Stable Air mass (cPWs)

(4) Continental Polar Warm Unstable Air Mass (cPWu)

(B) Maritime Polar Air Masses (mP)	(5) Maritime Polar Cold Stable Air Mass (mPKs)
	(6) Maritime Polar Cold Unstable Air mass (mPKu)
	(7) Maritime Polar Warm Stable Air Mass (mPWs)
	(8) Maritime Polar Warm Unstable Air Mass (mPWu)
(C) Continental Tropical Air masses (cT)	(9) Continental Tropical Cold Stable Air Mass (cTKs)
	(10) Continental Tropical Cold Unstable Air Mass (cTKu)
	(11) Continental Tropical Warm Stable Air Mass (cTWs)
	(12) Continental Tropical Warm Unstable Air Mass (cTWu)
(D) Maritime Tropical Air masses (mT)	(13) Maritime Tropical Cold Stable Air Mass (mTKs)
	(14) Maritime Tropical Cold Unstable Air Mass (mTKu)
	(15) Maritime Tropical Warm Stable Air Mass (mTWs)
	(16) Maritime Tropical Warm Unstable Air Mass (mTWu)

c = contientaal, T = tropical, m = maritime, K = cold, W = warm, u = unstable, s = stable

10.6 CHARACTERISTICS OF MAJOR AIR MASSES

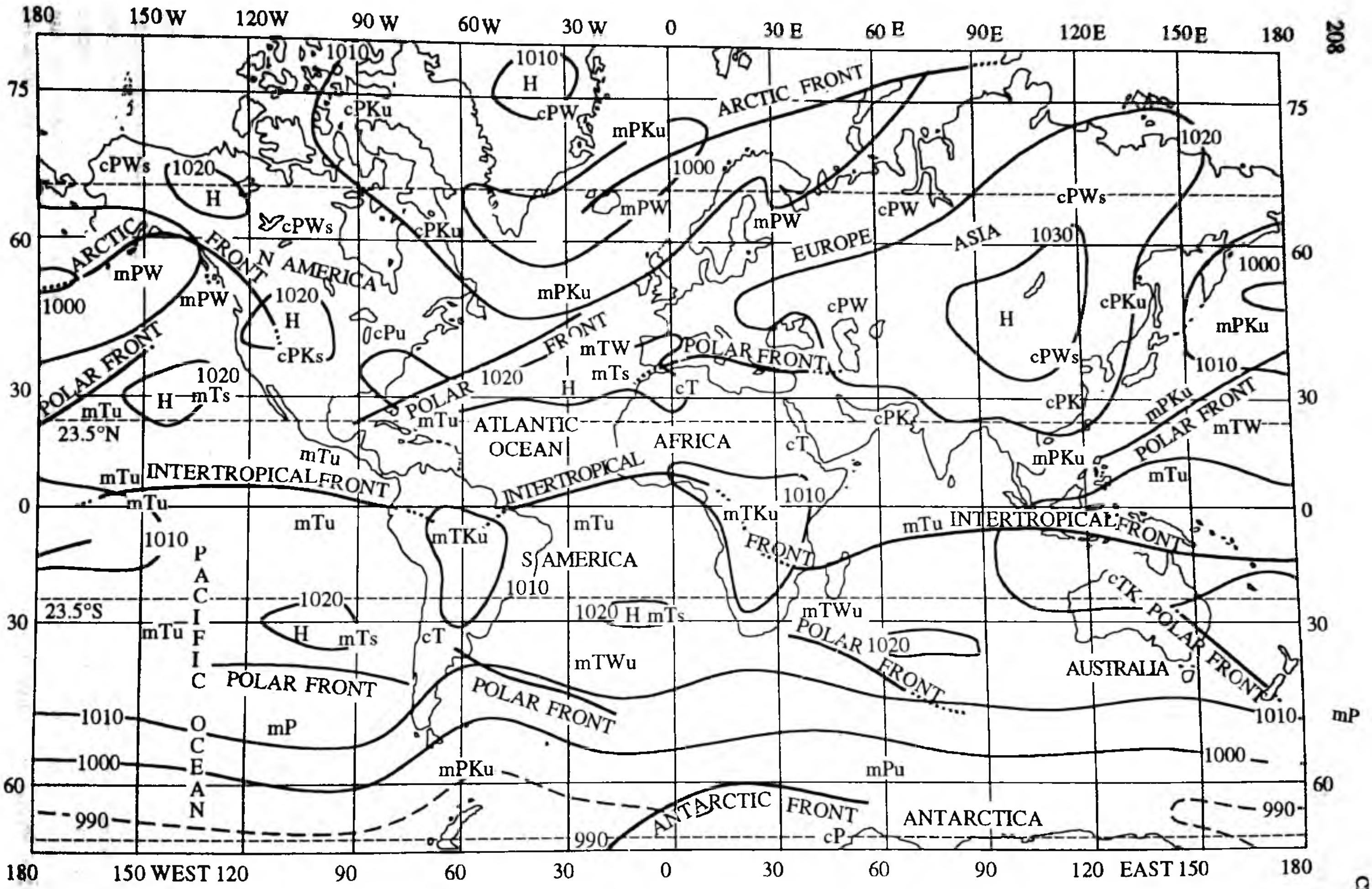
As mentioned above air masses fall in two broad categories on the basis of locational aspect of their source regions, namely (1) polar air masses, and (2) tropical air masses. These are further subdivided into (a) continental, and (b) maritime air masses. The characteristic features of these major air masses are discussed below :

1. Polar Continental Air Mass (cP)

The polar continental air masses originate over the extensive cold surfaces of central Canada and Siberia and move outward and are thermodynamically and mechanically (dynamically) modified. These air masses have different physical characteristics during summer and winter seasons. The polar continental air masses are generally cold and dry but when these move over warmer surfaces they are heated from below and become unstable and moist to some extent resulting into the formation of limited clouds mainly low stratocumulus. The source areas, due to their location in high latitudes, are frozen during winter season, the air mass is cold, dry and stable. Intense cold waves are generated in those areas which are visited by these extremely cold air masses. For example, the winter time polar continental air mass after being originated over frozen land surface of central Canada, bring extreme cold weather in the Mississippi plains of the USA. Even in the summer, sometimes frost conditions become common as far south as New Orleans, Galveston and Huston of the USA. In the summer, the snow covered surface gets rid off snow and ice because of its melting due to heating but still summer time continental polar air masses are cool and dry in their source regions of central Canada and Siberia. When these air masses move over the oceanic surfaces, they are warmed from below and become warm and give some precipitation through cumulus or low stratocumulus clouds.

2. Polar Maritime Air Masses (mP)

It may be mentioned that maritime polar air masses also have the same source regions as those of continental polar air masses. In fact, when continental polar air masses (cP) move out from their source regions and travel over oceanic surfaces of high latitudes, their lower parts are heated from below by the relatively warm surfaces of open oceans and thus become maritime polar air masses (mP) after such modifications. Such modification increases temperature lapse rate and causes convective instability in the lower parts. On the other hand, the upper part is dry and cool. When such modified maritime polar air masses strike the mountain barriers, they are mechanically forced to ascend, become unstable and the convective instability results in condensation and much precipitation on the windward slopes of the mountains but while descending on the leeward



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AIR MASS SYMBOLS : T = Tropical, P = Polar, m = Maritime, c = Continental, W = Warmer than, K = Colder than underlying surface, s = Stable aloft, u = Unstable aloft

Fig. 10.1 : *World distribution of air masses and fronts in January.* **Source :** *modified after Haurwitz and Austin, as reproduced in G. T. Trewartha, 1954.*

side of the mountains they are adiabatically warmed and become stable dry continental air masses. Such situations are found along the west coasts of North America where the Coast Ranges receive enough precipitation while the eastern slopes of the Rockies and the Great Plains go dry.

3. Continental Tropical Air Masses (cT)

The continental tropical air masses have their source regions in the subtropical high pressure areas of hot deserts located between 20^0-30^0 latitudes in both the hemispheres which are characterized by vertical descent and horizontal divergence of winds. These air masses are characterized by very high temperature (above 40^0C), least moisture content, steep lapse rate, atmospheric stability, and dry weather. These air masses seldom move out from their source regions, but whenever they move out to ocean surfaces, they are modified to maritime tropical air masses.

4. Maritime Tropical Air Masses (mT)

The maritime tropical air masses have their source regions over warm ocean surfaces of tropical regions confined between 30^0N and 30^0S latitudes. These are warm, moist and unstable air masses and more extensive in areal context. They are associated with convective instability, cumulus and cumulonimbus clouds which give abundant rainfall when the air mass is associated with frontal activity or is forced to ascend by mountain barriers. It may be mentioned that the maritime tropical air masses are modified and become stable when they move towards the poles and travel over colder water (of oceans) or land surfaces, whereas they become unstable when they move over warm land surfaces.

10.7 AIR MASSES OF NORTH AMERICA

(A) WINTERTIME AIR MASSES

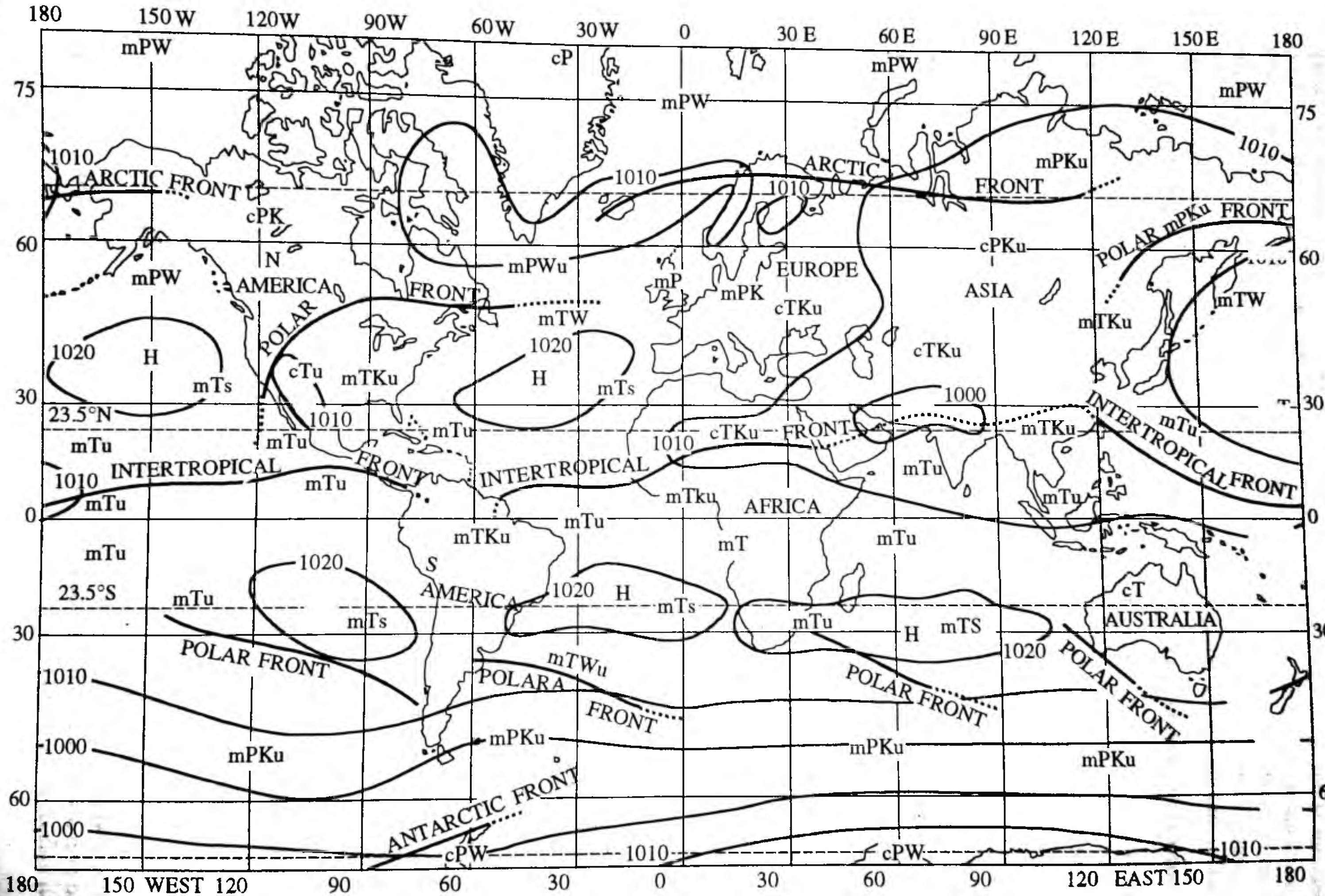
1. Continental Polar Air Mass (cP)

Continental polar air mass is cold (K), dry and stable (s), and originates over the snow-covered central Canada to the north of 50^0-60^0N latitude, and Alaska while continental arctic air masses originate over arctic basin and Greenland ice cap. These air masses move out of their source regions and enter the USA between the Rocky mountains and the Great Lakes. Extensive land surface with topographic homogeneity and slow anticyclonic circulation provide most ideal conditions for the origin and development of continental polar air mass. This air mass moves in southerly and south-easterly directions and brings extreme cold conditions. In fact, the arrival of this cP air mass produces intense cold waves in the vast area of the USA, with the result most of the places record temperature below freezing point.

After reaching the southern and south-eastern shores of the Great Lakes the continental polar cold air mass (cPK) is modified and thus becomes moist and unstable and yields heavy precipitation in the form of snowfall locally known as **lake-effect snow**. The modified air mass, when moves eastward, is forced to move upward along the Appalachians, becomes unstable, clouds are formed and the western slopes of the Appalachian mountain receive heavy snowfall. It may be pointed out that so long as the cold continental polar air mass moves over the snow covered source, it is least modified but as it crosses middle Illinois and enters the snow-free surface it is warmed from below and thus the cold air mass is modified to warm continental polar air mass (cPW) and the stability of the air mass decreases. The continental polar warm air mass (cPW) while moving through east-central USA meets maritime tropical (mT) air mass and polar front is formed which induces cyclonic conditions and winter precipitation occurs to the east of the Rocky mountains. The cPW air masses are modified in the south-eastern USA due to (i) mechanical turbulence produced by corrugated terrains of the southern Appalachians, (ii) subsidence of air from above and resultant stability, and (iii) instability in the lower layer of the air masses caused due to addition of heat and moisture.

2. Maritime Polar Pacific Air Masses (mP)

These air masses are called maritime polar Pacific air masses because these originate in the northern parts of the North Pacific, mainly near Aleutian Islands where winter low pressure is formed. This region is surrounded by continental polar air mass from all sides except in the south.



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AIR MASS SYMBOLS : T = Tropical, P = Polar, m = Maritime, c = Continental, W = Warmer than, K = Colder than underlying surface, s = Stable aloft, u = Unstable aloft

Fig. 10.2: World distribution of air masses and fronts in July. **Source :** *modified after Haurwitz and Austin, as reproduced in G.T. Trewartha, 1954*

The water surface is warmer than the air laying over it. Consequently, when the cold maritime polar air mass comes over this area it is warmed from below and thus becomes unstable. This mPKu air mass (maritime polar cold unstable air mass) picks up moisture throughout its journey south-eastward to the west coast of North America. This moist air mass gives sufficient precipitation while rising along the western slopes of the Coast Ranges. During summer season polar Pacific air mass becomes stable. When polar Pacific air mass reaches the Great Plains of the USA after crossing over the coastal ranges and the Rocky mountains, it undergoes the process of thermodynamic modifications and thus is transformed into cold, stable and dry continental polar air mass (cPWs) which induces anticyclonic conditions in the central states of the USA, with the result sky becomes clear and air circulation becomes slow and temperature returns to normal.

3. Maritime Polar North Atlantic Air Mass (mP)

This air mass originates over the North Atlantic Ocean mainly in the region between Greenland, Newfoundland, and Labrador where winter temperature ranges between 5^0F and 40^0F while during summer season it becomes 50^0 to 60^0F. Since the general air circulation in this region is form west to east and hence this air mass has little influence on North America. Some times cyclonic winds draw maritime polar North Atlantic air mass in the north-eastern parts of the USA mainly to the east of the Appalachians and to the north of Cape Hatteras. This air mass is dry and stable in its upper layers while it is moist and unstable in the lower parts. This air mass brings in bad weather which is locally known as **'north-eastern'** characterized by strong north-east cold winds, exceedingly low temperature well below freezing point, high moisture content in the air and possible precipitation mainly in solid forms such as snowfall, sleet and hailstorms.

4. Tropical Maritime Atlantic Air Masses

These air masses (mT) originate over Gulf of Mexico, Caribbean Sea and subtropical western portion of the North Atlantic Ocean. They are hot, moist and unstable and are capable of unleasing heavy showers. These air masses affect most parts of the USA east of the Rocky mountains. Temperature ranges between 21^0C and 26^0C and remains almost uniform in the source regions, with the result tropical maritime Atlantic air mass becomes warm and moist air mass. It may be pointed out that it becomes very difficult to this air mass to enter the southern and central USA in winters because there is complete dominance of continental polar air mass over these areas. Whenever tropical maritime Atlantic air mass enters the USA it is cooled from below because it is much warmer than the ground surface and thus becomes dry and stable. This modified air mass is known as maritime tropical stable warm air mass (mTWs). This stable air mass is incapable for precipitation but whenever it comes in contact with continental polar air mass, the upper air instability increases and the air mass is modified to maritime tropical warm unstable air mass (mTWu). As this air mass rises along the mountain barriers it yields heavy showers. In summer the maritime tropical warm air mass coming from over Mexican Gulf brings hot and sultry weather in the southern and south-eastern states of the USA. This air mass also produces several thunderstorms.

5. Tropical Maritime Pacific Air Masses

Pacific air mass originates over the subtropical portions of the East Pacific west of USA and Mexico mainly over the high pressure area located to the southwest of California. The air mass becomes stable because of subsidence of air from above due to anticyclonic circulation. This maritime tropical stable (mTKs) air mass is dry, cold and stable near the Pacific coast of the USA. Whenever this air mass is associated with cyclonic circulation it becomes unstable and brings rains. This air mass seldom crosses the Rockies.

(B) SUMMERTIME AIR MASSES

1. Polar Continental Air Mass (cP)

This air mass originates over the snow-covered central Canada and Alaska. The temperature becomes relatively higher in summers than in winters but adjoining oceanic areas have relatively low temperature. This air mass is cold, dry and unstable in the source regions but the air mass originating on cold arctic ocean during summer season is initially cold and stable. The stability of the cold and stable arctic air mass disappears when this air mass moves southward over relatively warm ground surface and hence is heated from below. The continental cold air mass (cPK) becomes warm due to thermodynamic modification when it moves over the ocean. When this air mass moves southward from its source areas, it does not cover long distances but it extends for long distances in the east. The southward movement of continental polar air mass brings chilly weather in the eastern and central USA due to which the effects of summer heat waves are eliminated and fine weather sets in. Whenever the continental polar air mass is associated with cyclonic circulation, it produces sporadic rainfall in the north-central and eastern parts of the USA.

2. Maritime Polar Atlantic Air Masses (mP)

These air masses originate over the area located between Cape Cod and Newfoundland. Initially, these are cold and stable. These reach as far south as northern Florida where temperature is reduced by 15^0 to 25^{0}F. Low temperature, clear sky and full visibility are the weather characteristics associated with these air masses. Thus, these air masses produce fine and pleasant weather in the region extending from Newfoundland to Cape Hatteras. There is no ground fog due to dry condition.

3. Maritime Tropical Atlantic Air Masses (mT)

These air masses originate near Barmuda where high pressure is formed. They move northwestward and control the weather conditions of vast areas of the USA east of the Rocky Mountains during summer months. Thermally induced low pressure over southern and central USA draws maritime tropical air masses (mT) far inland but the existence of polar front in the vicinity of the Great Lakes restricts their entry to Canada. Since temperature and moisture content in the air increases considerably due to arrival of these air masses in the central and eastern USA, the weather becomes oppressive and unpleasant. As these air masses move out from their source areas and enter the USA after crossing over the Gulf of Mexico, surface temperature increases, and they are modified into maritime tropical unstable air masses (mTKu) because the heating of overlying relatively cold air masses causes atmospheric instability. Thus, thunderstorms and cyclones are produced which yield heavy showers. As the air mass moves northward it loses its moisture content and becomes dry in the upper Mississippi valley. When these air masses move westward and rise along the Rocky Mountains they yield heavy downpour with cloud burst. Similarly, when they cross over the Appalachians they give heavy showers through thunderstorms.

4. Maritime Polar Pacific Air Masses (mP)

Maritime polar Pacific air masses originate in the area near Aleutian Islands in the north Pacific Ocean. The air mass becomes stable because of subsidence of air from above during summer season. Thus, this air mass becomes cold and stable (mPs). It may be pointed out that the continental surfaces are warmer than the water surfaces of the Pacific Ocean. Thus, the maritime air masses are warmed from below when they reach the continental areas. This causes greater turbulence in the lower layer, marked decrease in relative humidity, disappearance of clouds and dry weather. No doubt, the temperature of the west coastal areas of the USA, mainly Californian coasts, is reduced during summer season with the arrival of these air masses. After crossing over the Rocky Mountains maritime polar Pacific air masses are modified and resemble continental polar air masses (cP) in physical characteristics.

5. Maritime Tropical Pacific Air masses (mT)

These air masses originate in the tropical North Pacific Ocean off the west coast of Central America. These air masses are marginalized because of the prevalence of maritime polar Pacific air masses (as referred to above) along the west coasts of North America in summers.

6. Continental Tropical Air Mass (cT)

This air mass originates in the source region comprising Mexico, western Texas (USA) and eastern New Mexico (USA). The daytime characteristics are high temperature, significantly low humidity and scant rainfall. This air mass moves to Great Plains and causes extreme arid conditions. It produces drought conditions if it stays for a long period over an area.

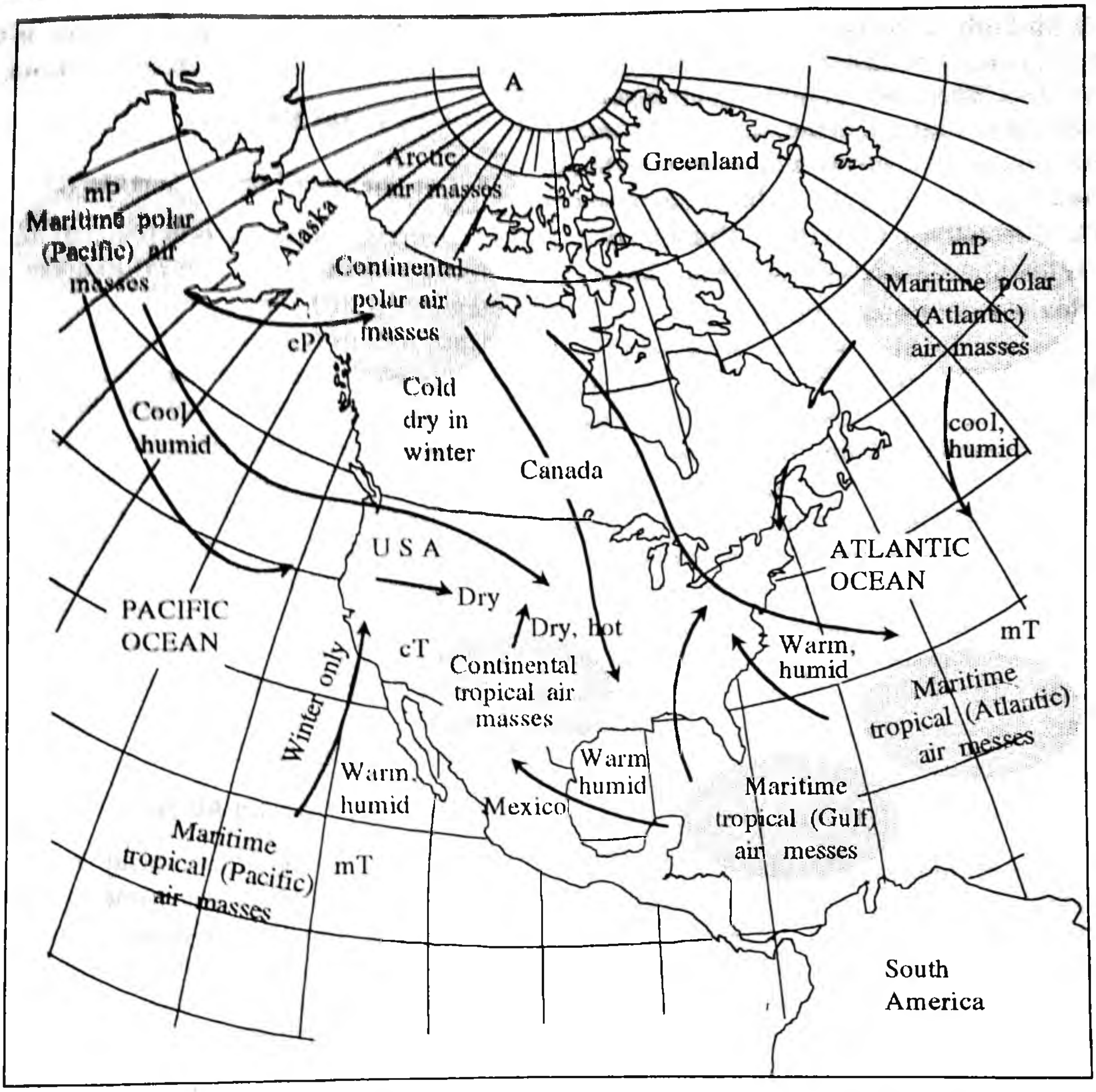


Fig. 10.3 : Air masses and their source regions of North America. **Source :** *based on J.M. Morgan and M.D. Morgan, in Oliver and Hidore, 2003.*

10.8 AIR MASSES OF ASIA

WINTER AIR MASSES

1. Continental Polar Air Masses (cP)

These air masses originate over extensive areas comprising Siberia and outer Mongolia having very cold ground surface. Initially, the air masses are very cold and dry in their source regions. The lower portion upto the height of one kilometre is characterized by inversion of temperature. The air masses move eastward and after covering long distances are mechanically modified as mechanical turbulence is produced when these air masses cross over the mountain barriers. This process leads to the disappearance of inversion layer resulting into increase of temperature and humidity in the lower layer. These air masses enter China through two routes viz. (i) through land surface, and (ii) through water surface. When high pressure lies over Mongolia and North China, then these air masses enter China by land route. They are much warmer in China than in their source areas. These air masses are associated with clear sky and dry weather and cold air. When these air masses come with high velocity, they bring with them immense quantity of dusts and sands and deposit them as loess. The continental polar air masses in their modified forms affect the weather conditions of most parts of Asia during winter season. These air masses do not enter the Indian subcontinent because of effective barrier of the Himalayas.

When high pressure lies over Manchuria and Japan Sea, the continental polar air masses enter China by sea route after moving over Japan Sea, and Yellow Sea and thus pick up abundant moisture. These air masses are relatively warmer and more humid than the continental polar air masses coming by land route. Until they are associated with fronts, they are characterized by clear sky and pleasant weather. The lower portion is unstable and thus they give precipitation when they ascend along the mountain barriers. The continental air masses coming through sea and land routes converge along the eastern coasts of Asia and form cyclones through frontogenesis and cause precipitation.

2. Maritime Polar Air Masses (mP)

These air masses after originating over the Sea of Okhotsk influence only the coastal margins of Siberia, Manchuria and South Korea while the eastern coasts of Asia south of Korea are deprived of their influences because (i) the winter air circulation is off shore *i.e.* from west to east due to which the westward advance of maritime polar air masses is blocked, and (ii) continental polar air mass while entering China through sea route attains the characteristics of maritime polar air mass (mP). These air masses (mP) also invade Japan in early summer and form fronts when they converge with overlying maritime tropical air masses and bring moist weather with overcast sky and light precipitation.

3. Maritime Tropical Air Masses (mT)

Maritime tropical air masses do not effectively influence the weather conditions of the eastern Asia during winters because of the dominance of continental polar air masses. These air masses are experienced only upto southern China. They are warmer and more humid than all of the wintertime air masses. Unstable maritime tropical air masses are more effective in south-west Pacific Ocean and in eastern Indonesia.

SUMMER AIR MASSES

1. Continental Polar Air Masses (cP)

The source areas of polar air masses extend further northward in central Asia because of high temperature during summer season due to northward migration of the sun. The air becomes relatively warm but continental polar air masses do not effectively influence the weather conditions of eastern and southern Asia because maritime tropical air masses become more dominant during summer season. The continental polar air masses enter China only through sea route from Japan Sea and Yellow Sea. These air masses are colder than maritime tropical air masses. They are associated with clear weather, scant precipitation, and negligible thunderstorms. They produce cyclonic conditions whenever they converge with maritime tropical air masses.

2. Maritime Tropical Air Masses (mT)

The weather of south and south-east Asia is largely controlled by maritime tropical air masses which are known as **summer monsoons.** They are warm, more humid and unstable. They yield torrential rainfall when they are forced to ascend by mountain barriers. After being originated in southern oceans they move north and north-eastward and after entering the mainland they are heated from below because of warm ground surface and hence they become unstable and convectional currents are produced. The south-west summer monsoons of Indian subcontinent are typical representatives of maritime tropical summer air masses. These air masses produce cyclonic conditions when they converge with continental polar air masses during springs in central China and during middle summer in Manchuria.

3. Maritime Polar Air Masses (mP)

These air masses originate over Okhotsk Sea from where they move westward and influence the weather conditions of eastern Asia north of 40^0N latitude. These air masses are more active during summers than during winters. They are more effective in Manchuria and east Siberia. Though these air masses extend upto southern Japan in early summer but later they are pushed northward by maritime tropical air masses.

10.9 AIR MASSES OF EUROPE

The absence of effective mountain barriers along the western coastal areas of Europe allows maritime air masses to penetrate the continent upto greater distances inland. If we compare the situation of North America and Europe, we find contrasting conditions. Contrary to European situation, the eastern and the western parts of North America are bordered by effective mountain barriers (*e.g.* the western cordillera-Rockies, in the west and the Appalachians in the east) and hence maritime air masses are obstructed by these barriers and the air masses reach the inner parts of the country in modified form. The east-west orographic situations of North America and Europe are also contrasting because there is total absence of any east-west stretching mountain barrier in North America and hence polar continental air masses reach, without any obstruction, as far south as the Gulf Coast while the Pyrenese, Alps and Caucasus mountain chains extend west to east in southern Europe and hence do not present any obstruction in stopping Atlantic air masses and westerlies from reaching the far inland location of the continent. The European continent is influenced by (1) continental polar air masses (cP), (2) maritime polar air masses (mP), (3) maritime tropical air masses (mT), and (4) continental tropical air masses (cT) during winter and summer seasons.

WINTERTIME AIR MASSES

1. Continental Polar Air Masses (cP)

There are three source regions of continental air masses in Europe, namely (1) Fenno-Scandian Region, (2) western Russia, and (3) Arctic Russia. All of these source regions are located from 45^{0}N latitude to the North Pole and are characterized by frozen ground surface. The continental polar air masses in winter are cold, less humid and stable in source regions. The arctic continental polar air mass is coldest of all the winter time continental polar air masses, but it is not very frequent but whenever it arrives in Europe it brings with it severe cold. The air masses from the first two source regions (as mentioned above) affect western and central Europe but the general westerly circulation of air stricts their further westward journey. The weather is generally characterized by clear skies and severe cold condition.

2. Maritime Polar Air Masses (mP)

The main source region of maritime polar air masses of Europe is the North Atlantic Ocean north of 60^{0}N latitude wherein two subregions are very significant, namely (i) Arctic Ocean east of Greenland, and (ii) Arctic Ocean north of Iceland. Besides, air masses of North America after moving over the Atlantic Ocean also invade western Europe, though they are in modified form and are mild, humid and unstable. The air masses having their origin over North Atlantic ocean surface are characterized by more humid conditions and whenever these are associated with temperate cyclonic fronts, they are uplifted and yield heavy precipitation over plains and very heavy precipitation over highlands. It may be mentioned that the characteristic features *i.e.* physical properties of winter time marine polar air masses depend on the distance covered by them over ocean surfaces and the distance of movement depends on the routes followed by them. Generally they follow three routes, namely (i) if the air masses after being originated in Greenland-Spitz Bergen region of North Atlantic Ocean reach the western Europe, following shorter route, they maintain the cold characteristics of the source region and are less modified and hence are very cold and stable air masses, (2) when the air masses after being originated over the frozen surface of the Arctic Ocean reach the western Europe after following longer route, they are modified over the Atlantic Ocean surface and hence become relatively warm and humid air masses and thus attain the general characteristics of common maritime polar air masses (mP), and (3) when the mP air masses follow more southerly route, they become warmest of all the three branches of mP air masses. The absence of any mountain barrier paralleling the west coast of Europe, except the Norway coast, allows free entry of mP air masses and hence the weather of western and central Europe is more influenced by mP air masses than cP air masses during winter season.

3. Maritime Tropical Air Masses (mT)

The source region of maritime tropical air masses which invade the south-western parts of Europe is the eastern part of subtropical high pressure area over Atlantic Ocean. The source region is characterized by subsidence of air and divergence of air (*i.e.* anticyclonic conditions). The winter time marine tropical air masses are relatively warmer and more humid than winter continental polar air masses because they are more modified by the physical properties of the Atlantic Ocean over which they move to reach south-west coast of Europe. 'Ordinarily it yields little or no rain on lowland except where it is involved in cyclonic systems, under which widespread precipitation is common. Providing the warm-sector air masses in cyclonic storm, mT air is an extensive rain and snow bringer to western and central Europe'. (G. T. Trewartha).

4. Continental Tropical Air Mass (cT)

The source regions of continental tropical air masses are west North African Sahara desert and dry areas of S.W. Asia mainly Arabian desert. The cT air masses in their source regions are warm and dry and stable in their upper parts. These air masses after passing over the Mediterranean Sea are modified as they pickup moisture and give precipitation when they join the warm sector of western disturbances (temperate cyclones). In fact, cT air masses provide heat energy to these cyclones. The cT air masses mainly influence the weather of Italy and eastern Mediterranean Sea.

SUMMER AIR MASSES

1. Continental Polar Air Masses (cP)

According to G.T. Trewartha the continental polar air masses of Europe are, in fact, modified maritime polar air masses (mP). As regards thermal characteristics the continental polar air mass is cooler than continental tropical air mass but is warmer than maritime polar air mass of western and central Europe. The lapse rate is not steep in these three air masses, that is why the summers are characterized by more or less uniform weather conditions in western and central Europe but since the eastern Europe has interior location, the temperature contrast is more pronounced.

2. Maritime Polar Air Masses (mP)

There is vast variation in the physical properties of different branches of maritime polar air masses during summer season. The variation depends on the place of origin of mP air masses within the extensive North Atlantic source region and the length of trajectories followed by these air masses. The mP air mass originating from the northern part of primary source has to cover shorter distance over the North Atlantic Ocean and reaches the western Europe without being greatly modified, and hence becomes moderately unstable which may yield much precipitation when uplifted by frontal activity (temperate cyclogenesis). On the other hand, when mP air mass after originating over the southern part of the primary source region of North Atlantic covers longer distance over the Atlantic Ocean before reaching the western Europe, it is greatly modified and becomes stable air mass, but these air masses, when associated with cyclonic activities, produce heavy precipitation, otherwise the weather of western Europe remains cool and pleasant in summer.

3. Continental Tropical Air Masses (cT)

The summer continental tropical air masses of Europe originate from two sources, namely (1) Sahara desert of north Africa, and (2) the south-eastern Europe and Asia Minor, wherein the former is the principal source region. The cT air mass is very hot and dry in its source region (Sahara) but becomes moist when moves northward over the Mediterranean Sea. The northward moving air is locally known as Sirocco which is a warm, dry and dusty wind (full of sands). Sirocco, while passing over Mediterranean Sea picks up moisture and yields rainfall in the southern part of Italy where the rain associated with sirocco is called **blood rain** because of fallout of red sands with falling rains. It may be remembered that sirocco while blowing over Sahara Desert picks up red sands which settle down with rain in south Italy. Sirocco becomes very strong and active at the time of the origin of cyclonic storms over Mediterranean Sea. The cT air mass from Sahara affects the summer weather of the southern Europe and southwestern Siberia. Occasionally, they produce haze and mist in southern and eastern Europe and southwestern Siberia. The second branch of cT air masses originates over southeastern Europe and Asia Minor but is less frequent. It is more or less stable air mass because it is associated with anticyclonic conditions.

4. Maritime Tropical Air Masses (mT)

The source region of mT air mass of Europe during summer season is around Azores high pressure area in the Atlantic Ocean. The mT air mass becomes stable air mass (mTs) because (i) its source region is characterized by subsidence of air from above and hence anticyclonic condition, and (ii) it passes over cool ocean surface. This is the reason that mTs air mass is not rain bringer in summer but whenever is force-uplifted by mountain barrier, it becomes unstable and convective activity produces showers. It may be mentioned that summer mT air mass has limited influence over summer weather of western Europe.

10.10 IMPORTANT DEFINITIONS

Air mass : Air mass is defined as a homogeneous body of air in which the upward gradients of temperature and moisture are uniform over extensive area covering thousands to millions of square kilometers.

Blood rain : The fall out of red sands with falling rains associated with Sirocco local wind in south Italy is called blood rain.

Cold air mass : The air mass having less temperature than the temperature of underlying surface is called cold air mass.

Lake-effect snow : The heavy precipitation in the form of snowfall from the continental polar air mass in winter in the southern and southeastern shores of the Great Lakes in the USA is locally called 'lake effect snow.'

Mechanical air mass modification : The changes brought in the physical properties of an air mass due to vertical (upward uplift or downward descent) and advectional movements are called mechanical or dynamic modifications of air mass.

North-eastern : The bad weather brought by winter maritime polar North Atlantic air mass in the north-eastern USA is locally called 'north-eastern' which is characterized by strong northeast cold winds, exceedingly low temperature well below freezing point, high moisture content in the air, snowfall, sleet and hailstorms.

Synoptic dimatology : Synoptic climatology is defined 'as the study of climates in relation to atmospheric circulations; it emphasizes the relationships among circulation, weather types, and climatic regional differences' (Oliver and Hidore, 2003).

Thermodynamic modification : Thermodynamic modification of an air mass involves its heating and cooling from below while passing through different surfaces away from the source region.

Warm air mass : A warm air mass is that whose temperature is greater than the surface temperature of the region over which it moves.

11

FRONTOGENESIS, CYCLONES AND ANTI-CYCLONES

11.1 FRONTS AND FRONTOGENESIS

The sloping boundary between two converging air masses of contrasting characteristics in terms of temperature, velocity, humidity, density etc. is normally called front. In fact, a front represents a transitional zone between weather conditions of two contrasting converging air masses. Thus, a front is considered as a **line of discontinuity** to represent transition zone between two airmasses having contrasting weather conditions. F.W. Cole (1975) defined front as an interface or transition zone between two air masses of different densities. Three Norwegian meteorologists are given credit for introducing the concept of front and frontal surfaces in meteorology to describe weather conditions in middle latitudes (temperate regions). The concept of front was first introduced in the year 1918. Thus, the contributions by V.J. Bjerknes, H. Solberg, and T. Bergeron made it possible to understand middle latitude weather characteristics and variations.

Front is that sloping boundary which separates two opposing air masses having contrasting characteristics in terms of air temperature, humidity, density, pressure, and wind direction. An extensive transitional zone between two converging air masses is called **frontal zone** or **frontal surface** which represents zone of discontinuity in the properties of opposing contrasting air masses. Frontal zone is neither parallel nor vertical to ground surface, rather it is inclined at low angle. Though fronts differ from each other in terms of their location, types and areal extent but they are characterized by the following common characteristics e.g. large differences in air temperature across a front, bending isobars, abrupt shift in wind direction, cloudiness and precipitation.

The term frontogenesis was introduced in meteorology by the Norwegian meteorologist Tor Bergeron to describe the processes of formation of new fronts. But the term of frontogenesis was extended to include the process of formation of both new fronts and old and decaying fronts. Thus, the process of frontogenesis is defined as follows—the process associated with the creation of new fronts or regeneration of old and decaying fronts already in existence is called **frontogenesis.** The region having convergence of contrasting air masses is called the **region of frontogenesis.**

It may be mentioned that the process of formation of fronts or simply frontogenesis is responsible for the formation (origin) of fronts, the process of which is called **cyclogenesis.**

The process of destruction or dying of fronts is called **frontolysis** which is opposite to the process of frontogenesis. The frontolysis may be effected when either two contrasting air masses move away or are merged with each other in such a way that temperature and density variations are removed and there prevails a condition of almost uniformity in temperature and air density.

11.2 CONDITIONS FOR FRONTOGENESIS

If the distribution of air fronts over the globe is closely observed, it appears that fronts originate only in limited areas which means that fronts originate only when some favourable conditions are available. The necessary conditions for frontogenesis include the presence of two opposing air masses having contrasting properties of air temperature, air pressure, density, humidity and wind direction.

1. Temperature Difference

Two opposing air masses must have contrasting temperatures e.g. one air mass should be cold, dry and dense while the other should be warm, moist and light. In such conditions, when two air masses coverage, then cold and denser air mass invades the area of warm and light air mass and pushes it upward and thus front is formed. It may be pointed out that inspite of convergence of two air masses at the equator no front is formed due to uniform temperature conditions of two air masses (trade winds). A few meteorologists have described the process of frontogenesis near the equator.

2. Opposite Directions of Air Masses

Convergence of two contrasting air masses is a prerequisite condition for frontogenesis because when two thermally contrasting air masses meet face to face (converge), they try to penetrate into the region of one another and thus a wave-like front is formed. Contrary to this when two air masses diverge, they move in opposite directions. This situation leads to destruction of fronts, if any. Patterson has identified four types of air circulation wherein only the last two are conductive for frontogenesis.

(i) Translatory circulation involves movement of air in horizontal manner from one place to another in the same direction (fig. 11.1A). This circulation system does not produce temperature variations as the isotherms are parallel and widely spaced. This type of air circulation does not favour the creation of fronts.

(ii) Rotatory circulation involves the circulation of air in cyclonic or anticyclonic pattern. In other words, air circulation is circular (fig. 11.1B and C). Though rotatory air circulation produces temperature variation but front is never created.

(iii) Convergent and divergent circulation : Convergent circulation involves meeting of winds at common point from all directions (fig. 11.1D) while divergent circulation refers to spread of

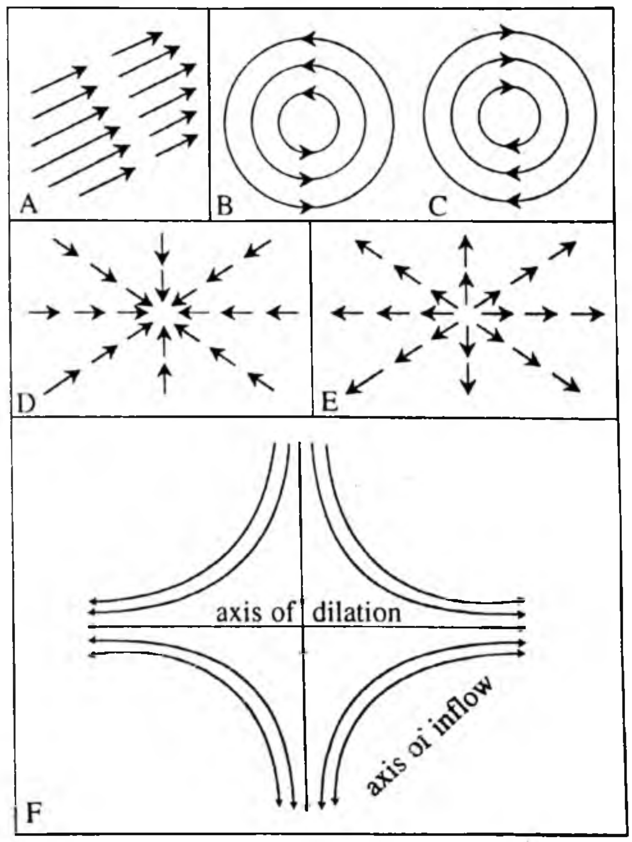


Fig. 11.1 : A = translatory air circulation, B = rotatory air circulation (cyclonic), C = rotatory circulation (anticyclonic), D = convergent circulation, E = divergent circulation, and F = deformation circulation.

winds outward in all directions from a central point (fig. 11.1E). Though temperature difference is produced in convergent circulation but this situation occurs at a point and not along a line and thus front cannot be created because for frontogenesis it is necessary that temperature difference does exist along a line and not a point.

(iv) Deformatory circulation involves convergence of two contrasting air masses and horizontal spread along a line which is called as axis of outflow or axis of dialation (fig. 38. IF), while the other axis is called axis of inflow. This type of air circulation is most favourable for frontogenesis.

11.3 CREATION OF FRONTS

When two contrasting air masses converge in deformation circulation, they spread horizontally along the **axis of outflow** or **dialation** (fig. 11.2i). In such situation the creation of front depends on the angle between the axis of outflow and isotherms. Fronts do not form when this angle exceeds 45 degrees. As the convergence of air continues, this angle decreases and isotherms try to become parallel to the axis of outflow and frontogenesis is activated. The steepness and intensity of fronts depends on temperature gradient. If two contrasting air masses are parallel to each other and there is no upward displacement of air, **stationary front** is formed (fig. 11.2ii). Such fronts are climatically insignificant because they are not conducive for cloud formation and precipitation. But such situation is not very common because two contrasting and converging air masses are generally separated by sloping boundary due to deflective force (coriolis force) of the earth and cold and dense air mass pushes warm and light air mass upward (fig. 11.2iii). It may be pointed out that fronts are not linear between two converging contrasting air masses but are zonal in character having a width of 5 to 80 kilometres.

11.4 CLASSIFICATION OF FRONTS

Fronts are classified into four principal types on the basis of their different characteristic features e.g. (1) warm front, (2) cold front, (3) occluded front, and (4) stationary front.

1. Warm Front

Warm front is that gently sloping frontal surface along which warm and light air becomes active and aggressive and rises slowly over cold and dense air (fig. 11.3A). The average slope of warm fronts in middle latitudes ranges between 1: 100 to 1 : 400. The gradually rising warm air along the gently sloping warm front is cooled adiabatically, gets saturated and after condensation precipitation occurs over a relatively large area for several hours in the form of moderate to gentle precipitation.

When the warm air becomes active and rises over the cold air, the resultant front is called **ana-front** while **kata-front** is formed when warm air sinks, and there is little difference of temperature between two converging warm and cold air masses.

(2) Cold Front

Cold front is that sloping frontal surface along which cold air becomes active and aggressive and invades the warm air territory and being denser remains at the ground but forcibly uplifts the warm and light air. Since the air motion is retarded at the ground surface due to friction while the free air above has higher velocity and hence the cold front becomes much steeper than warm front. This is why the slope of cold front varies from 1 : 50 to 1 : 100 (which means the rise of the wedge of cold air at the rate of one kilometre for every 50 to 100 kilometres). A cold front is associated with bad weather characterized by thick clouds, heavy downpour with thunderstorms, lightning etc. Some times cold frontal precipitation is also associated with snowfall and hailstorms.

3. Occluded front

Occluded front is formed when cold front overtakes warm front and warm air is completely displaced from the ground surface (fig. 11.3C). The occluded fronts are of two types e.g. (1) warm front occlusion, and (2) cold front occlusion. The occlusion of front may be defined as overtaking of warm front by cold front and dominance of cold air and disappearance of warm air from the ground surface. The **cold front occlusion** occurs when the cold air behind the cold front is colder than the

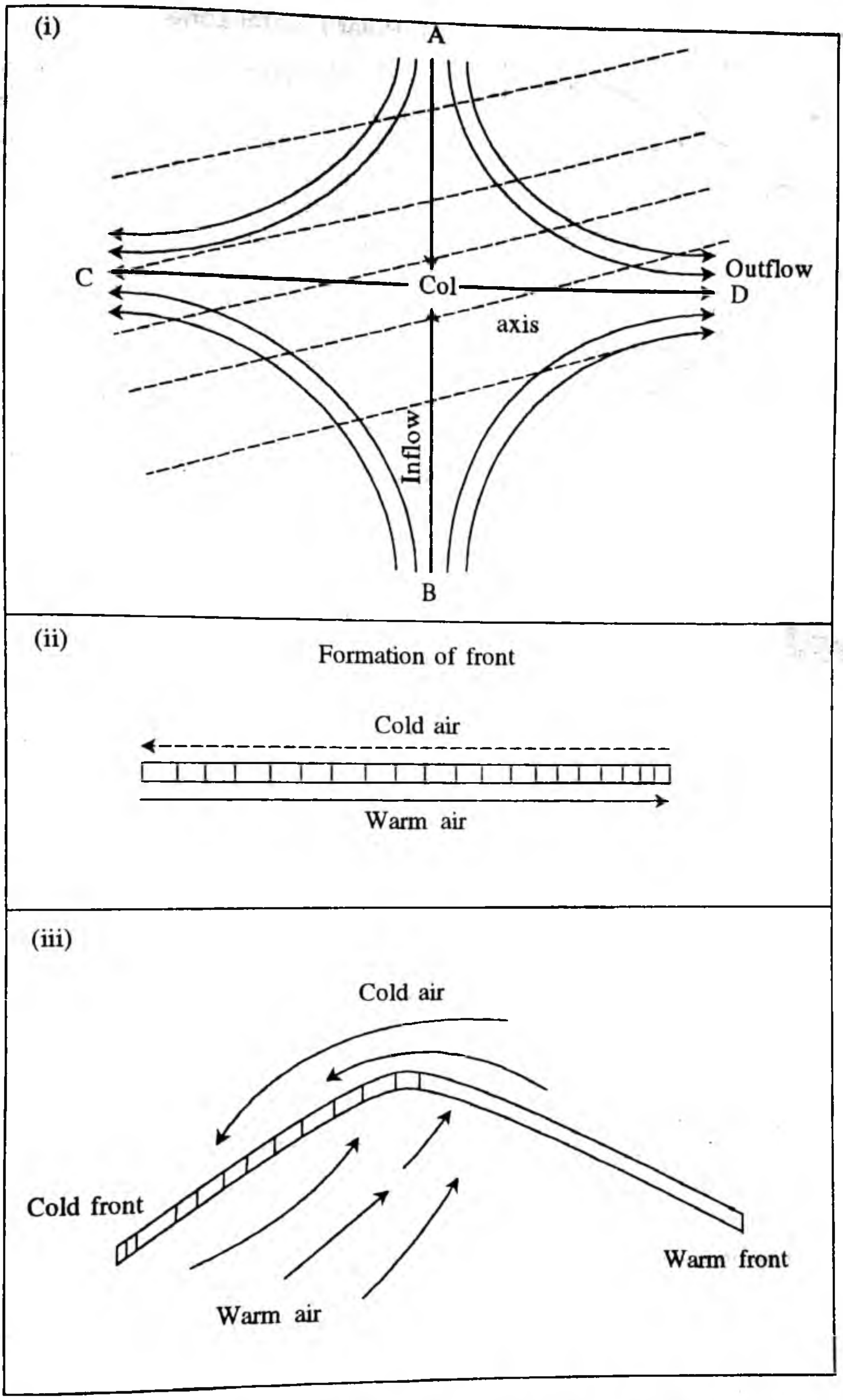


Fig. 11.2 : (i) Frontogenesis, (ii) stationary front, (iii) fully developed front.

advancing cold air which is ahead of warm front and thus the cold front overtakes warm front. The **warm front occlusion** occurs when the air behind the cold front is warmer than the advancing air which is ahead of warm front and thus the retreating air overtakes the advancing air.

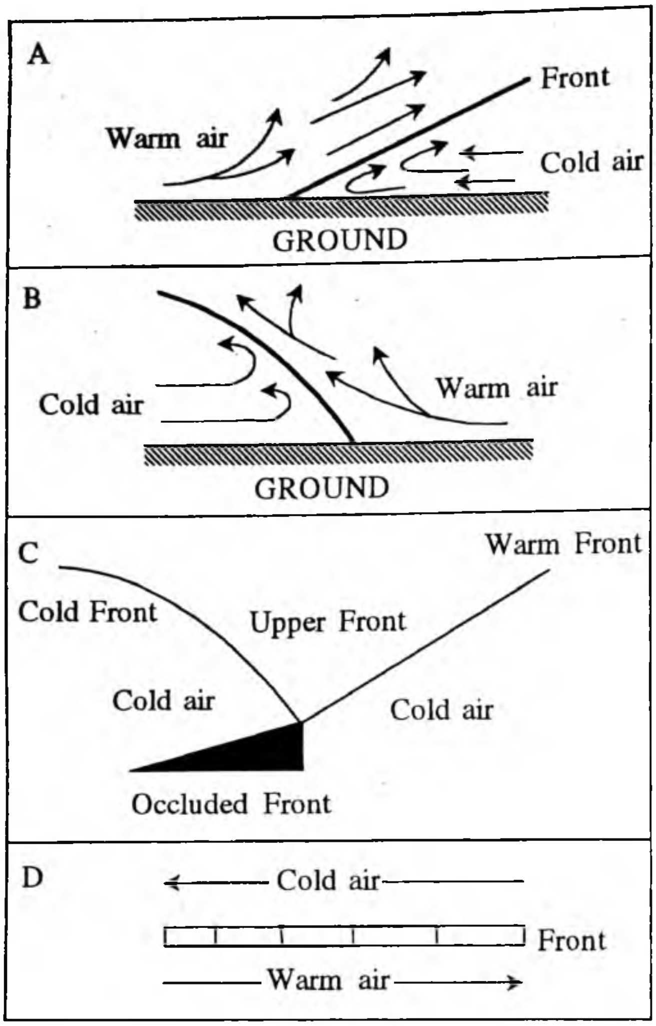


Fig. 11.3 : A = warm front, B = cold front, C = occluded front, and D = stationary front.

4. Stationary Front

Stationary front is formed when two contrasting air masses converge in such a way that they become parallel to each other and there is no ascent of air. In fact, the surface position of stationary front does not move either forward or backward.

11.5 FRONTAL ZONES

There are two principal zones on the globe where two air masses converge along a line e.g. (1) equatorial low pressure belt, and (2) subpolar low pressure belt. It may be noted that fronts are not formed every where but they are formed only in those areas where two air masses converge. There are 3 principal frontal zones on the earth's surface e.g. (1) polar frontal zone, (2) arctic frontal zone, and (3) intertropical frontal zone.

1. Polar Frontal Zone

This frontal zone is also known as Atlantic polar front because fronts are formed over the north-western parts of the Atlantic Ocean. Polar fronts are formed in the middle latitudes in both the hemispheres because of convergence of polar continental air mass (cold and dense air) and tropical maritime air mass (warm and light). These fronts are more developed in the northern parts of the Pacific and Atlantic oceans. They are more active during winter seasons because the temperature contrast is more pronounced between polar continental and tropical maritime air masses. The temperate cyclones produced along polar front travel from west to east under the influence of the westerlies and yield widespread precipitation over large area extending from the eastern parts of North America to the western Europe. Polar front is weakened during summer season because the temperature contrast between two air masses decreases to minimum.

2. Arctic Frontal Zone

Arctic fronts are created in the arctic areas due to convergence of continental and maritime polar air masses. These fronts are not always very strong and active because of less temperature contrast between two air masses. Active fronts are formed when relatively warm polar maritime air mass meets extremely cold arctic air mass due to which temperature contrasts are accentuated. These fronts develop along the arctic coasts of Eurasia and north America.

3. Mediterranean Frontal Zone

This frontal zone is formed due to convergence of cold continental European air mass and winter air mass of North Africa along Mediterranean-Caspian Sea line. The winter cyclonic storms developed over Mediterranean Basin move towards east and north-east. Some of these frontal weather disturbances reach Pakistan and north-west India and account for winter precipitation of north India.

(4) Pacific-Arctic Frontal Zone

Fronts develop along a line running from the Rocky mountains to the Great Lakes during winter season. The winter disturbances or cyclones associated with this frontal zone move south-eastward to such locations as Texas and northern Mexico and bring intense cold waves throughout southern United States.

(5) Pacific Polar Frontal Zone

Two frontal zones develop during winter season over the north Pacific Ocean e.g. (i) near north-east Asiatic coast, and (ii) near north-west North American coast. The frontal disturbances developed along the frontal zone of north—east Pacific Ocean (north-west coast of North America) influence the wintertime weather conditions of the western coast of North America extending from the Gulf of Alaska to southern California, and western Mexico. These storms account for winter precipitation of the western coasts of North America.

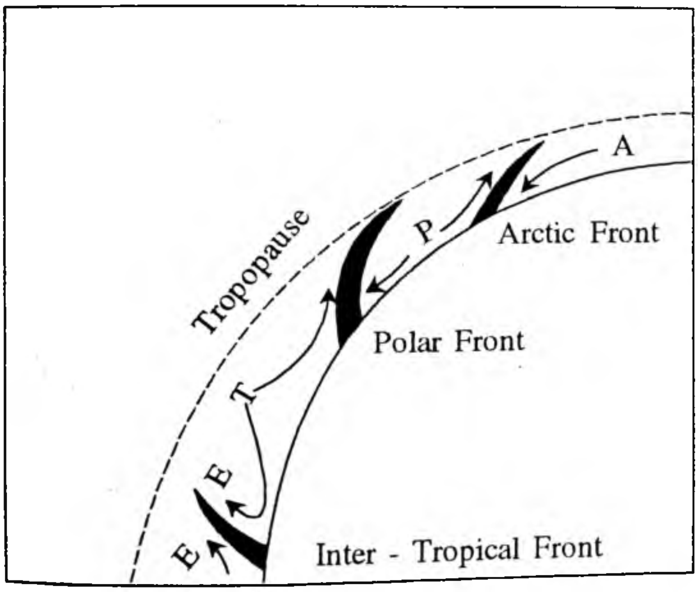


Fig. 11.4 : Major frontal zones over the globe.

6. Intertropical Frontal Zone

According to some meteorologists tropical front is formed near the equator due to convergence of north-east and south-east trade winds. It may be pointed out that there is no temperature contrast between these two air masses (trades) of similar origin and same properties.

11.6 WEATHER ASSOCIATED WITH FRONTS

Since fronts are formed due to convergence of two air masses of contrasting temperatures and hence contrasting weather conditions are found from north to south or south to north. Differences in terms of temperature, humidity, precipitation, cloudiness, and wind direction are experienced along different fronts e.g. warm and cold fronts.

1. Weather Associated With Warm Fronts

Warm air becomes active and aggressive along warm front as it invades cold air zone and thus being lighter it gradually rises over cold air and is cooled adiabatically from below. Cooling of warm air causes condensation and cloud formation followed by precipitation. If the aggressive warm air is stable and less humid, condensation occurs at great height and hence much lifting of air is required. On the other hand, if the warm air is moist and unstable, only a slight lifting causes condensation and precipitation. The warm front precipitation is of long duration, moderate but widespread because of gentle slope of warm front. There are frequent changes in cloud types. The sequence of clouds from above downward comprises cirrus, cirro-stratus, alto-stratus and nimbo-stratus. When warm front advances forward, the warm sector comes over the observation place. There is sudden change in weather conditions with the arrival of warm sector e.g. sudden increase in temperature and specific humidity, decrease in air pressure, disappearance of clouds, clear sky, and break in precipitation.

2. Weather Associated With Cold Front

Cold and dense air becomes active and aggressive along cold front wherein cold air invades warm air region and pushes it upward while it, being denser, settles downward. If cold front passes away soon, weather also becomes clear soon, otherwise if the front becomes stationary, the sky becomes overcast with cumulo-nimbus clouds provided that cold air is moist and unstable, and frontal thunderstorms are formed. Heavy precipitation occurs but is of short duration. The consequent weather is characterized by decrease in temperature, increase in air pressure, decrease in specific and relative humidity and change in wind direction from 45^0 to 180^0. Precipitation is accompanied by lightning and cloud thunder. Some times, rainfall is associated with hailstorms. After the passage of cold front, clouds disappear, precipitation terminates and weather becomes clear and north-west cold winds set in.

11.7 CYCLONES

Cyclones are centres of low pressure surrounded by closed isobars having increasing pressure outward and closed air circulation from outside towards the central low pressure in such a way that air blows inward in anticlockwise in the northern hemisphere and clockwise in the southern hemisphere (fig. 11.5). Cyclones are also termed as atmospheric disturbances. They range in shape from circular, elliptical to 'V' shape. When the velocity of winds increases to such an extent that they attain gale force, the atmospheric disturbance or cyclone is called a **cyclonic storm.** From the locational point of view cyclones are classified into two principal types e.g. (i) extratropical cyclones (also called as temperate cyclones or wave cyclones), and (ii) tropical cyclones.

11. 8 TEMPERATE CYCLONES

Temperate cyclones, also called as **extratropical cyclones** or **wave cyclones** or simply **depressions,** are atmospheric disturbances having low pressure in the centre and increasing pressure outward. They are in fact low pressure centres produced in the middle latitudes characterized by converging and rising air, cloudiness and precipitation. Because of their varying shapes such as near circular, elliptical or wedge (V) they are variously called as **'low'**, **'depressions'** or **'troughs'**. They are formed in the regions extending between 35^0-65^0 latitudes in both the hemispheres due to convergence of two contrasting air masses e.g. warm, moist and light tropical air masses (westerly winds) and cold, and dense polar air masses. The polar fronts created due to these two opposing air masses are responsible for the origin and development of temperate cyclones. After their formation temperate cyclones move in easterly direction under the influence of westerly winds and control the weather conditions in the middle latitudes.

1. Types of Temperate Cyclones

Though temperate cyclones are mainly originated due to convergence of two contrasting air masses in terms of temperature, pressure, and humidity but some local cyclones also form due to other reasons related to temperature variations and consequent pressure differences. Based on above considerations temperate cyclones are divided into 3 categories viz. (i) dynamic cyclones, (ii) thermal cyclones, and (iii) secondary cyclones.

(1) **Dynamic cyclones** are, in fact, real temperate cyclones because they are formed due to convergence of cold polar air masses and warm and moist maritime tropical air masses. These cyclones affect the weather conditions of very large areas in middle latitudes. Different fronts (e.g. warm front and cold front) and sectors (e.g. warm and cold sectors) are fully developed in dynamic cyclones. They are called dynamic because they are dynamically produced e.g. due to convergence and invasion of two contrasting air masses into the territories of one another.

(2) **Thermal cyclones** : According to Brunt thermal cyclones are formed due to development of low pressure centres on the continents in summers in temperate regions and as such winds blow from all directions towards low pressure centres. Such thermally induced temperate cyclones are stationary at their places of origin and different fronts are not developed. Such thermally induced cyclones in the middle latitudes have been named by Humphreys as **insolation cyclones.** According to Humphreys thermal cyclones are produced due to development of low pressure centres over warm water surfaces of seas surrounded by cold land surfaces during winter season. It may be pointed out that both types of cyclones as referred to above are, in fact, thermal cyclones because they are directly related to insolation. The only difference is that they develop over land surfaces in summers (e.g. over Iberian Peninsula, Alaska, S.W. USA and N.W. Australia) and over sea surfaces in winters (e.g. over Okhotsk Sea, Norwegian Sea, to the south of Iceland and Greenland etc.).

(3) **Secondary cyclones** are those which develop due to passage of cold winds over warm sea after the occlusion of main (original) cyclone. They are short-lived and very weak.

2. Characteristic Features of Temperate Cyclones

Shape, Size and Velocity

Temperate cyclones are of different shapes e.g. circular, semi-circular, elliptical, elongated or 'V' shaped, but all of them are characterized by low pressure in their centres and closed isobars. The pressure difference between the centre and periphery is about 10 to 20mb but some times it increases to 35mb. It means that pressure increases from the centre towards outer margin. Temperate cyclones also greatly vary in size and extent. Average large diameter of an ideal cyclone is about 1900km (1200 miles) while short diameter measures 1000 km (640 miles). It may be pointed out that no two cyclones are identical in terms of their size as their diameters range from 150km to more than 3000km. Some times, temperate cyclones are so large and extensive that they cover an area of 1,000,000 square kilometers. The vertical extent of an average cyclone is about 10-12 km. The temperate cyclones move eastward under the influence of westerly winds with average velocity of 32km per hour in summers and 48km per hour in winters.

Wind System

Since there is low pressure in the centre of temperate cyclone and air pressure increases outward and hence winds blow from the periphery towards the centre but these winds do not reach the centre straight rather they cut the isobars at the angle of 20^0 to 40^0 due to friction and **coriolis force** and thus wind direction becomes anticlockwise in the northern hemisphere and clockwise in the southern hemisphere. The centre-bound inward air circulation becomes of convergent pattern but the winds do not aggregate at the centre but they ascend upward and expand outward so that low pressure centre is always maintained so long as the cyclone is alive. Since temperate cyclones are formed due to convergence of two contrasting air masses (i.e. cold, dry and dense air mass and warm, moist and light air mass) and hence it is natural that there are variations in the nature and direction of winds in different parts of the cyclones. The tropical and subtropical warm and moist air is generally of westerly direction while polar cold air is generally easterly. The convergence of these air masses

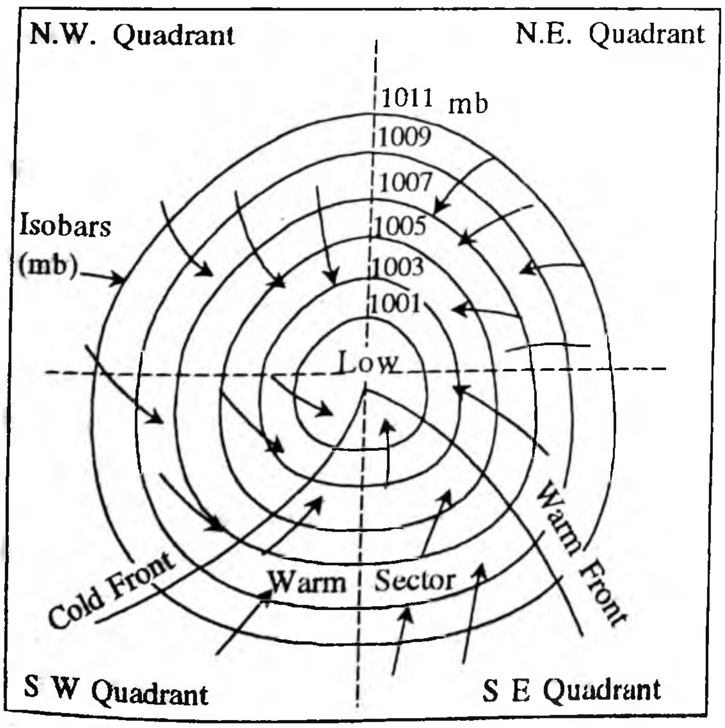


Fig. 11.5 : An average temperate cyclone in northern hemisphere.

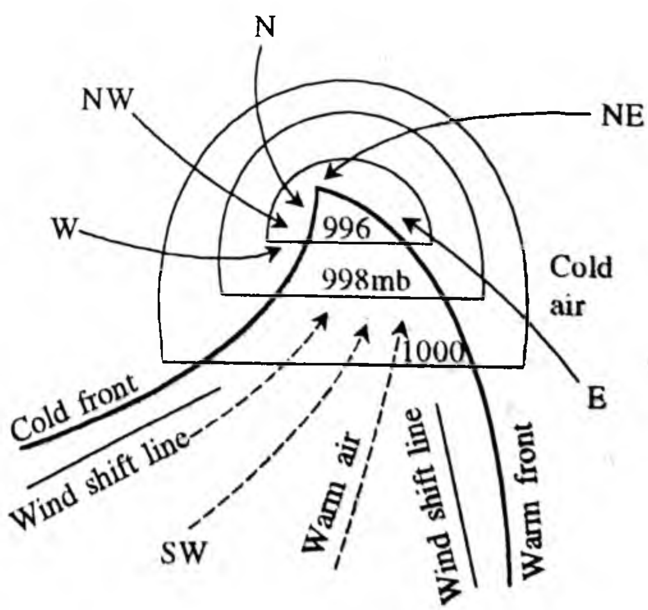


Fig. 11.6 : Wind pattern in temperate cyclone (northern hemisphere).

forms warm front, warm sector, cold front, and cold sector. Before the arrival of warm front the wind direction is easterly but it changes to southerly and southwesterly at the time of the arrival of warm front. The warm front and warm sector are, thus, characterized by warm southerly and southwesterly winds while the direction of winds changes to westerly, northwesterly and northerly at the arrival of cold front and cold sector. The cold front and cold sector are characterized by cold winds. It is apparent that there is sudden change in wind direction along the warm and cold fronts. The line along which wind changes its direction is called **wind shift line** (fig. 11.6).

Temperature

Different temperatures are noted in different parts of temperate cyclones because of their origin due to convergence of two thermally contrasting air masses. The southern part of cyclone records higher temperature because of the dominance of warm air while the north-eastern, northern and north-western parts record low temperature because of the dominance of cold polar air mass. The western part records lowest temperature. The temperature within the cyclones depends on the properties of air masses, general weather conditions and moisture content in the air. Isotherms generally tend in north-northeast to southwest direction (fig. 11.7) in the northern hemisphere.

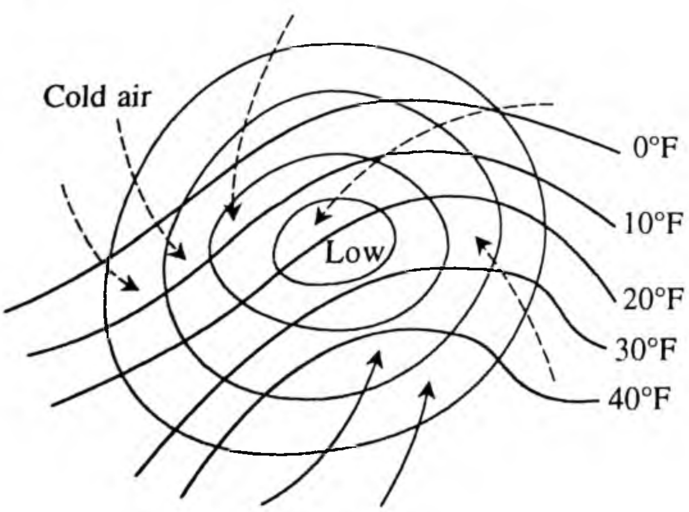


Fig. 11.7 : Temperature and isotherms in temperate cyclones (northern hemisphere).

3. Source Regions and Tracks of Movement

The areas frequented by temperate cyclones mostly lie in the middle and high latitudes extending between 35^0-65^0 latitudes in both the hemispheres. These cyclones move, on an average, in easterly direction but since their tracks are highly variable and hence cyclonic tracks are always considered in zonal pattern rather than in linear pattern. The paths followed by these cyclones are called **'storm tracks'**. The following are the most favourable breeding areas of temperate cyclones. (1) Cyclones after originating in the north Pacific off the north-east and eastern coasts of Asia move in easterly and north-easterly direction towards the Gulf of Alaska and ultimately merge with Aleutian Lows from where they follow southerly direction and reach as far south as southern California. The cyclones moving inland dissipate and are occluded at the windward western slopes of the Rocky mountains. (2) There are four principal areas of frontogenesis in North America e.g. (a) area east of Sierra Nevada Range, (b) eastern Colorado, where temperate cyclones are called **Colorado Lows,** (c) area east of Canadian Rocky mountains, where cyclones are known as **Alberta Lows,** and (d) Great Lakes region. (3) The cyclones originating in the Gulf of Mexico follow northerly trajectory to the east of the Appalachians and following the course of the Gulf Stream merge with the Icelandic Zone of frontogenesis. (4) North-West North Atlantic off the north-east coast of North America-the cyclones originating in this area move in easterly direction and enter the northwestern parts of Europe. (5) Cyclones originating in the area between Iceland and Barents Sea follow easterly trajectory and affect the weather conditions of north Europe. (6) There are two main zones of frontogenesis in continental Europe e.g. (a) Baltic Sea and (b) Mediterranean Sea. Some of the cyclones originating over the Mediterranean Sea after following easterly direction reach Pakistan and north India in winter season where most of the winter precipitation is received through these storms. Majority of the cyclones of Mediterranean origin move north-eastward and reach Commonwealth of Independent States (CIS, some Republics of former USSR).

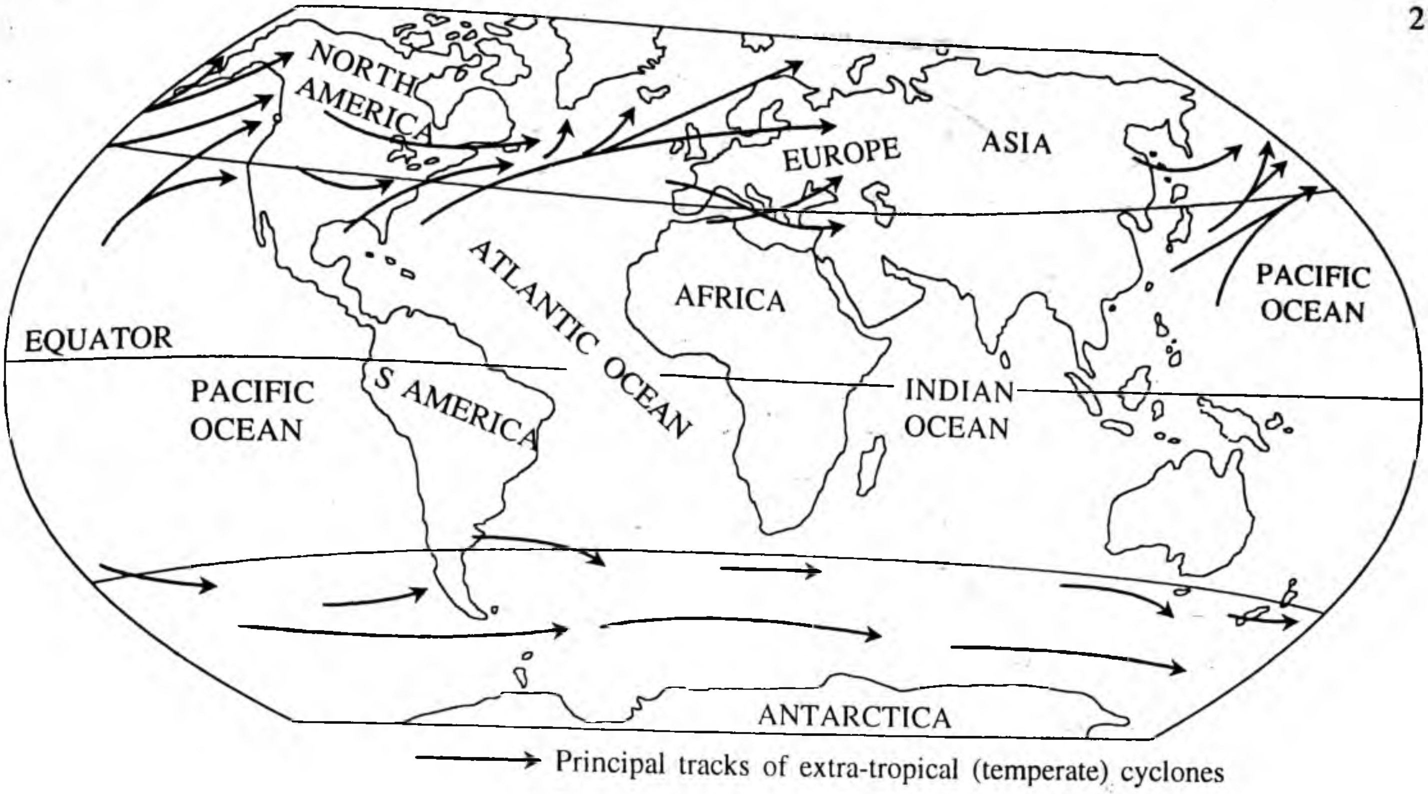


Fig. 11. 8 : Tracks of temperate cyclones. **Source :** *after Petterson, in G.T. Trewartha, 1954.*

4. Weather Conditions Associated With Temperate Cyclones

Different parts of temperate cyclones are associated with varying weather conditions because of different types of air masses and varying temperature conditions. The observation point of a moving temperate cyclone experiences different weather conditions at the time of arrival and passage of warm front, warm sector, cold front and cold sector.

(i) **Arrival of cyclone :** When the cyclone coming from the western direction draws nearer to the observation point, wind velocity slows down considerably, air pressure decreases and the sun and the moon are encircled by **halo** which is infact the reflection of thin veneers of cirrus and cirrostratus clouds in the west. Temperature suddenly increases when the cyclone comes very close to the observation point, wind direction changes from easterly to south-easterly, the cloud cover thickens and the sky becomes overcast with dark, thick and low clouds, mainly nimbostratus clouds (fig. 11.9).

(ii) **Warm Frontal Precipitation :** Clouds become very thick and dark with the arrival of warm front of the cyclone and heavy shower begins with nimbostratus clouds. Since the warm air rises slowly along the front, and hence the precipitation is slow, gradual but of long duration. The warm frontal precipitation largely depends on the amount of moisture and instability of the rising warm air. If the air is full of moisture and is unstable, there is sufficient precipitation, the sky is overcast and the sun is not visible for several hours.

The region of warm front precipitation is characterized by foggy weather and poor visibility. Some times, the warm air ascends over cold air suddenly, and becomes unstable and yields heavy precipitation through strong convection. 'In winter, ice pellets or freezing rain may occur when rain falls from the warm air through the cold mass below. The succession of weather can include snow, ice pellets, and then rain as the front approaches, clouds lower, and temperature rises' (H.J. Critchfied, 2002).

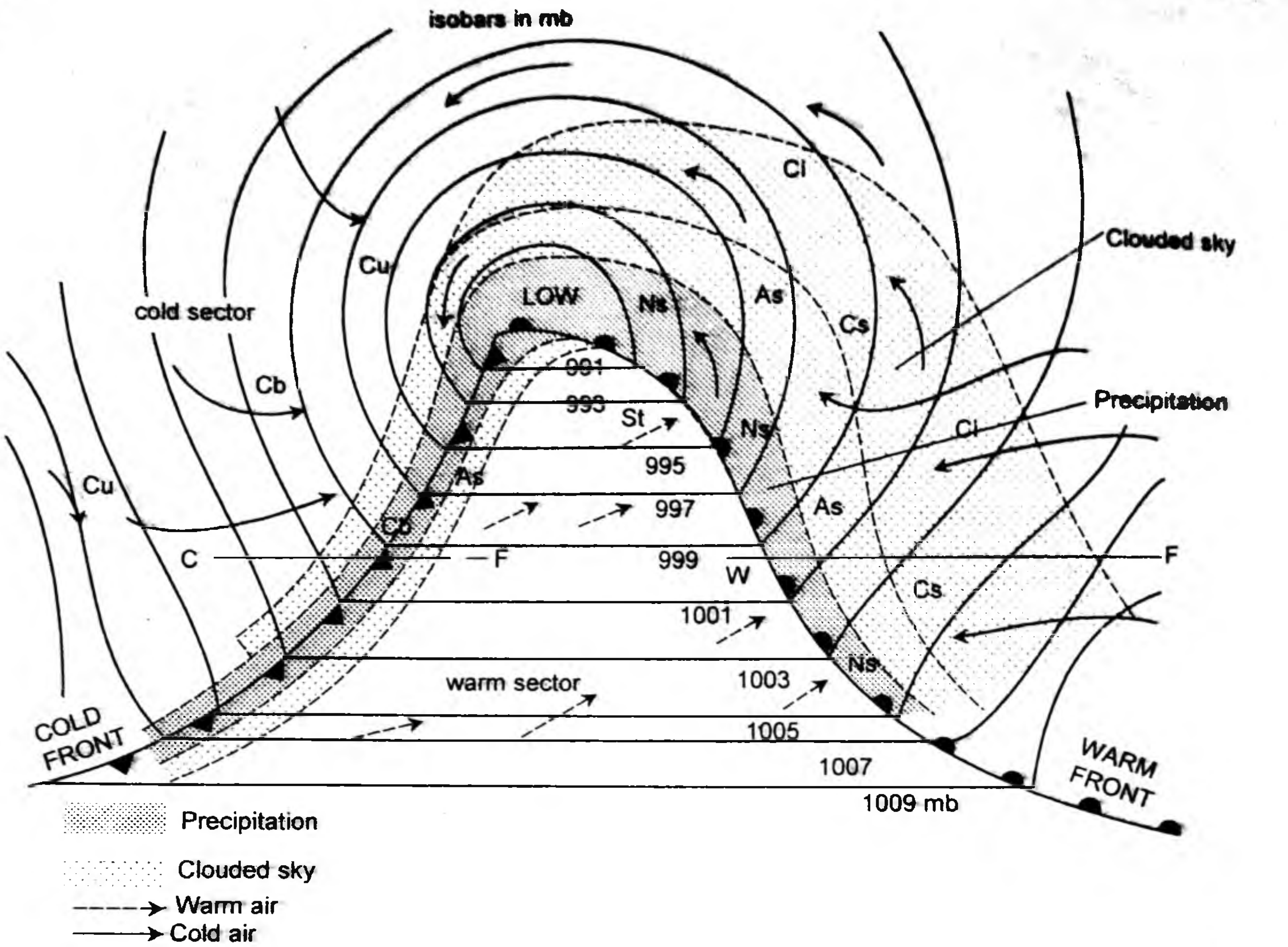
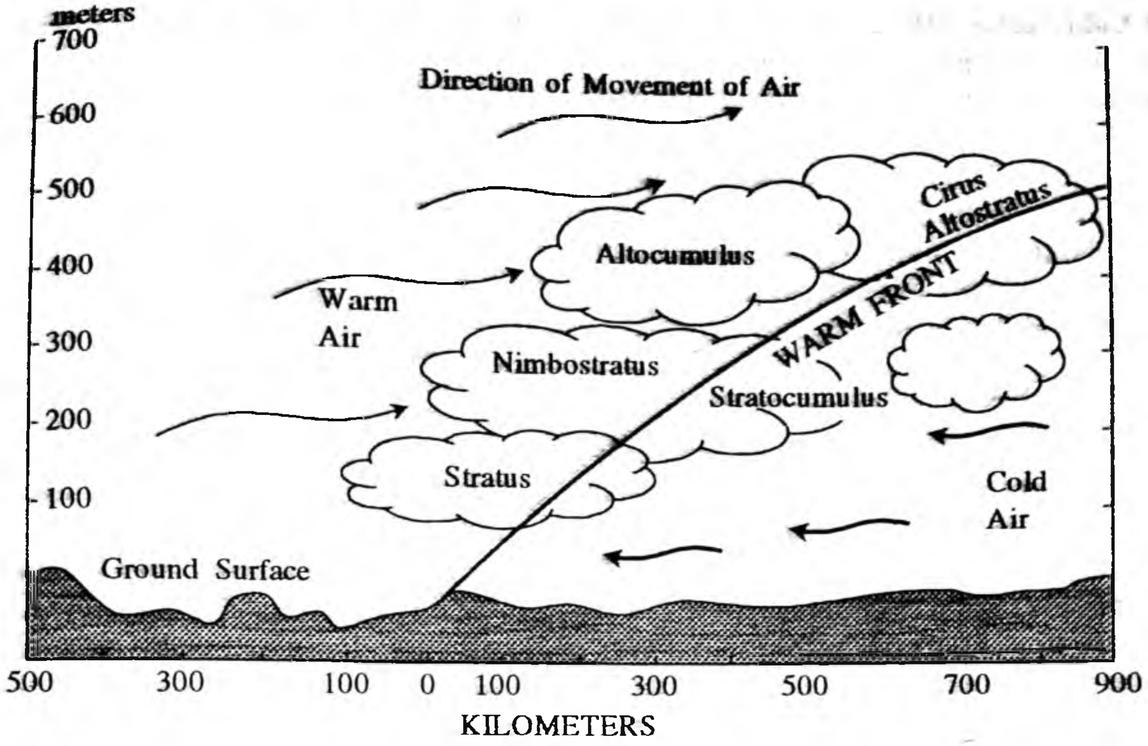


Fig. 11.9 : A section through a fully developed temperate cyclone and weather phenomena associated with different fronts and sectors. WF = vertical cross-section along warm front (fig. 11.10), CF = vertical cross-section along cold front (fig. 11.11), Ns = nimbostratus cloud, Cs = cirro-stratus cloud, As = alto-stratus clouds, Cb = cumulonimbus cloud.

(iii) **Warm Sector :** The warm sector comes over the observation point after the passage of warm front, and there is sudden change in the pre-existing weather condition. The wind direction becomes southerly and southwesterly. The sky becomes cloudless and clear. There is sudden rise in temperature and increase in the specific humidity of the air but air pressure decreases remarkably. Though weather becomes clear but the moist and warm air becomes conditionally unstable which may produce occasional convective showers or drizzles through strato-cumulus clouds. In all, the weather is clear and pleasant.

(iv) **Cold front :** Temperature registers marked decrease with the arrival of cold front. Cold increases considerably. The cold air pushes the warm air upward and there is change in wind direction from southerly to south-westerly and westerly. Sky is again covered with clouds which soon start precipitation.

(v) **Cold Frontal Precipitation :** Sky becomes overcast with cumulonimbus clouds which yield heavy showers. Since the warm air is forcibly lifted upward hurriedly, the cold frontal precipitation is in the form of heavy downpour with cloud thunder and lightning but the precipitation is of short duration and less widespread because the cold sector is very close.



11.10 : *Vertical cross-section across warm front (along WF line in fig. 11.9). Based on H.J. Critchfied, 2002.*

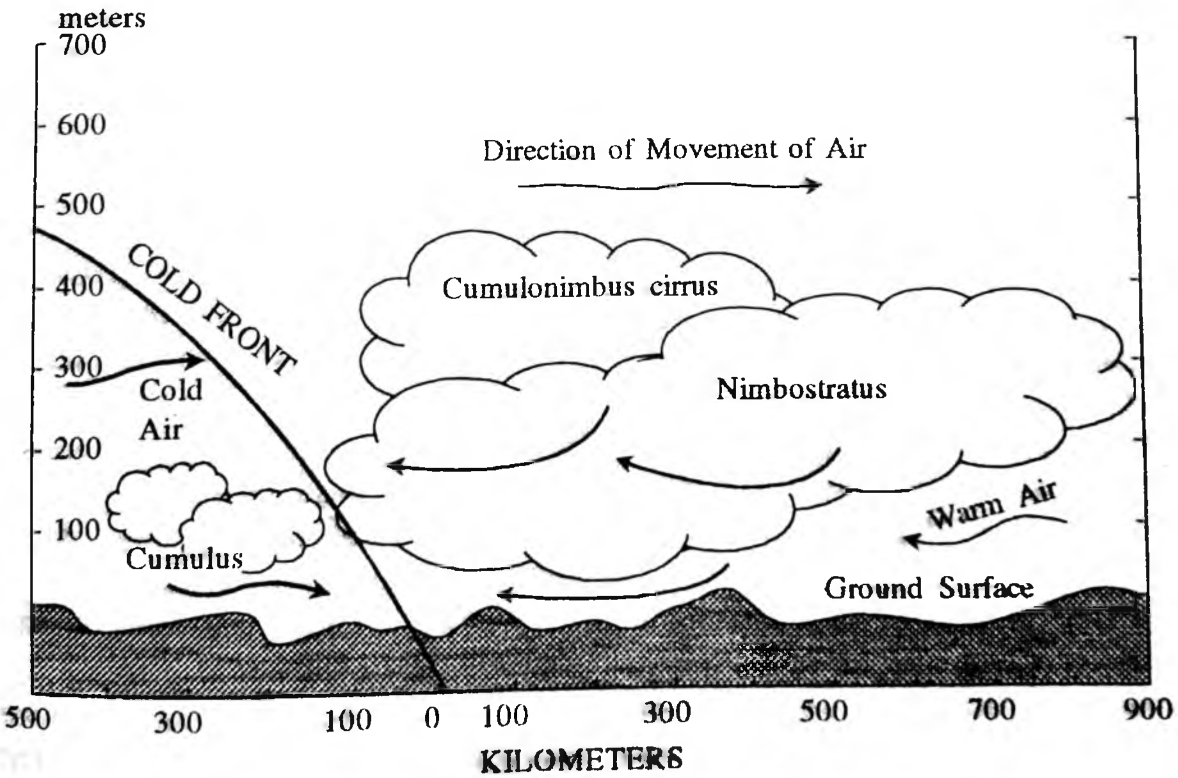


Fig. 11.11 : *Vertical cross-section across cold front (along CF in fig. 11.9). Based on H.J. Critchfield, 2002.*

(vi) **Cold Sector :** Weather again changes remarkably with the passage of cold front and arrival of cold sector. Sky becomes cloudless and hence clear. There is sharp fall in air temperature and considerable rise in air pressure but decrease in specific humidity. Wind direction changes from 45^0 to 180^0 and thus it becomes true westerly. After the occlusion of cyclone the weather conditions of pre-cyclone period again set in.

(vii) Occluded Fronts

Occlusion of cyclonic front is defined as overtaking of warm front by cold front. Occlusion is of two types, namely (1) **Cold front occlusion,** and (2) **warm front occlusion** depending upon relative temperatures and densities of air masses. The weather associated with occluded fronts is very complex. The cold front occlusion is characterized by weather of cold front. The lifting of conditionally unstable warm air produces convective thunderstorms and resultant heavy precipitation. But after the passage of cold front occlusion, calm weather prevails. The weather of warm front occlusion is more or less similar to warm frontal weather. It may be mentioned that in both types of occlusions the warm air is uplifted and hence is cooled, condensed and precipitation occurs on the basis of amount of moisture content in the air, the nature of uplifting (ascent) of warm air mass and velocity of wind (see fig. 11.3c)

5. Origin of Extratropical (Temperate Cyclones)

The riddle of the problem of the origin of extratropical (temperate) cyclones still remains unresolved as no commonly acceptable theory of their origin could be postulated as yet. The availability of more information and authentic satellite data about upper air circulation has opened new vista in this field. The chronological development of concepts of cyclogenesis in middle latitudes may be presented as follows.

(1) The first pioneer serious attempt to unfold the riddle of the origin of temperate cyclones was made by **Fitzroy** in the year **1863**. He postulated that extratoropical cyclones originated because of the convergence of two opposing air masses of contrasting physical properties i.e. temperature, air pressure, density, wind direction and velocity, and moisture content in the air. According to him the convergence of warm and moist air masses of tropical origin and cold and denser air masses of polar origin along a line produces fronts which develop into cyclones. It maybe mentioned that Fitzroy is given full credit to take a lead in this precarious field of cyclogenesis in temperate regions. In fact, his concept paved the way for future scientists to develop this concept for the formulation of theory to explain extratropical cyclones.

(2) **Abercromby** opened a new vista in the field of formulation of theory of cyclogensis in the middle latitudes with his publication **'Weather'** in the year **1887**. He tried to explain the physical processes which were responsible for the origin of temperate cyclones but his new ideas based on mathematical modeling and model diagram of a typical temperate cyclone were overshadowed by traditional scientists who were more interested in descriptive approach rather than analytical approach of the explanation of these cyclones.

(3) **Shaw** and **Lempfert** opined that temperate cyclones originated due to convergence of winds from all directions towards the center. In fact, they elaborated the dynamic concept of Abercromby and postulated their **dynamic theory** of cyclogenesis in temperate regions in the year **1891**. In this way the theory of cyclogensis of Fitzroy was further enriched by more scientific basis due to inclusion of more new upper air data and scientific explanation.

(4) At a later date **convective current theory** was postulated to explain the origin of temperate cyclones but this theory was severely criticised and discarded.

(5) After the rejection of convective current theory, **eddy theory** was postulated to explain the origin of extratropical cyclones. According to this theory temperate cyclones originate due to the formation of eddies caused by obstructions in the advancing air masses.

(6) Two Norwegian meteorologists, **V. Bjerknes** and **J. Bjerknes** postulated an entirely new theory of the origin of temperate cyclones, popularly know as **polar front theory** in the year **1918**. This theory is also known as **wave theory of**

Bergen theory, on the name of famous Swedish scientist.

(7) Lately, **baroclinic theory** was formulated for cyclone development in the middle latitudes on the basis of recent meteorological data from middle and upper troposphere derived through satellites and radars.

1. Polar Front Theory

Polar front theory also called as **'frontal theory'** or **'wave theory'** or **Bergen theory** as propounded by V. Bjerknes and J. Bjerknes in 1918, is primarily based on the processes of the formation of fronts. It may be pointed out that fronts are formed due to convergence of two air masses of different physical properties coming from opposite directions. One air mass is polar in character and is cold, denser and north-easterly in direction while the other air mass is tropical or subtropical in origin and is warm, moist, lighter and south-westerly in direction (in the northern hemisphere). When these two contrasting air masses converge along a line in the middle latitudes (temperate regions), they move parallel to each other and thus a **stationary front** is formed (fig. 11.12A). No cyclone can develop from such stationary front because there is no vertical movement in the air, rather winds are more or less stable and thus stable waves soon dissipate and hence no active front can be formed which may initiate cyclogenesis. On the other hand, when two opposing air masses collide against each other and try to attack the territory of one another, **unstable waves** are formed which help in the origin and development of temperate cyclones (fig. 11.12B). In the beginning the surface separating two air masses (more technically called as **surface of discontinuity**) is almost straight but it becomes unstable and wave-like when the warm and cold air masses attempt to penetrate in the regions of one another. Such unstable wavy front is called **polar front.**

When south-westerly warm and moist air mass enters the territory of cold polar air mass along the polar front, it being lighter rises upward, with the result a centre of low pressure is formed. Now winds from all directions rush up towards this centre of low pressure and thus a cyclone is formed. It may be pointed out that the cyclone forming wave developed due to convergence of cold and warm air masses is divided into two parts e.g. the eastern part of the wave, where eastward advancing warm tropical or subtropical air mass ascends over a wedge of cold air mass is called **warm front** (fig. 11.12C) while the western part, where cold polar air mass pushes warm air mass upward forcibly, is called **cold front** (fig. 11.12C). It is to be remembered that warm air mass is aggressive along the warm front where it over-rides cold air mass whereas the cold air mass becomes aggressive along the cold front because it replaces warm air by pushing it upward. The southwestern and north-western sectors of the cyclone are called **warm sector** and **cold sector** respectively.

The low pressure in the eastern part of the cyclone is intensified with the arrival of warm air. This draws the winds towards the centre from nearby areas, with the result cold front advances more rapidly than warm front. Consequently, cold and warm fronts come close to each other resulting into the destruction of warm front. The cyclone dies due to disappearance of warm front. This process of cyclone destruction is called **occlusion** (fig. 11.12E and F). Some times, weak and feable minor cyclone is formed after the occlusion of main cyclone. Such **secondary cyclone** is called **subcyclone.** Secondary cyclone is generally formed when some warm air still remains in the cold front after the occlusion of main front with the result a centre of low pressure is re-established and winds blow towards this centre from all sides forming a new weak cyclone. It may be pointed out that though the formation and development of temperate cyclones is a quick process but it passes through a series of successive stages. The period of a cyclone from its inception (cyclogenesis) to its termination (frontolysis or occlusion) is called the **'life cycle of cyclone'** which is completed through six successive stages (fig. 11.12).

(1) **First stage** involves the convergence of two air masses of contrasting physical properties and directions. Initially, the air masses (warm and cold) move parallel to each other and a stationary front is formed. The warm and cold air masses blow parallel to the isobars as the former has

straight easterly direction (east to west) while the latter follows westerly direction (west to east). The stable front remains in equilibrium state. This is called **initial stage.**

(2) **Second stage** is also called as **'incipient stage'**, during which the warm and cold air masses penetrate into the territories of each other and thus a **wave-like front** is formed. This is unstable front.

(3) **Third stage** is the mature stage when the cyclone is fully developed and isobars become almost circular. This is called mature stage. Warm and cold fronts are fully developed and are separated by warm sector, which is progressively narrowed down because of the movement of cold front at faster rate than the warm front. It may be pointed out that it is the warm air which is forced to ascend along both warm and cold fronts and hence if it contains enough moisture, it yields precipitation through adiabatic cooling and consequent condensation. The warm front precipitation is gradual and slow but of longer duration as the warm air ascends slowly while the cold front precipitation is in the form of heavy downpour but of shorter duration because the warm air is forcibly uplifted due to under running of cold air. The cold front precipitation is also mixed with snowfall and hailstorm depending upon local conditions.

(4) **Fourth stage :** warm sector is narrowed in extent due to the advancement of cold front at faster rate than warm front, and cold front comes nearer to warm front.

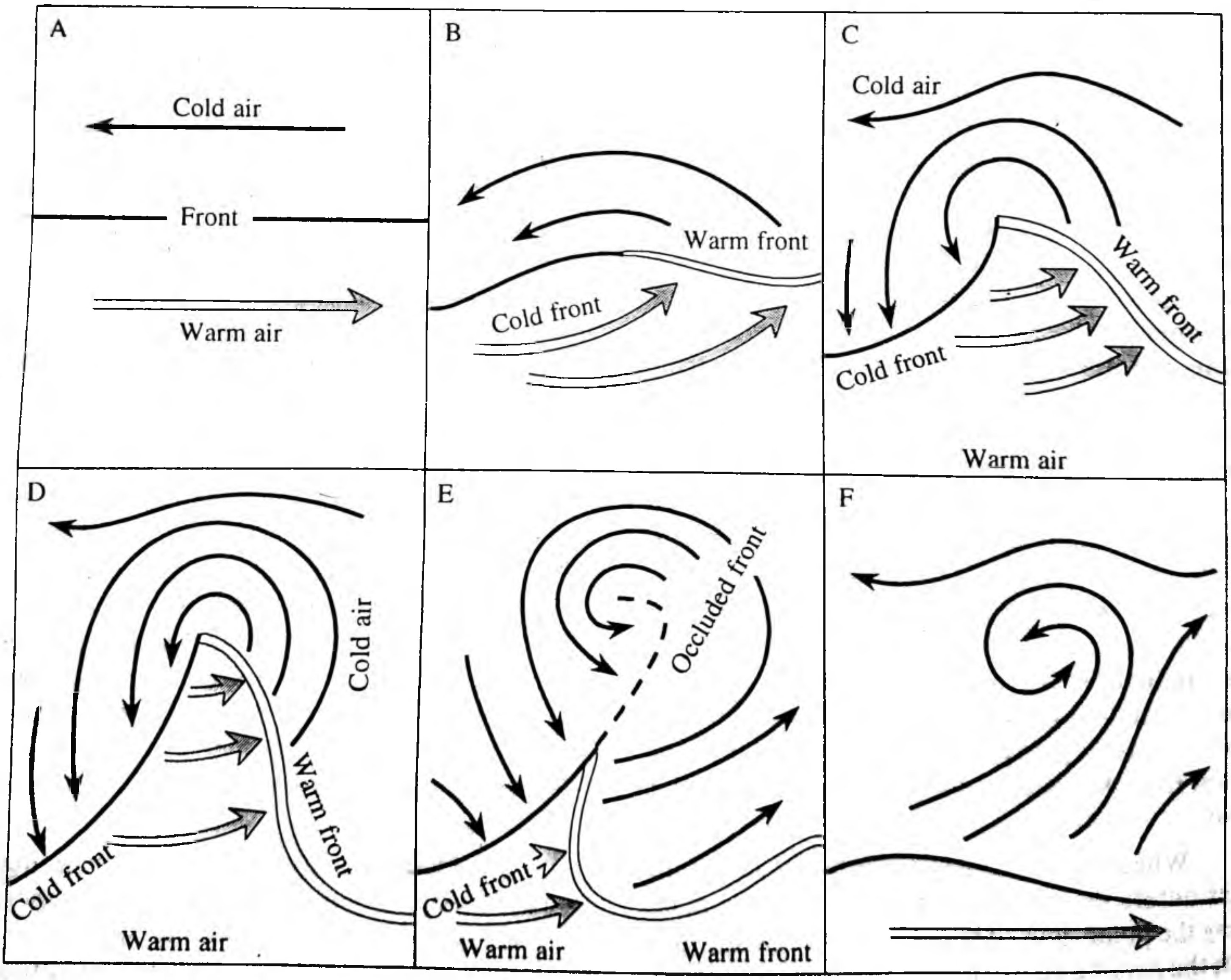


Fig. 11.12 : ***Stages of life-cycle of a cyclone.***

(5) **Fifth stage** starts with the occlusion of cyclone when the advancing cold front finally overtakes the warm front and occluded front is formed.

(6) **Sixth stage** : warm sector completely disappears, occluded front is eliminated and ultimately cyclone dies out.

2. Baroclinic Wave Theory

It may be mentioned that at the time of formulation of frontal wave theory or polar front theory detailed information and data about upper air circulation patterns were not available and hence the frontal wave theory could not be based on mathematical models and numerical analysis of data, rather it was based on descriptive technique involving surface air data. But now this classical concept of cyclogenesis of temperate depressions in the middle latitudes has been modified on the basis of availability of more and more information and data of upper air (tropospheric) circulation through satellites and radars. The recent views on the origin and development of temperate cyclones include (i) **conveyer belt model** wherein warm and moist, and cold and dry air masses act as conveyers of energy in the central part of the cyclone; (ii) the occlusion of fronts does not always occur due to overtaking of warm front by cold front but occlusion may also occur due to elongation of central low pressure area of the cyclone (it may be remembered that the warm and cold fronts meet at this central point), alternatively front occlusion may also take place due to sliding of cold front along warm front; (iii) the upper air circulation is wave like and this wavy upper air circulation contains several troughs and ridges, the meridional pattern of which intensifies troughs resulting into separation of these deepening troughs from west-east wavy circulation, the process continues over and over again; (iv) extratropical cyclones are not necessarily always formed by front formation, rather they are also formed even without preexisting fronts between two contrasting air masses in terms of temperature, air pressure, humidity and density i.e. polar and tropical air masses; (v) the cyclones and anticyclones are part and parcel of general circulation of the atmosphere and they are energy transporters; (vi) use of **barotropic and baroclinic models in the formation of extratropical cyclones etc.**

It has now become necessary to understand the concepts of barotropic and baroclinic surfaces. **Barotropic surface** represents that region where density does not vary along the surfaces of constant pressure i.e. the surfaces of constant pressure and constant density (and hence temperature) do not intersect rather are parallel and hence there is no possibility of the formation of fronts, because there is no chance for either convergence or divergence of air. On the other hand, **baroclinic surface is that** where surfaces of constant pressure intersect surfaces of constant density (which is taken to be dependent on temperature). Thus, the baroclinic situation provides ideal conditions for the formation of cyclones and anticyclones. The **multi-level baroclinic models** are now employed by the modern meteorologists to explain the process of cyclogenesis. Since the baroclinic surface represents intersecting surfaces of constant pressure and constant density and hence this becomes a frontal zone wherein the potential energy of zonal air circulation is converted into kinetic energy to form eddies which are developed into cyclones and anticyclones (horizontal air flow is now changed to eddy or circular flow). The baroclinic state of the atmosphere representing intersection of constant pressure and density surfaces and unstable atmospheric conditions, is created due to steep temperature gradient from the equator towards the poles. Whenever upper air divergence becomes active, surface convergence becomes the consequent result of the former, baroclinicity is intensified because of closer association of warm and cold air masses resulting into the formation of fronts. In such circumstances, the front develops into frontal wave which causes the sequential stages of cyclone development as envisaged in frontal wave theory or polar front theory.

11.9 ANTICYCLONES

As the word 'anticyclone' implies the air circulation having opposite conditions and characteristics of a cyclone is called anticyclone. The term 'anticyclone' to indicate divergent air circulation in all directions from high pressure center, was first introduced by **F. Galton in the year 1861.**

Surrounded by almost circular isobars anticyclone is such a wind system which has highest pressur at the center and pressure decreases outward in such a way that it becomes lowest at the outer margin and the winds blow from the center outward in clockwise direction in the northern hemisphere and anticlockwise direction in the southern hemisphere (fig. 11.13). Thus, anticyclones are high pressure systems and are more common in the subtropical high pressure regions but are practically absent in the equatorial regions. They are generally associated with rainless fair weather. This is why anticyclones are called weather less phenomena.

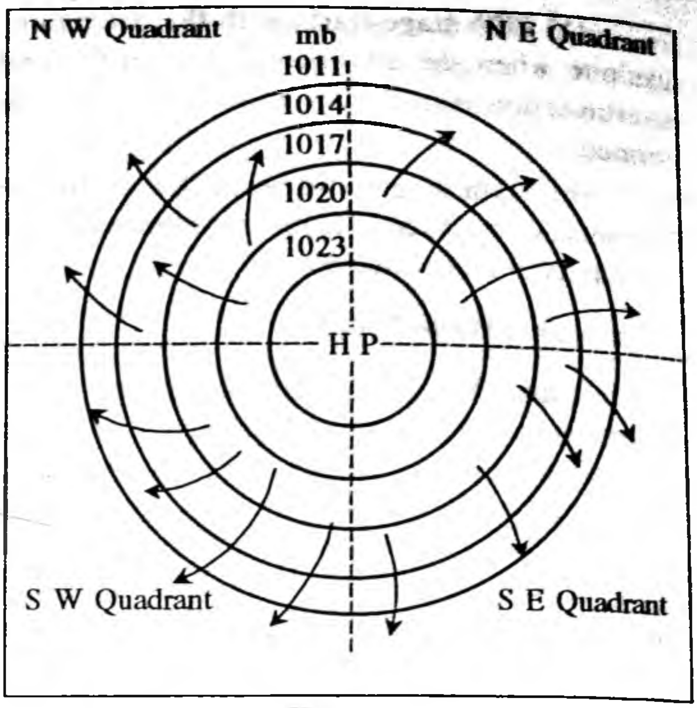


Fig. 11.13 : Air pressure and wind system in an anticyclone.

General Characteristics

The anticyclones are characterized by the following properties :

(1) They are usually circular in shape but some times they also assume 'V' shape. There is maximum air pressure at the centre and it decreases outward. The difference of pressure between the centre and periphery of anticyclone ranges between 10-20mb and some times it becomes 35mb.

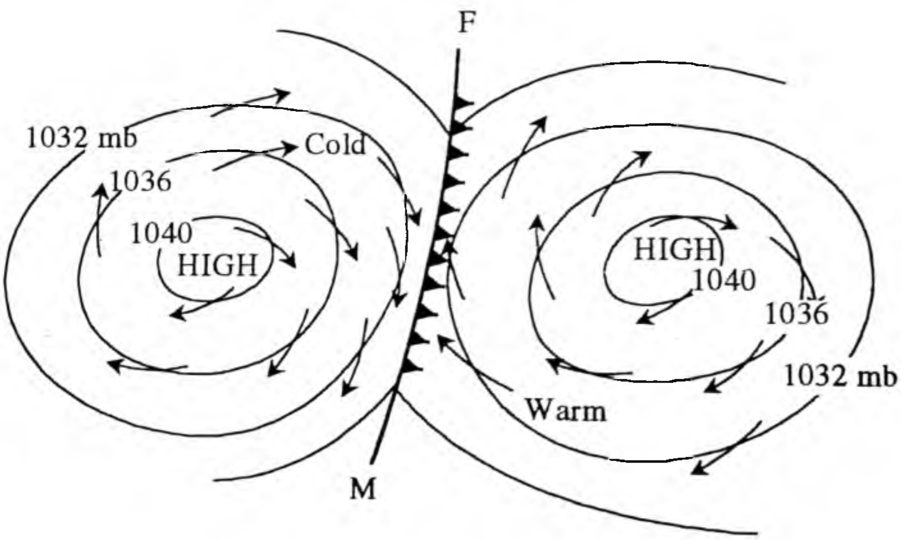


Fig. 11.14 : Meridional front at the intersection line of two anticyclones. **Source** *: After H.J. Critchfield, 2002.*

(2) They are much larger in size and area than temperate cyclones as their diameter is 75 percent larger than that of the latter.

(3) Though anticyclones follow cyclones but their track is highly variable and unpredictable. They move very sluggishly and some times they become stationary over a particular place for few days. The average velocity of anticyclones is 30-50km per hour.

(4) Because of high pressure at the centre winds blow outward clockwise in the northern hemisphere and anticlockwise in the southern hemisphere.

(5) Winds descend from above at the centre and thus weather becomes clear and rainless because the descending winds cause atmospheric stability.

(6) Temperature in anticyclones depends on weather, nature of air mass and humidity in the air. They record high temperature during summer season due to development of warm air masses whereas they carry low temperature during winter season due to polar cold air masses.

(7) Anticyclones do not have front but sometimes, 'wind shear and convergence may generate frontal activity in the trough of low pressure between two anticyclones (fig. 11.14). The resulting front often has north-south alignment and is known as **meridional front** (M-F in fig. 11.14)' (H.J. Critchfield, 2002).

Wind System

Wind system is not fully developed in anticyclones because of weak pressure gradient. On an average, wind circulation is of divergent system wherein winds spread in all directions from high pressure centre to low pressure periphery. There is westerly wind in the front portion of an eastward advancing cold anticyclone while the rear portion is characterized by easterly winds (fig. 11.13). The winds are very much sluggish in the rear portion in comparison to the winds in the front portion. The centre is characterized by light breeze. Wind system is seldom developed fully in warm anticyclones.

Shape and Size

Anticyclones are generally of circular, near circular or wedge shape but are very large in size. Some times, they become so large in size that their diameters become 9,000 km. There is little difference between the length and width of anticyclones. Temperate anticyclones are so extensive that a single anticyclone covers nearly half of the USA.

Temperature

Anticyclones are originated due to the descent of either polar cold air mass or warm tropical air mass. It is, thus, obvious that cold anticyclones are associated with extremely low temperature and they cause cold waves during winter season but when they come in summer season, weather becomes pleasant. On the other hand, warm anticyclones bring heat waves during summer season in the tropical regions.

Weather Conditions

Generally, anticyclones are rainless and sky is free of clouds because of the fact that descending air in the centre of anticyclone is warmed up at dry adiabatic rate due to subsidence. This causes rise in temperature which reduces normal lapse rate of temperature, with the result the stability of air increases resulting into marked increase in the aridity of air. This is why anticyclones are indicative of dry weather. This does not mean that anticyclones are always rainless. While passing over oceans some times they pick up moisture and yield light rains or drizzles with moderate clouds. The arrival of anticyclones is heralded by clearing of clouds, if already present in the sky, clear weather and decrease in wind velocity. The weather of Canada, USA, and north Eurasia is mostly affected by anticyclones.

Types

Anticyclones were classified into (i) warm anticyclones, and (ii) cold anticyclones by Hanzilk in 1909, while Humphreys divided them into 3 types viz. (i) mechanical or dynamic anticyclones, (ii) thermal or heat anticyclones, and (iii) radiation anticyclones. A.E.M. Gaddes has classified anticyclones into 3 types e.g. (i) large anticyclone, covering the whole of the continent, (ii) temporary anticyclone, which has a diameter of 250 to 300km and covers only the marginal areas of the continents, and (iii) cyclone-originated anticyclones, which develop due to high pressure caused between two temperate cyclones. Normally, anticyclones are divided into (i) cold anticyclones, (ii) warm anticyclones, and (iii) blocking anticyclones.

(i) **Cold anticyclones** : after originating in the arctic regions cold anticyclones advance in easterly and south-easterly directions. Though they are smaller than warm anticyclones in size but move more rapidly than the latter. They are of very low thickness. Very few cold anticyclones are higher than 3,000 m. Harwitz and Noble have observed upper atmospheric low pressure above surface anticyclones at US-Canada border but such situation is not a permanent feature. Cold anticyclones are divided into two subtypes e.g. (i) temporary anticyclones, which die out in the transit while moving forward, only a few reach tropical regions, and (ii) semipermanent anticyclones, which cover longer distances and are more active. Cold anticyclones are thermally induced because they do not develop due to descent of air from above. They are originated due to development of high pressure because of very low insolation during winter season in the arctic regions. Cold anticyclones follow two tracks. (i) Anticyclones after originating in the north of Canada move in easterly and south-easterly direction and affect the weather conditions of Canada and USA. (ii) Anticyclones originating in the north of Siberia move towards China, Japan and Alaska. Anticyclones affecting north-west Europe originate with temperate cyclones (in their rear portion). While entering tropical region cold anticyclones die out due to increase in temperature.

(2) **Warm anticyclones** originate in the belt of subtropical high pressure where winds diverge in opposite directions. Thus, warm anticyclones are originated due to descent of air from above and consequent divergence at the surface. They, thus are dynamically induced. They are large in size but are very sluggish in movement. Some times, they become stationary over a place for several days and weeks. They are associated with light wind, cloudless sky and clear weather. Warm anticyclones mostly influence the weather of S.E. USA and western Europe.

(3) **Blocking anticyclones** develop due to obstruction in the air circulation in the upper troposphere. This is why they are called blocking anticyclones. They develop over N.W. Europe and adjoining Atlantic Ocean and the western part of the N. Pacific Ocean between 140^0-170^0W longitudes. They are similar to warm anticyclones as regards wind system, air pressure and weather but are small in size and move very slowly.

11.10 IMPORTANT DEFINITIONS

Alberta low : The temperate cyclones developed to the east of Canadian Rocky mountains are called Alberta lows (because of the name of Alberta state of Canada).

Ana front : When in a temperate cyclone warm air becomes active and rises over cold air, the resultant front is called ana front.

Anticyclone : The air circulation having opposite conditions and characteristics of cyclone is called anticyclone which is characterized by almost circular isobars, highest pressure at the center and lowest pressure at the outer margin, sinking of warm air from above at the center, divergent wind flow in all directions from the center, cloudless clear and dry weather, clockwise air circulation in the northern hemisphere and anticlockwise in the southern hemisphere.

Baroclinic surface : Baroclinic surface is that where surfaces of constant pressure intersect surfaces of constant density i.e. where isotherms and isobars intersect them.

Barotropic surface : Barotropic surface represents that region where density does not vary along the surfaces of contant pressure i.e. the surfaces of constant pressure and density do not intersect, rather become parallel (i.e. isobars and isotherms are parallel).

Blocking anticyclone : The anticyclone, developed due to obstruction in the air circulation in the upper troposphere is called blocking anticyclone.

Cold front : Cold front is that sloping surface in a temperate cyclone along which cold air becomes aggressive and invades the warm air territory, forcibly uplifts the warm air and itself being denser remains at the ground surface.

Cold front occlusion : Cold front occlusion occurs when cold air behind the cold front is colder than the advancing cold air which is ahead of warm front and thus cold front overtakes warm front.

Colorado low : The temperate cyclones developed in east Colorado state of the USA are locally called Colorado lows.

Convergent circulation : Convergent circulation of air involves meeting (convergence) of winds at common point (center of low pressure) from all directions.

Cyclongenesis : The process of formation of fronts or simply frontogenesis is called cyclogenesis or the process of the origin and development of cyclone is called cyclogenesis.

Cyclones : Cyclones are centers of low pressure surrounded by closed isobars having increasing pressure outward and closed air circulation (convergent air circulation) from outside towards the central low pressure in such a way that winds blow in anticyclockwise and clockwise directions in the northern and the southern hemispheres respectively.

Defomatory circulation : Defomatory circulation involves convergence of two contrasting air masses and horizontal spread along a line which is called axis of outflow or axis of dialation.

Divergent circulation : Divergent air circulation refers to spread of winds outward in all direction from a central point of high pressure.

Dynamic cyclone : Dynamic cyclones are real temperate cyclones because they are formed due to convergence of cold polar air masses and warm and moist maritime tropical air masses.

Front : Front is that sloping boundary which separates two opposing air masses having contrasting characteristics in terms of air temperature, humidity, density, pressure, and wind direction.

Frontal theory : The theory which explains the origin of temperate cyclones involving frontogenesis is called frontal theory or polar front theory.

Frontal zone : The region of the formation of fronts (region of frontogenesis) is called frontal zone.

Frontogenesis : The process associated with the creation of new fronts or regeneration of old and decying fronts already in existence is called frontogenesis.

Frontolysis : The process of destruction or decaying of fronts is called frontolysis which is opposite to the process of frontogenesis.

Halo : The white milky ring around the moon during night caused by the reflection of thin veneer of circus and cirrostratus clouds, is called halo.

Insolation cyclone : Thermally induced temperate cyclones in the middle latitudes have been named insolation cyclones by Humphreys. Such cyclones are stationary at the places of their origin and different fronts are not properly developed.

Kata front : Kata front in a temperate cyclone is formed when warm air sinks and there is little difference of temperature between two converging warm and cold air masses.

Line of discontinuity : Line of discontinuity is a transition zone between weather conditions of two contrasting converging air masses of different temperature and density.

Occlusion : Occlusion of a front of a cyclone is defined as overtaking of warm front by cold front.

Occluded front : Occluded front is formed when cold front overtakes warm front and warm air is completely displaced from the ground surface.

Polar front : The unstable wavy front formed due to convergence of cold and dense polar air mass and warm, moist and light tropical and subtropical air mass along a line of discontinuity is called polar front.

Rotatory circulation : The circulation of air in cyclonic or anticyclonic pattern is called rotatory circulation.

Secondary cyclones : Secondary cyclones are those which develop due to passage of cold winds over warm sea after the occlusion of main (original) cyclone. These are short-lived and very weak.

Stationary front : Stationary front is formed when two contrasting air masses converge in such a way that they become parallel to each other and there is no ascent of air. Such fronts are climatically insignificant as they are not conductive for cloud formation and precipitation.

Storm tracks : The paths followed by cyclones are called storm tracks.

Thermal cyclone : The cyclones formed due to development of low pressure centers on the continents in summer in temperate regions are called thermal cyclones.

Translatory circulation : Translatory air circulation involves movement of air in horizontal manner from one place to another place in same direction.

Warm front : Warm front is that gently sloping frontal surface along which warm and light air becomes active and aggressive and rises slowly over cold and dense air.

Warm front occlusion : The warm front occlusion occurs when the air behind the cold front is warmer than the advancing air which is ahead of warm front and thus the retreating cold air overtakes the warm front and advancing air.

Wave cyclone : The cyclone formed along the wavy polar fronts is called wave cyclone.

Wave theory : The popularly known polar front theory of the origin and development of temperate cyclones is called wave theory.

12

ATMOSPHERIC EXTREME EVENTS AND HAZARDS

12.1 EXTREME EVENTS AND HAZARDS : MEANING AND CONCEPT

'Those events or accidents, whether caused by natural processes or by human factors, are called **extreme events** which occur very rarely and aggravate natural environmental processes to cause disaster for human society such as sudden tectonic movements leading to earthquakes such as the disastrous earthquake with the magnitude of 8.9 on Richter scale, which occurred in the Indian Ocean off the coast of Sumatra on December 26, 2004, generated a 10 m high tsunamis (sea waves) which claimed thousands of human lives-more than 165,000-in Indonesia, Thailand, Sri Lanka, India and other south-east Asian countries within few hours) and volcanic eruptions, continued dry conditions leading to prolonged droughts, heavy and widespread rainfall for longer duration in continuation leading to severe floods, atmospheric disturbances (*e.g.* tropical cyclones, tornadoes, hurricanes, typhoons etc.) etc. (Savindra Singh, 1991, 2003). **Natural hazards** may be defined as those atmospheric and terrestrial extreme events which exceed the tolerable magnitude within or beyond certain time limits, make adjustment to changed circumstances very difficult, cause irreparable loss to human society and draw the attention of world community. **Environmental hazards** include all those extreme events which are caused either by natural processes or by human factors or by both together (*e.g.* man-induced earthquakes, landslides etc. which are activated and accelerated in both frequency and magnitude by human activities).

There are alternative or say parallel terms, namely environmental hazards, environmental stresses, and environmental disasters which are used in one way or the other to deal with the extreme events whether natural or man-induced. A distinction must be drawn between the processes (causal factors and their agents) and responses (results) of extreme events. **'Hazards'** are generally taken as the processes, both natural and anthropogenic, which cause an accident/extreme event or danger whereas **'disaster'** is a sudden adverse or unfortunate extreme event which causes great damage to human society as well as plants and animals. Disasters occur rapidly, instantaneously and without making any discrimination. It is, therefore, evident that hazards are processes whereas the disasters are the results or responses of hazards. It may be mentioned that environmental/atmospheric hazards and disasters are always viewed in terms of human beings. The intensity of environmental/natural disasters is ascertained and determined in terms of magnitude and quantum of damage done to human society. It is, thus, obvious that hazardous environmental/natural processes create extreme events but not all the extreme events become disasters. The hazards may become disasters only when they occur in inhabited areas and adversely affect human beings. For example, a very strong tropical cyclone (typhoon, hurricane, or tornado) becomes extreme event only when it occurs and dies out in the midst of an ocean but it becomes disaster when it strikes the inhabited coastal area and inflicts colossal loss to human property and lives (*e.g.* the Super Cyclone of Orissa in 1999 proved to be the most disastrous atmospheric extreme event in the cyclone history of India). Similarly, a severe volcanic eruption in uninhabited area of land or ocean is never disaster but when it occurs in densely populated area, it becomes disaster. When the cumulative effects of environmental hazards, environmental disasters and other forms of environmental degradation and pollution become so immense that the tolerance limit of the natural environmental system to sustain and assimilate them is surpassed and the environmental balance is disturbed, the resultant state of highly disturbed and destabilized natural environment is called **environmental stress.**

It may be further pointed out that to majority of the people environmental hazards and environmental disasters are synonymous terms because these are related to extreme events in one way or the other. The present author also intends to use these significant terms of environmental science as synonyms.

Generally, the environmental hazards and disasters are natural and hence these are also termed as **natural hazardous processes.** It may be pointed out that the concept and perception of environmental hazards and disasters are closely related to their impacts on the organisms in general and mankind in particular. In other words, the natural sudden physical processes and events become hazards and disasters when people live close to a potential danger. For example, if an earthquake of more than 10 on Richter scale occurs in totally uninhabited area, it is not a disaster at all but an earthquake even of lower intensity, say below 7 on Richter scale, occurs in heavily populated area, it becomes a severe hazard and disaster. It may be further pointed out that it is not the frequency which makes any extreme event hazardous and disastrous rather it is the intensity, magnitude and dimension and the quantum of damage done by any event which make it hazardous and disastrous. It is also important to note that environmental hazards are not always destructive and disastrous in themselves rather it is the effects of these events on other natural processes which become disastrous. For example, the Tajik area (of former southern USSR) 'is seismically a highly active region, shaken by upwards of 3000 tremors a year but these cause few direct casualities. But, 'the Tajik earthquake on January 21, 1989, for example, was only of magnitude 5.5, but its timing unfortunately coincided with highly unstable slope conditions caused by high pore-water processes resulting from snow-melt' (C. Embleton, 1989) and thus became disastrous.

12.2 TYPES OF EXTREME EVENTS AND HAZARDS

Extreme events are basically divided into two types, namely (1) natural extreme events, and (2) man-induced extreme events. Natural extreme events are further subdivided into (i) terrestrial extreme events, and (ii) extra-terrestrial or extra-planetary extreme events, while man-induced extreme events are subdivided into (i) physical, (ii) chemical, and (iii) biological extreme events (and hazards). The following is the detailed classification of extreme events and hazards :

1. **Natural Extreme Events and Hazards**
    - (1) **planetary extreme events and hazards**
        - (A) terrestrial extreme events
            - (i) volcanic eruptions
            - (ii) earthquakes
            - (iii) landslides
        - (B) atmospheric extreme events
            - (i) abnormal or infrequent events
                - (a) severe storms

(b) lightning

(c) hailstorm

(d) thunderstorms

(ii) cumulative events

(a) floods

(b) droughts

(c) cold waves

(d) heat waves

(2) **extra-planetary extreme events and hazards**

(a) collision between the earth and asteroids

(b) collision between the earth and meteorites

(c) collision between the earth and comets

2. **Man-induced Extreme Events and Hazards**

(A) **physical hazards**

(i) earthquakes (reservoir induced seismicity-RIS)

(ii) landslides

(iii) accelerated soil erosion

(B) **chemical hazards**

(i) release of toxic chemicals

(ii) nuclear explosions

(C) **biological hazards**

(i) population explosions

(ii) eutrophication

12.3 ATMOSPHERIC EXTREME EVENTS AND HAZARDS

Atmospheric extreme events and hazards represent unstable aspects of weather which include mainly atmospheric disturbances such as severe atmospheric storms (*e.g.* tropical cyclones, hailstorms, duststorms, snow storms, thunderstorms etc.). In fact, severe atmospheric storms are originated due to unequal spatial and temporal distribution of atmospheric energy and these storms exchange and transfer energy at global level. Since the atmospheric extreme events are caused by atmospheric processes which originate due to unequal distribution of energy within the atmosphere and hence these extreme weather events are also called as **exogeneous natural extreme events and hazards.** The atmospheric extreme weather events may be divided into two major groups, namely (1) **abnormal and infrequent events,** the mean duration of their occurrences ranges from milliseconds (such as lightning), minutes (tornadoes, thunderstorms, hailstorms etc.), to hours (*e.g.* duststorms, snowstorms, blizzards, flash floods), and (2) **cumulative atmospheric extreme weather events,** which prolong for days (such as tropical cyclones, arctic cyclones, floods, heat waves, cold waves, Nor' easters), weeks (regional floods), and even months (droughts).

Some of the extreme weather events leave instantaneous effects and cause human causalities, when they hit human beings (such as lightning), some of them have impacts both during the events and after the events such as floods, while some extreme events have longlasting and far-reaching impacts such as super cyclone of Orissa (India) in 1999, severe Gujarat and Rajasthan droughts during 1980s and 1990s. It may be mentioned that the frequency, recurrence interval, size and dimension, spatial and temporal characteristic features of atmospheric extreme events widely vary depending on the duration of such events. Tropical cyclones, regional floods and droughts are 3 most notorious atmospheric extreme events at global scales and these need detailed discussion.

12.4 TROPICAL CYCLONES

Tropical cyclone, representing a closed low pressure system generally having a diameter of about 650 kilometers, counterclockwise and clockwise air circulation in the northern and southern hemispheres respectively, energy power equivalent to more than 10,000 atomic bombs which were hurled at Nagasaki in Japan during World War II, is one of the most powerful, destructive, dangerous and deadly atmospheric storms on the planet earth. Tropical cyclones are differentially called in different parts of the globe such as **hurricanes** in the North Atlantic Ocean mainly in the Caribbean Sea and southeastern USA; **typhoons** in North Pacific Ocean, mainly in

China Sea, eastern and southern coasts of China, Japan, Philippines and S.E. Asia; **cyclones** in Bangladesh and eastern coastal areas of India; and **willy willy** in Australia.

Tropical cyclones become more disastrous natural hazards because of their high wind speed of 180 to 400 kilometres per hour, high tidal surges, high rainfall intensity (highest recorded rainfall value exceeded 2000 mm per day in Philippines), very low atmospheric pressures causing unusual rise in sea level, and their persistence for several days or say about one week. The total cumulative effects of high velocities of wind, torrential rainfall and transgression of sea water on to the coastal land become so enormous that the cyclones cause havoc in the affected areas and thus tremendous loss of human lives and property is the ultimate result of such atmospheric deluge. The **'storm surge'** or **'tidal surge'** refers to unusual rise in sea-level caused by very low atmospheric pressure and the stress of the strong gusty winds on the sea surface. These storm surges or tidal surges, when coincide with high tide, are further intensified and after intruding into the coastal land cause widespread inundation of coastal areas and great damage of human lives and property. The following case histories of a few most powerful and disastrous tropical cyclones may unravel the magnitude of destructions wrought by these natural atmospheric disturbances.

1. Characteristics of Tropical Cyclones

Cyclones developed in the regions lying between the tropics of Capricorn and Cancer are called tropical cyclones which are not regular and uniform like extratropical or temperate cyclones. There are numerous forms of these cyclones which vary considerably in shape, size, velocity, and weather conditions. The weather conditions of low latitudes mainly rainfall regimes are largely controlled by tropical cyclones. They are characterized by the following salient features.

(1) Size of tropical cyclones varies considerably. On an average, their diameters range between 80km and 300km but some times they become so small that their diameter is restricted to 50km or even less.

(2) They advance with varying velocities. Weak cyclones move at the speed of about 32km per hour while hurricanes attain the velocity of 180km per hour or more.

(3) Tropical cyclones become more vigorous and move with very high velocity over the oceans but become weak and feeble while moving over land areas and ultimately die out after reaching the interior portion of the continents. This is why these cyclones affect only the coastal areas of the continents (*e.g.* south and south-east coasts of the USA, Tamil Nadu, Orissa and West Bengal coasts of India, southern coastal regions of Bangladesh etc.).

(4) The centre of the cyclone is characterized by extremely low pressure. Isobars are more or less circular but are fewer in number. This is why winds hurriedly rush up towards the centre and attain gale velocity. The air pressure at the center sometimes becomes as low as 650 millimeters.

(5) Like temperate cyclones, tropical cyclones are not characterized by temperature variations in their different parts because they do not have different fronts (warm and cold fronts).

(6) There are no different rainfall cells in the tropical cyclones as is the case of temperate cyclones and hence each part of the cyclones yields rainfall.

(7) Tropical cyclones are not always mobile. Some times, they become stationary over a particular place for several days and yield heavy rainfall causing flood deluge and environmental disaster.

(8) The tracks of tropical cyclones vary considerably in different parts. Normally, they move from east to west under the influence of trade winds. The general direction is westerly upto 15^0 latitude from the equator, poleward between 15^0-30^0 latitudes, and thereafter easterly. These cyclones weaken when they enter subtropical regions.

(9) Tropical cyclones are confined to a particular period of the year, mainly during summer season. The frequency and affected areas of tropical cyclones are far less than those of the temperate cyclones.

(10) Tropical cyclones become disastrous natural hazards because of their high wind speed of 180 to 400 km per hour, high tidal surges, high rainfall intensity (highest recorded rainfall value exceeded 2000mm per day in Philippines), very low atmospheric pressure causing unusual rise in sea-level, and their persistence for several days or say about one week over a particular place.

2. Types of Tropical Cyclones

It may be pointed out that tropical cyclones are so varied in size, weather conditions and their general characteristics that no two cyclones are identical and therefore it becomes very difficult to classify them into certain categories. Generally, they are divided into 4 major types.

(1) Tropical disturbances or easterly waves

(2) Tropical depressions

(3) Tropical storms

(4) Hurricanes or typhoons

On the basis of intensity they are divided into two principal types and 4 subtypes.

(1) Weak cyclones

(i) Tropical disturbances

(ii) Tropical depressions

(2) Strong and furious cyclones

(iii) Hurricanes and typhoons

(iv) Tornadoes

(1) **Tropical disturbances** are migratory wave-like cyclones and are associated with easterly trade winds. They are also called **easterly waves.** Winds move towards centre with low speed. Though they move in westerly direction under the influence of trade winds with low velocity but they are most extensive and wide-spread and influence the weather conditions of both tropical and subtropical areas. Most of the easterly waves develop between 5^0 and 20^0 north latitudes in the western parts of the oceans. Some times, they are so sluggish that they remain stationary over an area for several days. They are associated with heavy cumulus or cumulonimbus clouds which yield moderate to heavy rainfall with thunder-storms. Some times, the easterly waves are so greatly intensified that they develop into hurricanes. Generally, they develop in the Carib-bean Sea and North Pacific Ocean during summer months.

(2) **Tropical depressions** are centres of low pressure surrounded by more than one closed isobars and are very small in size. Wind velocity around low pressure centre ranges between 40-50km per hour. Their direction and velocity are highly variable. Some times, they remain station-ary at a place for several days. They usually develop in the vicinity of inter-tropical conver-gence (ITC) but seldom develop in the trade wind belt. Tropical depressions generally influence the weather conditions of India and north Australia during summers. After being originated in the Bay of Bengal these cyclones move in north-westerly and westerly directions and reach inner parts of India. Some times, they become so strong that they yield heavy downpour resulting into severe floods.

(3) **Tropical storms** are low pressure centres and are surrounded by closed isobars wherein winds move towards the centre with the velocity ranging between 40 to 120 km per hour. They frequently develop in the Bay of Bengal and Arabian Sea during summer season. They also develop in the Caribbean Sea and in the vicinity of Philippines. Many of these cyclones become violent and disastrous atmospheric hazards as they cause heavy rainfall and thus inundate lowlying areas of Bangladesh, delta region of West Bengal and coastal areas of Orissa, Andhra Pradesh and Tamil Nadu. The northern parts of Bay of Bengal mostly the Ganga Delta plains of West Bengal, India and Bangladesh very often suffer from frequent severe cyclonic storms and resultant storm surges (tidal waves) because of a combina-tion of several natural conditions and phenomena such as astronomical tides, funneling coast con-figuration, low and flat terrains of coastal areas and frequent occurrence of severe cyclonic storms. The most disastrous cyclone, which hit the coastal low land of Bangladesh on November 12, 1970, claimed 3,00,000 human lives. Similarly, the deadly cyclone of 1737 claimed the lives of 3,00,000 people in the east coast of India. The disastrous cyclone of 1977 moving with a speed of 175km per hour killed 55,000 people, destroyed

the homes of 2,000,000 people and ruined 1,200,000 hectares of agricultural crops and made most of the coastal land barren and wasteland because of deposition of thick layer of salt on the soils by storm surges in Andhra Pradesh. Super cyclone of Orissa of 1999 (Oct. 29-31) with wind velocity of more than 300 km per hour killed about 100,000 people (official figure, 10,000), washed out 200 villages, damaged standing crops of 1.75 million hectares and claimed loss of property worth 1,000 billion rupees in the coastal districts.

(4) **Hurricanes and Typhoons** : The extensive tropical cyclones surrounded by several closed isobars are called hurricanes in the USA and **typhoons** in China. They are also called **willy willy** in Australia, **cyclones** in Indian Ocean, **'baguio'** in Philippines, **'taifu'** in Japan etc. Hurricanes are, in fact, most violent, most awesome, and most disastrous hazards of all the atmospheric disturbances. They move with average speed of more than 120km per hour. Though hurricanes are most extensive and violent but their climatic importance is limited because of their fewer numbers and their occurrence in limited areas. Though hurricanes and temperate cyclones look similar in appearance but they may be differentiated on the following grounds—(1) Hurricanes are represented by more symmetrical and circular isobars. Pressure increases sharply from the centre towards the outer margin resulting into steep pressure gradient. This is why hurricanes move with great force and high speed. (2) The rainfall occurring from hurricanes is in the form of heavy downpour and is widespread and uniformly distributed whereas precipitation from temperate cyclones is confined to only warm and cold fronts. Warm and cold sectors are devoid of precipitation. (3) There is no temperature variation in hurricanes. They are also not characterized by different types of fronts (warm and cold fronts) and contrasting air masses as is the case with temperate cyclones. (4) There is no change in wind direction in hurricanes. Winds blow from the outer margin towards the centre and then rise upward (5) Hurricanes are not associated with anti-cyclones. (6) Unlike temperate cyclones they move from east to west.

Besides, hurricanes are characterized by the following properties. The diameters range between 160 and 640 km. The size of hurricanes is usually small at their origin points near the equator but the size gradually increases away from the equator. The pressure at the centre ranges between 900 and 950 mb which is perhaps the lowest pressure of all the tropical cyclones. The pressure gradient between the centre and outer margin ranges from 10 mb to 55 mb. The areas of 6 to 48 sq km around the centre of hurricane is generally dry and rainless and winds are feeble. This is called **'eye of the cyclone'**. The waves caused in the oceans due to ferocity of hurricanes are called **hurricane waves** which are generally from 3 to 6m in height. These storm surges inundate the coastal areas with immense volume of oceanic water and thus cause immense loss to human health and wealth. Hurricanes extend upto 12,000 m above the ocean surface. They last for many days and some times for more than a week.

3. Origin of Tropical Cyclones

There is no commonly acceptable viewpoint for the origin of tropical cyclones because the exact mechanism of the formation and development of these cyclones could not be properly understood as yet. According to the advocates of **frontal theory** all types of cyclones originate because of frontogenesis. Inspite of the absence of two contrasting air masses in the equatorial region fronts are formed due to meeting of land and sea winds. Initially, different fronts are formed but later they disappear. This **frontal concept** of the origin of tropical cyclone is no longer acceptable because tropical cyclones in no case are related to fronts. In fact, tropical cyclone is like a heat engine which is energised by the latent heat of condensation. On an average, tropical cyclones are formed due to the development of low pressure of thermal origin. They develop when the following requirements are fulfilled.

(1) There should be continuous supply of abundant warm and moist air. Without doubt tropical cyclones originate over warm oceans having surface temperature of 27°C during summer season. (2) Higher value of coriolis force is

required for the origin of these cyclones. It is apparent that tropical cyclones are practically absent in a belt of 5^0-8^0 wide on both sides of the equator where coriolis force is minimum. It means that cyclonic circulation of air is caused due to deflection in wind direction resulting from coriolis force. Majority of the tropical cyclones originate within a belt of 5^0-20^0 latitudes in the western parts of the oceans. (3) They are associated with inter-tropical convergence (ITC) which extends from 5^0 to 30^0N latitudes during summer season. (4) Pre-existing weak tropical disturbances intensify and ultimately develop into high intensity violent tropical cyclones. (5) There should be anticyclonic circulation at the height of 9000 to 15000 m above the surface disturbance. The upper air anticyclonic circulation sucks the air from the ocean surface above and thus the upward movement of air is accelerated and low pressure centre at the surface is further intensified. (6) Tropical cyclones develop around small atmospheric vortices in the inter-tropical convergence zone (ITC).

The necessary conditions required for the formation of tropical cyclones (all types) may be summarized as follows: (1) continuous supply of warm and moist air, (2) suitable source of sensible and latent heat (of condensation), (3) vertical air motion and convergence of air, (4) powerful trigger mechanism in the form of intruding low pressure system at high altitude, (5) warm water surface of the oceans (having atleast 27^0C temperature) upto the depth of 60-70 meters, (6) presence of preexisting disturbances at lower altitude to be intensified and transformed into fully developed tropical cyclones, (7) higher values of coriolis force, (8) divergent circulation in upper troposphere, (9) existence of small atmospheric vortices in the intertropical convergence zone, (10) weak vertical wind shear etc.

4. Structure of Tropical Cyclones

The horizontal structure of the tropical cyclones comprises 6 more or less circular belts though there are no clear cut dividing boundaries between them as all the six belts are continuous and parts of the cyclones. A brief characteristics of these belts from the center of the cyclone towards its outer margin are given as follows:

(1) **Eye of the cyclone** represents the central and core area of the tropical cyclone which is characterized by minimum wind speed, highest temperature and lowest pressure, highest relative humidity, almost clear sky and hence clear weather etc.

(2) **Eye wall** is a narrow band of high wind speed and surrounds the eye of the cyclone. The eye wall is infact a ring of cumulonimbus clouds around the eye (center) of the cyclone. The belt is characterized by highest wind speed, intense thunderstorms, violent vertical motions, heaviest rainfall through explosive cumulonimbus clouds of thunderstorms etc. The average width of eye wall belt ranges between 10-20 kilometers.

(3) **Spiral bands** surrounding the eye and eye wall of the cyclone are also called **rainbands** or **feederbands** because they are associated with dense cumulonimbus clouds and thunderstorms which yield heavy rainfall. In fact, the zone outside eyewall consists of two spiral bands which are 50 to 80 kilometers apart.

(4) **Annular belt** surrounds spiral bands and are characterized by low relative humidity, weak cloudiness, little rainfall because of sinking of air from above.

(5) **Outer convective belt** surrounding annular belt is characterized by intense convective activity due to instability which is caused by the convergence of out flow of sinking air from above and main inflow of air towards the center of the cyclone, and hence increased cloudiness and rainfall.

(6) **Peripheral belt** representing the outermost limit of the tropical cyclone is characterized by suppressed cloudiness (*i.e.* scanty clouds), weak convective activity, and hence low rainfall.

Vertically the tropical cyclones comprise three zones from the ground surface upward, namely (1) the **inflow layer** represents the lowest zone which extends upto 3 kilometers upward from the ground surface. This zone is characterized by air motion towards the center, evaporation of water from warm ocean surfaces, condensation of atmospheric moisture, development of convective activity, formation of cloud, release of latent heat of condensation which provides energy to the storms etc.; (2) the **middle layer** stretches from 3 kilometers (the upper limit of the lowest inflow layer) to 6-7 kilometers up in the atmosphere and is characterized by main cyclonic circulation which is more or less circular; and (3) the **upper** or **outflow layer** extends from the upper limit of the middle layer (6-7km) to the tropopause and is characterized by divergent air circulation (anticyclonic circulation) and tropospheric westerly winds (anti-trades).

5. Weather Conditions Associated With Tropical Cyclones

The arrival of tropical cyclones at a particular place is heralded by sudden increase in air temperature and wind velocity, marked decrease in air pressure, appearance of cirrus or cirrostratus clouds in the sky, and emergence of high waves in the oceans. The clouds are thickened and become cumulonimbus which yield heavy rains. The clouds are also associated with thunder and lightning. On an average, a single storm yields 100 to 250 mm of rainfall but if obstructed by relief barrier it may give as heavy rains as 750 to 1000 mm. The visibility becomes zero because the sky is overcast with thick and dark thunder clouds. Such destructive conditions persist for a few hours only. The arrival of the centre or the eye of the cyclone is characterized by calm breezes, clear sky, rainless fine and settled weather, and low pressure at the centre. Such weather conditions do not persist for more than half an hour. The weather suddenly changes with the arrival of the rear portion of the cyclone as the sky again becomes overcast, wind direction changes, and pressure sharply goes up. There is heavy downpour with cloud thunder and lightning and storm becomes very severe and furious. This situation persists for several hours. Slowly and slowly the ferocity of cyclone starts declining and the weather becomes calm after the cyclone has passed off. The sea surface also becomes calm and clear weather sets in.

6. Distribution of Tropical Cyclones

Tropical cyclones mostly develop over the ocean surface between 5^0-20^0latitudes in both the hemispheres and influence the weather of coastal areas of the continents. There are 6 major regions of tropical cyclones *e.g.* (1) West Indies, Gulf of Mexico, and Caribbean Sea, (2) Western North Pacific Ocean including Philippines Islands, China Sea, and Japanese Islands, (3) Arabian Sea and Bay of Bengal, (4) South Indian Ocean coastal regions off Madagascar (Malagasi), and (5) Western South Pacific Ocean, in the region of Samoa and Fiji Island and (6) the east and north coasts of Australia.

North Atlantic Ocean : It may be pointed out that the occurrences of tropical cyclones are rhythmic in nature because they are restricted to a certain season of a year which varies from one region to the other region. On an average, about 7 cyclones develop every year in the southern and south-western parts of the Atlantic Ocean, most of which become hurricanes. They develop (i) in August and September around Cape Verde Island, (ii) between June and October to the north and east of West Indies and to the south of the Atlantic coast of the USA, (iii) from May to November in the north Caribbean Sea, (iv) from June to October in the south Caribbean sea, and (v) from June to October in the Gulf of Mexico.

North Pacific Ocean : The cyclones after originating off the western coast of Mexico move north-westward and affect the weather of California. Some times, they also reach Hawaii Island. About 5 to 6 tropical cyclones develop each year between June and November and two of them gain hurricane intensity.

South-West North Pacific Ocean : Normally tropical cyclones develop in China Sea, off the coasts of Philippines Islands and South Japan between May and December. They have disastrous effects of the eastern coasts of China where they gain the ferocity of typhoons. About 12 typhoons develop every year.

South Pacific Ocean : Tropical cyclones develop to the east of Society Island (east of 180^0 longitude) during December-April and influence the weather of north-east coast of Australia.

North Indian Ocean : After originating in the Arabian Sea and Bay of Bengal tropical cyclones (also called as depressions) influence the weather conditions of India and Bangladesh on a large-scale between April and December.

South Indian Ocean : Cyclones originate off the coasts of Re Union, Madagascar, and Maritius islands between November and April.

7. Tracks of Tropical Cyclones

The tropical cyclones after their formation over warm water surfaces of the tropical oceans move westward in general between a zone of 5^0-20^0 latitudes in both the hemispheres under the influence of easterly trade winds but after reaching the western margins of the oceans and striking the continental coastal lands they curve north-westward and poleward. The equatorial warm ocean currents also help in the westward movement of tropical cyclones. After reaching 20^0-30^0 latitudes the tropical cyclones, if not exhausted and finished, move eastward under the influence of westerly winds. It may be mentioned that when the tropical storms strike the coast land, they start losing energy and dissipation as the source of required energy of latent heat of condensation, which is over the warm water surface of the tropical oceans, is cut off. Some times the tropical cyclones become stationary at a particular place for most part of their life cycle.

It may be remembered that the tracks followed by tropical cyclones vary considerably in different parts. Normally, they move from east to west under the influence of easterly trade winds and equatorial warm ocean currents. The general direction is westerly upto 15^0 latitude from the equator, poleward between 15^0-30^0 latitudes, and thereafter easterly (fig. 12.1)

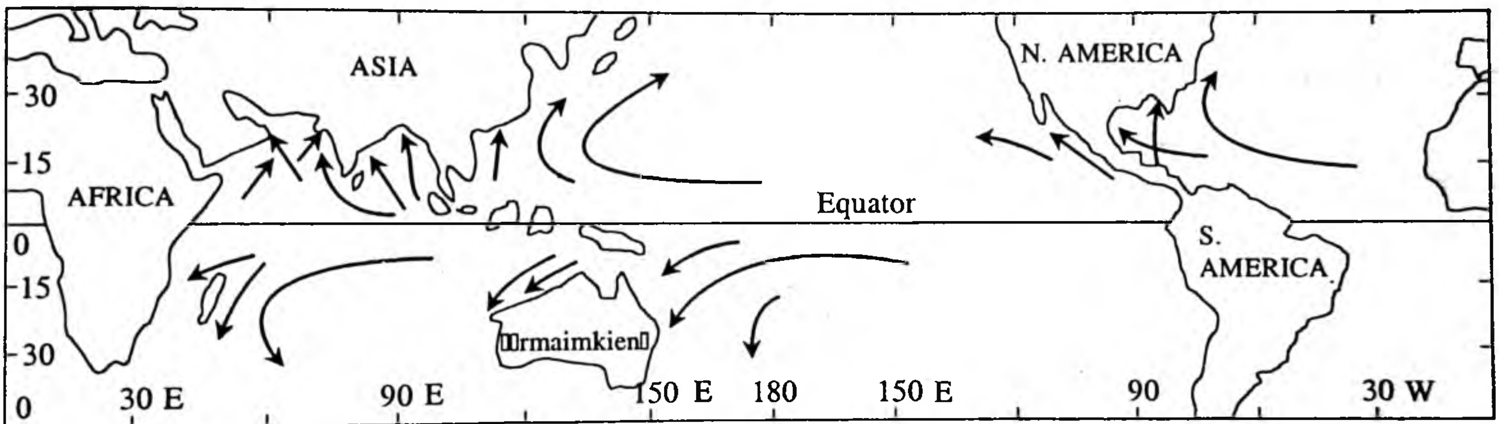


Fig. 12.1

Fig. 12.1 : Tracks of Tropical Cyclones.

8. Effects of Tropical Cyclones

Tropical cyclones are very severe disastrous natural hazards which inflict heavy loss to human lives and property in terms of destruction of buildings, transport systems, water and power supply system, disruption of communication system, destruction of standing agricultural crops, domestic and wild animals, natural vegetation, private and public institutions, etc. through damages caused by high velocity winds, floods and storm surges. Tables 12.1 to 12.3 depict the death toll of human life by tropical cyclones in different parts of the world.

It is now desirable to discuss the damages done by **hurricanes** in the USA, by **cyclones** in India and Bangladesh, by **typhoons** in China and Japan, and by **willy willy,** separately but before that a general global picture of tropical cyclonic destruction is presented as follows :

Destructions by tropical cyclones include loss of human lives and property in terms of destruction of buildings, transport systems, water and power supply systems, disruption of communication system, destruction of agricultural crops, domestic and wild animals, natural vegetation, private and public institutions and so on. The deadliest impacts of tropical cyclones and tornadoes are on human beings. There are 6 major regions in the world which are responsible for the origin of tropical cyclones *e.g.* , (i) West Indies, Gulf of Mexico, and Caribbean Sea; (ii) Western North Pacific Ocean including Philippines islands, China Sea and Japanese islands; (iii) Arabian Sea and Bay of Bengal; (iv) Eastern Pacific coastal region off Mexico and Central America; (v) South Indian Ocean, off Madagascar (Malagasi); and (vi) Western South Pacific Ocean, in the region of Samoa and Fiji Island and the east- north coast of Australia. It may be pointed out that the occurrences of tropical cyclones are rhythmic in nature because they are restricted to certain seasons of a year. The seasons of the occurrences of tropical cyclones vary from one region to the other region. For example, hurricanes mostly affect the U.S.A. between May and November wherein the maximum frequency is recorded in the end of summer and the beginning of autumn seasons.

The following tables (12.1, 12.2 and 12.3) portray the death toll of human lives caused by tropical storms and local storms in different parts of the world :

Cyclone Nargis (2008)

The recent cyclone **Nargis** of May 2, 2008 ravaged Irrawadi Delta area including the cities of Yangon, Bogalay, Labutla, Pyapton etc. in Myanmar. The following are the salient features of this disastrous cyclone :

- total people killed = more than 1,00,000
- total missing people = > 43,000
- wind speed = 241 km/hour
- total rainfall = 510 mm
- massive destruction of mangroves and human settlements and property

This intensity and severity of cyclone **Nargis** has been assigned to global warming by the scientists.

Table 12.1 : Some noteworthy Indian tropical cyclonic disasters

Year	Human death	year	Human death
1737	300,000	1789	20,000
1833	50,000	1839	20,000
1864	50,000	1977	55,000
1990	598	1998	>1000
1999	>10,000		

Note : The intensity of 1990 Andhra cyclone was 25 times greater than the 1977 Andhra cyclone but human casuality could be contained because of correct prediction and better warning systems but the property damage could not be stopped. On the other hand, inspite of timely warning of 1999 super cyclone of Orissa death toll of human beings could not be avoided because of inefficient government machinery.

Table 12.2 : Notable tropical cyclonic disasters in Bangladesh

Year	Human deaths	Year	Human deaths
1822	40,000	1876	100,000
1879	175,000	1960	5,149
1963	11,488	1970	300,000
1976	100,000	1985	11,000

Table 12. 3 : Typhoon disasters in the Far East

year	Country	Human deaths
1881	China	300,000
1923	Japan	2,50,000
1950	Japan	5,000

Hurricanes in the United States of America

The hurricanes are chronic disasters in the Gulf coastal and Atlantic coastal areas of the United States of America. Before attempting description of hurricanes onslaught in the USA it is desirable to discuss the hurricane damage scale as devised by Saffir-Simpson popularly known as **Saffir-Simpson Hurrican Damage Scale** (table 12.4) wherein 5 point scale has been developed on the basis of size, intensity in terms of duration of occurrence in minutes, wind velocity in km/hour, height of storm surge and quantam of damage. The scale starts from a value of 1 for the weakest hurricanes of the shortest duration to the value of 5 for the strongest and most severe and hazardous hurricanes.

Hurricanes very often strike the southern and the south-eastern coasts of the USA. Gulf coasts of Louisiana, Texas, Alabama and Florida are worst affected areas. The Galveston, Texas (U.S.A.) disaster of September 8, 1900 tells the story of devastation caused by hurricanes in the Gulf coastal region of the U.S.A. The terrible hurricane generated a strong storm surge (tidal wave) which raced inland and killed 6000 people mostly through drowning caused by inundation under 10 to 15 feet (3 to 4.5 m) deep water and destroyed 3000 houses. Flying planks and timbers under the force of strong gale winds also caused several deaths and damage to human structures.

It may be pointed out that Mississippi Delta Plains of the state of Louisiana (U.S.A.) have the equivalence of the Ganga Delta Plains of India and Bangladesh as regards the frequency and intensity of tropical cyclones but the damages mainly in the form of human casualities are far less in the former than in the latter because of more advanced and better warning systems. The **Audrey Hurricane** of June, 1957 struck the Louisiana coast between New Orleans and Galveston. Though the storm was very severe as it smashed houses and floated them away, uprooted sealed concrete tombs and floated them 32 kilometres away from their resting places, but only 550 human deaths could be caused because of better warning systems and spontaneous response of people to the warning and predictions. In fact, the water level used to rise at the rate of 1.5 feet per hour. Thus most of the people had ample time to evacuate them to safer places before the water level forced by strong storm surge could reach its peak of 8 to 12 feet (2.4 to 3.6 m) above high tide water.

Table 12.4 : Saffir - Simpson hurricane damage scale

Scale number	Central pressure (mm)	Wind speed (km/hour)	Storm surge(meters)	Description
1	980	118-152	1.5	minimum damage, mainly to vegetation and mobile houses.
2	965-979	153-176	2.0-2.5	moderate damage, mainly uprooting and blowing of trees, roofs of buildings are damaged.
3	945-964	177-208	2.5-4.0	extensive damage to trees, mobile houses, roofs of buildings, structural damage to small buildings.
4	920-944	209-248	4.0-5.5	extreme
5	<920	>248	>5.5	catastrophic, windows, glass panes, roofs of houses and industrial buildings etc. are severely damaged.

Source : Summarized from J.E. Oliver and J.J. Hidore, 2003. It is apparent from table 12.4 that hurricanes are divided into 5 types based on the quantum of damage done by them, namely (1) hurricanes of minimum damage, (2) hurricanes of moderate damage, (3) hurricanes of extensive damage, (4) extreme hurricanes, and (5) catastrophic hurricanes.

Table 12.5 : Category-wise number of hurricanes is the USA from 1990 to 1996.

	Saffir-Simpson damage scale (vide table 12.4)					
	1	2	3	4	5	Total
			Scale Number			
USA	58	36	47	15	2	158
Florida	17	16	17	6	1	57
Texas	12	9	9	6	0	36
Louisiana	8	5	8	3	1	25
North Carolina	10	4	10	1	0	25

Source : J.E. Oliver and J.J. Hidore, 2003.

Table 12.6 : Deadliest US Hurricanes

Location (name)	year	Category Saffir-Simpson scale	Human deaths
TX (Galveston	1900	4	8000 (may be 10,000 to 12,000)
FL (Lake Okeechobee)	1928	4	1836
FL (Keys) S. TX	1919	4	600
NE	1938	3	600
FL (Keys)	1935	5	408

FL = Florida, TX = Texas, NE = New England

Source : J.E. Oliver and J.J. Hidore, 2003.

Table 12.7 : Most Expensive US Hurricanes (property damage in US billions of dollars)

Name of the hurricane	Year of occurrence	Damage cost
1. Andrew	1992	30.5
2. Hugo	1989	8.5
3. Agnes	1972	7.5
4. Betsy	1965	7.4
5. Camille	1969	6.1
6. Floyd	1999	6.0

Source : J.E. Oliver and J.J. Hidore, 2003.

Severe hurricances cause havoc in the U.S.A. as regards the damage of property. 'In a ten-year period from 1961 to 1971 property damage from United States Hurricanes averaged some $ 440 million annually. Single hurricane in this period caused damage valued at $ 1.5 billion.' According to R.F. Abey (1976) tornadoes cause the property loss of about 100 million US dollars and 150 human causalities per annum. 'Since 1950 every year in the U.S.A. there has been an average of 662 tornadoes, resulting in 114 deaths.' Efforts are being made to forecast the origin and travel paths of hurricanes and tornadoes in the U.S.A. on the basis of the study of synoptic situation combining seven elements viz. (i) convergence near the surface, (ii) mass divergence aloft, (iii) a buoyant airmass, (iv) wind shear in the vertical, (v) moist air mass in the lower layers, (vi) a trigger mechanism, and (vii) surface cyclogenesis. Attempts are also being made to develop effective devices of cloud seeding to decrease the intensity of hurricances and tornadoes. Further more, scientists are trying to develop scientific methods to divert the paths of hurricanes and tornadoes to such areas which are not so important from the stand point of human population and economic loss.

Cyclones in India and Bangladesh

Cyclonic hazards very often visit the eastern coastal areas of India and the southern coastal areas of Bangladesh. The disaster of the deadliest storm in the recorded history occurred on November 12, 1970 in the coastal lowland of Bangladesh. This Bay of Bengal disastrous cyclone tells the magnitude of environmental hazards in respect of its killer impact on the affected people as it caused as many as 300,000 deaths (some sources put the figure between 300,000 and 1,000,000 deaths in Bangladesh and West Bengal of India) wherein most of the deaths were caused by drowning in the storm surge of oceanic water (20 feet) on the land. The official record of Bangladesh presented the total loss as death of people-200,000, missing persons-50,000 to 100,000, cattle death-3,00,000, houses destroyed 40,000, crops losses of 63,000,000 US dollars, fishing boats destroyed-9,000 (off-shore) and 90,000 (inland water).

The tropical cyclones coming from over the Bay of Bengal also become hazardous to the east coastal lands of India (West Bengal, Orissa, Andhra Pradesh and Tamil Nadu). The deadliest hazardous cyclone struck the east coast in 1737 and claimed the lives of 300,000 people. Other disastrous cyclones occurred in 1977 (55,000 death), 1864 (50,000 deaths), 1839 (20,000 deaths), 1789 (20,000 deaths) etc.. The November, 1977 cyclonic storm struck Andhra coast and generated three successive '**storm surges**' of which the biggest surge of 6m height was recorded in the last. This deadly storm moved with a speed of 175 kilometres per hour. The biggest surge raced into the coastal low lying areas up to 20 kilometres inland and thus killed 55,000 inhabitants through drowing caused by sudden inundation, destroyed the homes of 2,000,000 people, ruined 1,200,000 hectares of agricultural crops and made most of the coastal land barren and wasteland because of deposition of thick layer of salt on the soils by storm surges. The saline land could be reclaimed only after three years.

The strongest and most notorious cyclone hit the Andhra coast on May, 9, 1990. It was 25 times stronger and more disastrous than the deadliest cyclone of November 1977 (which also struck the Andhra coast as referred to above) but could claim the lives of only 598 people (official figure but the actual figure might have crossed 1000 deaths). Besides killing 598 people, it adversely affected 3,000,000 people, rendered 300,000 people homeless, perished 90,000 cattle and caused loss of 1000 crore rupees worth of property. Very low figure of human casualities (598 deaths) in comparison to the killer cyclone of 1977 (55,000 deaths) inspite of 25 times more intensity of May, 1990 cyclone that the latter was particularly because of the advance monitoring and prediction of the cyclone from the time of its formation in the Bay of Bengal off the southern coast of Tamil Nadu on May 5, 1990.

This cyclone is termed most notorious in the sense it shifted its course almost by 90 degree. But more than 100 direct warning systems and even dying INSAT-1B provided direct audio-broadcasts from meteorological stations in Chennai and Hyderabad and 6 cyclone detection radars fitted all along the coastline provided minute by minute information about the movement of incoming cyclone. Initially, the cyclone was moving westward and was expected to strike the southern coast of Tamil Nadu near Nagapattinam but after May 6 it suddenly shifted its course northwards and eventually hit the coastal districts of Andhra Pradesh and unleashed the devastating force of its fury on five districts viz. Krishna, Guntur, East Godawari, West Godawari and Visakhapatnam. It may be pointed out that the cyclone was so strong and enormous that some of the major towns of Krishna and Guntur districts such as Vijayawada, Machlipatnam, Pamarru, Guntur, Bapatia, Repalle and Tenali, which could not be affected by the deadliest 1977 cyclone and tidal wave, were also hit this time by the powerful storm surges (tidal waves) caused by gale winds with a speed of 220 to 250 kilometres per hour.

Gujarat coast was struck by a very powerful cyclonic storm with a velocity of more than 200 km per hour on tuesday, June 9, 1998 and caused a surging tidal wave of 8 m height which transgressed into the coastal land and caused immense loss of property and human death unknown in the cyclonic history of Gujarat. The salt workers working in the salt pans in the Runn and the Little Runn areas of Kutch were washed away by high tidal waves. The storm was so powerful accompanied by heavy rainfall that human settlements were destroyed all the way from Surat and Amereli in Gujarat to Jalore and Jodhpur in Rajasthan. Mud-built houses were flattened, power supply was snapped, trees were uprooted and carried away as missiles, and communication and vehicular traffic were completely disrupted. The storm caused more than 1000 human deaths and economic loss worth more than 100 billion rupees (unofficial estimates put the number of death between 5,000 and 10,000). Kandla port was greatly damaged.

SUPER CYCLONE OF ORISSA, 1999

The 29th October, 1999 proved a black and killer day for the inhabitants of the coastal region of Orissa (India) when the strongest cyclone in the cyclone history of India struck the Orissa coast and caused a havoc of mass destruction through its notorious acts from October 29 to 31, 1999. Nearly one third of Orissa plunged into gloom and dispair. Prior to the final assault by this killer cyclone, a strong cyclone already knocked at the door of Orissa on October 18, 1999 with a velocity of 200 km per hour. This cyclone claimed the lives of 200 people, damaged 460 villages and adversely affected 500,000 people in Ganjam district. The people of Orissa were yet to recover from the trauma of this cyclone, the killer super cyclone hit the Orissa coast on October 29. The successive phases of the formation and advancement of super cyclone may be outlined as follows : (1) **October 25 : A depression** was formed 500 km east of Portblair in Andman Sea, which started to move in N-W direction from the midnight and soon turned into a **deep depression.**(2) **October 26** : The deep depression changed into a **cyclonic storm** by the morning of October 26 which was stationed about 350 km away from Portblair. The Indian Meteorological Department started to issue warning of advancing cyclonic storm. (3) **October 27** : By the morning of October 27, this cyclonic storm changed to **severe cyclonic storm** and was positioned 750 km away from Paradeep port. It remained stationary for 6 hours at the distance of 600 km from Paradeep. **(4) October 28** : Advancing towards north-west this severe cyclonic storm became a fully developed **supper cyclonic storm** and moved towards Paradeep with a velocity of 260 km per hour. (5) **October, 29** : Indian Meteorological Department (IMD) issued an alarm of warning about the arrival of the super cyclone between Paradeep and Puri. Though the Govt. of Orissa was posted with this warningby 5.30 AM but this warning could not be conveyed to the general public due to lack of radio and television network.

Ultimately, the super cyclone entered Orissa on October 29, 1999 and began to play its game of destruction in 10 coastal districts. Moving with a velocity of 300 km per hour the cyclone became stationary for 8 hours over this vast area. This disastrous cyclone generated 9 m high tidal surges which transgressed upto 15-20 km inside coastal region. Kendrapara, Jagatsinghpur, Balosore, Paradeep, Bhadrak and Khurda were worst affected. According to official sources more than ten thousand people were killed and 200 villages were completely washed out but the unofficial sources put human death toll at about hundred thousand. More than 6000 people were killed in Jagatsinghpur alone. Several hundred thousand cattle perished and countless people were rendered homeless. The standing kharif crops over 1.75 million hectares were destroyed. The loss of property mounted to about 10,000 crore rupees (1000 billion rupees). The severe super cyclonic storm resulted into the disruption of the supply of water and electricity. The communication system was thrown out of gear. Destruction and obstruction of roads and rails brought a grinding halt to rail and road transport which continued for weeks.

12.5 THUNDERSTORMS

1. Meaning and Concept

Thunderstorms, considered as tertiary atmospheric circulation, are local storms characterized by swift upward movement (updraft) of air and heavy precipitation including both rainfall, hailstorm and squal with cloud thunder and lightning. According to A.N. Strahler 'a thunderstorm is an intense local storm associated with large, dense cumulonimbus clouds in which there are very strong updraft of air.' 'Fundamentally the thunderstorm is a thermodynamic machine in which the potential energy of latent heat of condensation and fusion in moist conditionally or convectively unstable air is rapidly converted into kinetic energy of violent vertical air currents with associated torrential rain, hail, gusty surface squall winds, lightning, and thunder......A thunderstorm is therefore an intense instability outbreak' (G.T. Trewartha, 1954). Because of heavy downpour associated with thunderstorms they are also called **cloud bursts** but the rainfall is of very short duration. Thunderstorms differ from cyclones in that the latter are almost circular in shape wherein winds blow from out side towards the center while the former is characterized by strong updraft of air. They are considered to be special case of convective mechanisms.

2. Characteristics of Thunderstorms

The thunderstorms occurring in both tropical and temperate regions are characterized by the following salient features :

1. Thunderstorms are powerful local storms having swift updraft (upward movement) of air form the central point.
2. They are powerful thermodynamic machines wherein potential energy is transformed into kinetic energy through the input of latent heat of condensation and fusion. The resultant kinetic energy provides momentum to the storm.
3. Thunderstorm is a cellular type of vertical movement of moist air which comprises several convective cells.
4. Sometimes, a few thunderstorms coalesce and become powerful enormous storms, they are called **mesoscale convective complex.**
5. The thunderstorm having a single convective cell is not much powerful and hence is less violent but the storms having several convective cells become not only enormous convective machines but also become most disastrous.
6. The tropical thunderstorms are associated with heavy downpour, cloud thunder and lightning but in the middle latitudes they are also associated with hails, and squalls besides heavy precipitation, cloud thunder and lightning but in the regions of dry climate there may be no precipitation.
7. The occurrence of thunderstorms in the humid tropics is almost a daily phenomenon but the frequency of their occurrence is more over land surfaces than over the ocean surfaces because of less intense convective mechanism over the oceans than over the continents.
8. Thunderstorms are short-duration local weather phenomena as the life cycle of these storms is completed within an hour or two but sometimes these storms last for a few hours.
9. On an average, about 16 million thunderstorms occur each year in tropical, subtropical, and middle-latitude regions and daily average of occurrences of these storms have been reported to be 2000.
10. The strong thunderstorms associated with heavy precipitation through dense cumulonimbus clouds are characterized by strong downward movement of air (downdraft) which is called **downburst.**

3. Structure of Thunderstorms

The fully developed and strong thunderstorms comprise a few convective cells which may vary from 5 to 8 in number. These convective cells are characterized by strong updraft (also updraught) of air. Each cell covers a distance of a few kilometers and may last from one hour to 8-10 hours. The updraft of moist and unstable air is in the form of a chimney. The swift updraft of moist warm unstable air (chimney) allows the downdraft of relatively cool air as compensatory air movement. Each convective cell passes through three consecutive stages of its development and dissipation *e.g.* (1) **cumulus state, (2) mature stage,** and (3) **dissipating stage.** The stages of life cycle of thunderstorm are described in the following subsection.

4. Conditions for Thunderstorm Development

Atmospheric instability, updraft of potentially unstable air, abundant supply of warm and moist air, thick clouds etc. are the factors which favour the development of thunderstorms. The upward movement of warm and moist air is prerequisite condition for the origin of thunderstorms. Surface heating through intense insolation causes convective mechanism resulting into updraft of air and atmospheric instability. This is why thunderstorms originate mainly during summer season, warm day of a season, and warm hours of a day. It appears that warm, moist and rising unstable air is the most important factor in the development of thunderstorms. This becomes possible when **normal lapse rate** of temperature is greater than **adiabatic rate** of temperature change. Besides convective mechanism, warm and moist winds also rise and become unstable due to orographic obstacles. The greater the instability of warm and moist air, the greater the intensity and duration of thunderstorms.

There must be greater thickness of clouds between **cloud base** (*e.g.* level at which condensation and cloud formation begin) and **icing level** (*i.e.* the level at which water droplets change into ice particles). The higher the icing level above cloud base, the greater the thickness of clouds and thus the greater the intensity of convection. Since the icing level is at very low height in the middle latitudes, thunderstorms do not frequently develop there. On the other hand, thunderstorms are common features in the weather of low latitudes because of the higher height of icing and greater thickness of cloud cover.

The necessary favourable conditions for the origin and development of thunderstorms may be summarized as follows :

1. The atmospheric conditions should be in conditional or convective unstable state.
2. The normal lapse rate should be greater than adiabatic rate of temperature change.
3. There should be warm, moist and rising unstable air.
4. There should be enough supply of moisture from the ground surface to the air.
5. There should be greater thickness of cumulonimbus clouds between the condensation level (cloud base) and icing level.
6. Enough supply of latent heat of condensation and fusion which may transform potential energy into kinetic energy which provides strength to the storms.
7. There should be efficient trigger effects for causing and augmenting convective mechanisms. These may be effected through (i) insolational heating of ground surface and resultant rising convective air currents; (ii) forced ascent of moist air by mountain barriers; (iii) forced ascent of warm and moist air along cyclonic fronts (applicable in middle latitudes only) etc.

5. Stages of Thunderstorm Development

Like temperate cyclones, the origin and development of thunderstorms also passes through a life-cycle but unlike six-stage life-cycle of temperate cyclones thunderstorms pass through only three-stage life-cycle as follows (fig. 12.2) :

(1) **Cumulus stage,** the first stage of the life cycle of a thunderstorm, is also called **youth stage,** when ground surface is intensely heated, the moist air coming in contact with heated ground surface is also heated, expands and rises upward as strong convective current losing temperature at the dry adiabatic lapse rate of 10^0C per 1000 meters, reaches its condensation level and thus helps in the formation of clouds having precipitation particles. The updraft of moist air becomes stronger with greater wind speed exceeding 150-160 km per hour due to trigger effects as described in the previous subsection (4). Consequently the cumulus clouds become thick cumulonimbus clouds.

(2) **Mature stage** is the second stage of thunderstorm development characterized by both upward (updraft) and downward (downdraft) movement of air and occurrence of torrential rainfall from thick cumulonimbus clouds, maximum cloud thundering and lightning etc.

(3) **Dissipating stage** is the senile stage of thunderstorms. This final stage is characterized by downward movement of winds which laterally spread over the ground surface and stop vertical movement (updraft) of winds. Clouds spread in the sky in umbrella shape and become altostratus and cirrostratus resulting into dissipation of thunderstorm as these clouds are rainless. The downdraft of winds and end of updraft of winds causes the

stability of the atmosphere and the energy is ultimately finished (fig. 12.2).

6. Classification of Thunderstorms

Thunderstorms are generally classified on the basis of their mode of origin and lifting factors and mechanisms.

(1) **Air mass thunderstorms**
- (i) Heat (thermal) thunderstorms
- (ii) Orographic thunderstorms
- (iii) Advectional thunderstorms

(2) **Frontal thunderstorms**
- (i) Warm front thunderstorms
- (ii) Cold front thunderstorms

(1) **Thermal** or **local thunderstorms** originate due to intense heating of ground surface through insolation and resultant rising thermal convection currents. They are called local because they influence very limited area. **In fact, heat** thunderstorms are real thunderstorms which originate in the afternoon during summer season and die out by the evening. Heat thunderstorms are more common in the belt of **doldrum** because large amount of air moisture, high temperature and convergence of winds provide ideal conditions for their origin and development. Heat thunderstorms become stronger and more vigorous if the surface through which they travel is warmer, otherwise they are soon weakened if the surface is less warm. This is why they die out when they pass through water bodies (lakes, rivers, reservoirs etc.) because of no supply of heat from below. Heat thunderstorms also originate in the inner parts of the continents during summer season in middle latitudes. Heat thunderstorms are difficult to be predicted because of their highly uncertain and variable behaviour.

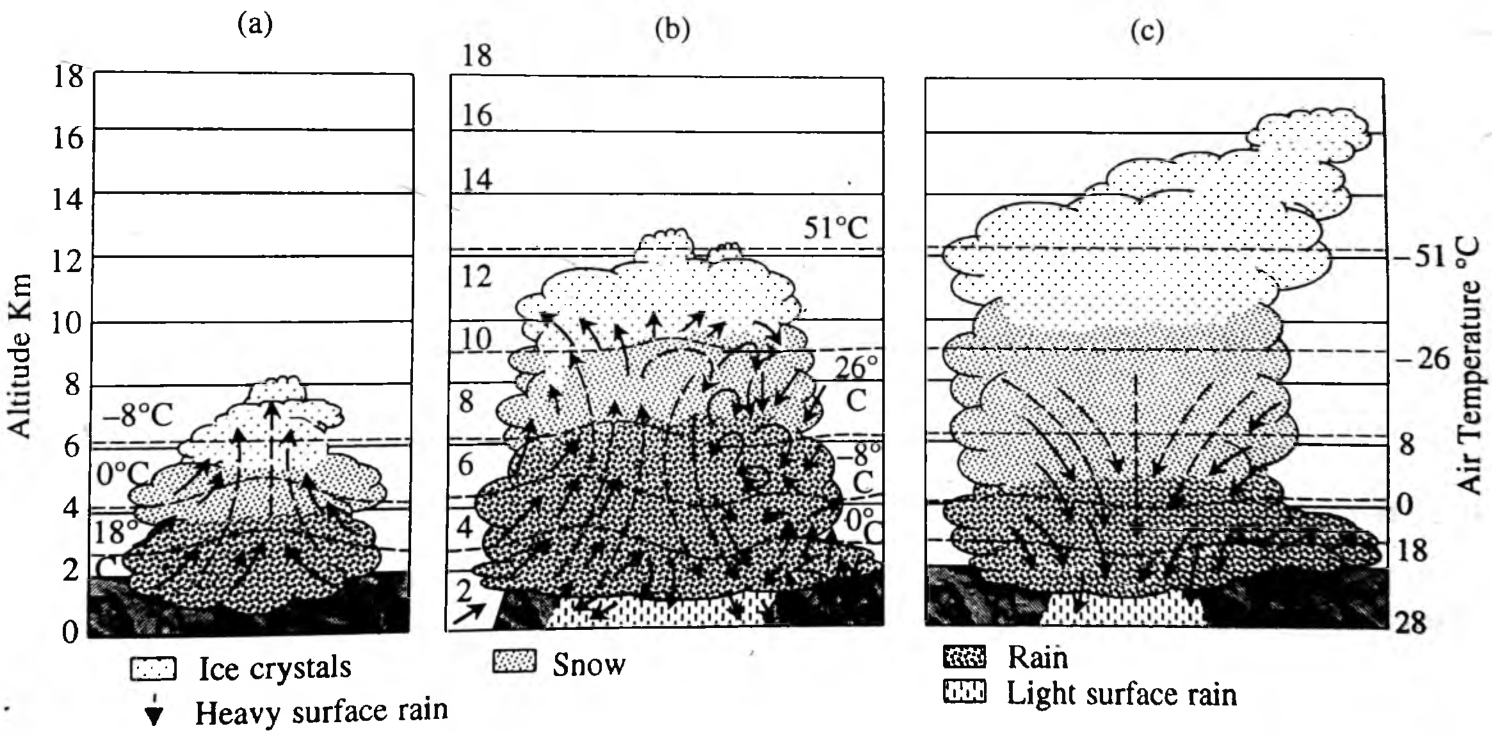


Fig. 12.2 : Development stages of a thunderstorm : (A) initial or cumulus stage marked by only updraughts, (B) mature stage marked by both updraughts and downdraughts, (C) dissipating stage marked by only downdraughts. Arrows indicate wind direction. Source : based on Byers and Braham; and Barry and Chorley, 2002.

(2) **Orographic thunderstorms** : when warm, moist and unstable air strikes a mountain barrier, it is forced to rise hurriedly along the hillslope. The latent heat of condensation (release of heat after condensation) accelerates the rate of upward movement of the air. This results in the formation

of most active and strong thunderstorm which yields copious heavy rains. This is called **cloud burst rain**. The southwest Indian monsoon winds after striking the hillslopes produce strong thunderstorms which yield more than 10,000 mm of annual rainfall at Cherrapunji. Orographic thunderstorms are more extensive, widespread, and active than heat thunderstorms and thus their forecast is easy.

(3) **Advectional thunderstorms** are produced due to substantial increase in normal lapse rate of temperature and consequent upward movement of unstable air when a cold air underlies a warm air. Such thunderstorms develop during dark nights when the sky is overcast because the upper layers of the clouds are cooled due to loss of heat through radiation, with the result cool and dense air settles downward and pushes underlying warm and light air upward resulting into convective mechanism in the air.

(4) **Warm frontal thunderstorms** are produced when sea breezes are more humid and unstable. They are not significant because they are very weak storms. Cumulus clouds do not form because the air ascends slowly.

(5) **Cold front thunderstorms** develop along the cold front of temperate cyclones when cold and dense air pushes warm and moist air upward with great force. Since they are associated with temperate cyclones, they are easily predicted. Cold front thunderstorms may develop at any time of a day or in any season of a year because their origin is not related to the heating of the ground surface.

6. Thunderstorms and Weather

(i) **Rainfall** in thunderstorms, unlike tropical cyclones, is in the form of heavy downpour with greatest intensity of all other forms of precipitation but is of short duration because of two factors viz. (i) the air rises abruptly with great force due to which there is quick condensation and cloud formation, and (ii) there is abundant absolute humidity due to high rate of evaporation consequent upon very high temperature during summer season. The rainfall of thunderstorm is closely related to its numerous cells. There is maximum rainfall in the centre and minimum at the periphery of each convective cell. Fully developed cell yields rainfall for about an hour whereas weak cell dies out within few minutes.

(ii) **Hailstorms** : when condensation occurs below freezing point, ice particles are formed which range from the size of a pea to a large ball. Hail is not associated with every thunderstorm. Not only this, hail is confined to only certain cells of a thunderstorm. Hails fall down on the ground surface when the rising convection currents become weak and feeble. Hails are of three types, namely (i) **soft hail** also known as **graupel**, is less than 5 mm in diameter and is crushed and broken when hits the ground; (ii) **small hail** is mixed with rain and remains intact when it hits the ground surface; and (iii) **destructive hail** also called as severe hail, is very large in size and weighs from few grams to several kilograms in weight. Such destructive hails cause maximum destruction. The sudden fall of hails inflicts great damage to human health and wealth, birds and animals and standing agricultural crops.

(iii) **Lightning** : electrical discharge centres are developed in a mature thunderstorm. The centres of positive and negative electrical charges develop in the upper and lower portions of the clouds respectively with discharge values ranging between 20 to 30 coulombs. Lightning is produced when the electrical potential gradient between the electrical positive and negative charges becomes very steep. According to another view lightning is produced due to splitting of large water drops. Each water drop has positive and negative electrical charges which remain in neutral state when they are evenly balanced. This balance is disturbed due to splitting of these drops resulting into difference in positive and negative charges.

(iv) **Thundering** sound is produced due to sudden and rapid expansion of air columns caused by intense heat (10,000°C) resulting from lightning strokes. This deafening noise produced by vibrating pressure wave due to rapid expansion of air column as mentioned above is called cloud thunder.

(v) **Squall** : the downward movement and divergence of cold air at the ground surface is called squall. The velocity of squalls is equal to and some times greater than hurricane velocity and hence they inflict great damage to human structures and vegetation. Squall is produced after the thunderstorm becomes mature and heavy precipitation occurs.

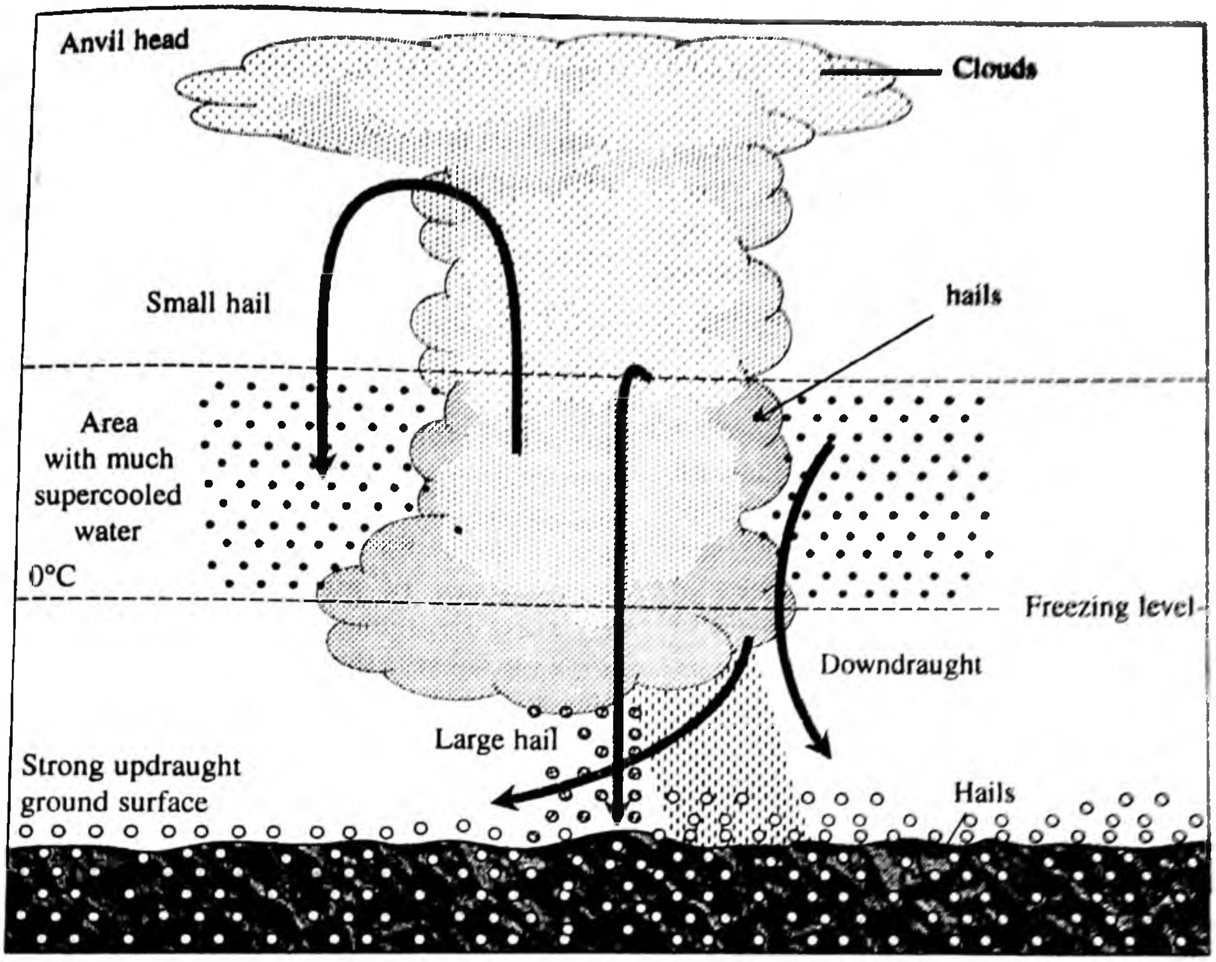


Fig. 12.3 : Formation of hails in cumulonimbus clouds. Source : after Oliver and Hidore, 2003.

12.6 TORNADOES

1. Meaning and Characteristics

Tornadoes are funnel shaped storms wherein the upper portion is like umbrella in shape while the lower portion is like pipe which touches the ground surface. Tornadoes are smallest but violent, awesome, disastrous of all the atmospheric storms and are notorious for destruction of human property and causes human deaths if not forecast well in time to facilitate evacuation. In fact, tornadoes are violently rotating columns of air having upper portion of funnel shape of cumulonimbus clouds which are attached to the ground by very narrow column of air. The tornadoes are characterized by the following salient features.

1. Tornadoes are very violent rotating systems of air wherein the air from the ground surface having lowest pressure is sucked by the upper air and is suddenly uplifted causing convective instability.
2. The pressure in the center of tornado, though not precisely measured as the instruments meant for measuring wind speed and air pressure are destroyed by gusty wind, is extremely low. The recorded lowest pressure (in 1904) of a tornado in the state of Minnesota of the USA was 813 mb.

   On an average, the center of a tornado is characterized by extremely low pressure, say 100 mb less than the outside environments.
3. The diameter of the upper funnel increases from 90m in the lower portion say at the base at the ground to 460 m in the upper portion, say at the top.

4. Because of steep pressure gradient winds rush up with great force towards the center having furious velocity ranging between 400 km to 800 km per hour depending upon the magnitude of pressure gradient. Thus, the swiftly inward rushing air is caught into a vortex of the storm and is rapidly lifted upward and cools adiabatically and forms thunderstorms. This is why tornadoes are always associated with violent thunder-storms.
5. The movement of tornadoes is not in well defined route and direction. Some times they become stationary at a place. Generally, they move with average speed of 40-60km per hour, though the speed of movement becomes zero for stationary tornadoes while it in exceptional cases may exceed 100 km per hour.
6. Tornadoes follow very narrow paths, the width of which ranges between a few meters to more than 2000 meters, while the average length of path followed by a tornado is about 40-50 km. The recorded long distance covered by a tornado in the states of Illinois and Indiana (USA) in May 1977 was 570 km.
7. The average duration of existence of a tornado ranges between 15-20 minutes but occasionally they may be in existence for a few hours.
8. Tornadoes look very dark in colour because of the dominance of dusts, sands, debris and condensed moisture.
9. The arrival of tornado is heralded by dark and thick clouds in the sky resulting into complete darkness, minimum visibility and low pressure.
10. Tornadoes move as a single unit or in a group consisting of an average 7-8 in number. The cluster or group of tornadoes is called **tornado family** while occurrence of several tornadoes in succession as a group or cluster is called **tornado outbreak**.

2. Formation of Tornadoes

It may be mentioned at the very outset that exact mode of formation and development of tornadoes is not properly understood by the storm experts and meteorologists because the measurement of wind speed, temperature, humidity, and pressure at the time of their occurrence becomes practically difficult as the instruments are also lifted up and destroyed by the furocity of the storms but majority of the meteorologists are of the opinion that the primary cause of the origin of tornadoes is violent convection of conditionally or convectively unstable column of warm and moist ascending air. The following are the prerequisite conditions for the formation of tornadoes: (1) mass convergence of air near the ground surface, (2) mass divergence aloft, (3) buoyant air mass, (4) wind shear in the vertical, (5) moist air mass in the lower layers, (6) a trigger mechanism, (7) unstable vertical temperature structure, (8) some preexisting mechanism for rotating the winds, (9) surface cyclogenesis etc.

The origin of tornadoes has also been related to fronts. The upthrusting of warm and moist tropical and subtropical air mass by cold polar air mass along the cold front presents ideal condition for tornado development. Some times intense local heating of the ground surface causes strong convection which induces ideal conditions for the formation of tornadoes. According to Californian scientist V.J. Rossaw tornadoes develop because of attraction of two cloud masses. Though tornadoes may develop at any time but they are more common during spring and summer seasons.

In the regions of polar frontogenesis tornadoes are formed due to strong collision of warm and moist air mass from tropical and subtropical regions with cold and dry air mass from polar regions. Due to such strong collision strong turbulence develops along the air mass collision boundary, this strong turbulence causes the development of several eddies which develop into powerful wind whirls having rotating winds, these whirls allow the warm, moist and unstable warm air to escape upward like smokes in a factory chimney. The trigger mechanism which causes violent exchange of air of contrasting properties requires some sort of disturbance which may be heat at the ground. The intensely heated ground radiates heat upward which provides energy to the ascending warm air. This causes extremely low pressure at the ground and strong convective mechanism above the groundsurface i.e. intense insolational heating of the ground. Extremely low central pressure draws air from all directions. Thus, a rising column of rotating warm air is developed and a tornado storm is formed. Such violent storm is comprised of several supercells. Further violent strong upward movement of warm and moist air results in the formation of enormous thunderstorm having numerous supercells which yield copious rainfall and hails. It may be mentioned that wind shear (change of speed and direction of wind) acts as a mechanism to rotate the winds rushing towards the central lowest pressure. As the storm develops into thunderstorm characterized by strong turbulence and updraughts, mamantus clouds are formed at lowest level of clouds *i.e.* near the ground surface while funnel clouds develop at the top of thunderstorm. All these are indicators of the formation of a tornado. The funnel clouds drop down and the tornado develops from the cloud wall.

3. Distribution of Tornadoes

Though tornadoes can develop in any part of the world except extreme cold regions but the United States of America is most important breeding region of tornadoes. The region to the south of 45^0N latitudes and to the east of the Rocky mountains is freequented by tornado outbreak from April to September. The Great Plains present most ideal conditions for the formation of tonadoes

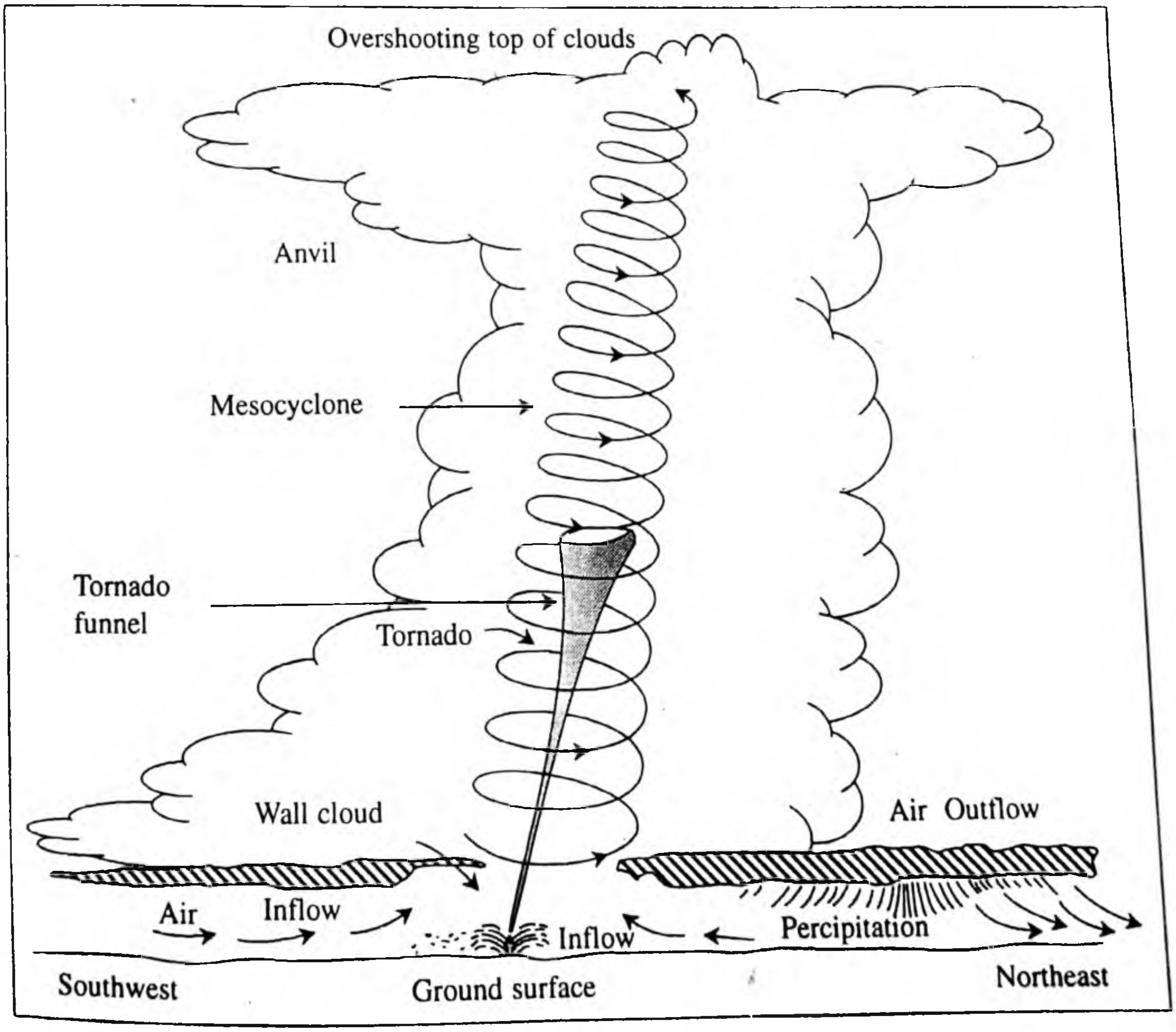


Fig. 12.4 : Development of tornado. **Source :** A.C. Donald, 1988, adapted from Oliver and Hidore, 2003.

where these are associated with frontal activity (cold fronts). The Great Plains are also called **Tornado Alley** because of maximum frequency of their occurrences. The most adversely affected states are Texas, Mississippi, Alabama, Missouri, Oklahoma, Arkansas, Kansas and Iowa. The occurrence of thunderstorms and tornadoes in the USA are synchronous (*i.e.* they occur at the same time-April to September, during daylight). The occurrence of tornadoes in groups involving large numbers on a specific day are called in the USA **tornado outbreak**. One such tornado outbreak occurred on Feb. 19, 1884 when 60 tornadoes struck the states of Virginia, North Carolina, South Carolina, Georgia, Alabama, Mississippi, Tennessee and Kentucky between 10 A.M. and 12 midnight wherein the most terrible devastation was caused by terrific wind storms ever experienced in the USA before this date. The second important outbreak of tornadoes, known as the Jumbo Outbreak comprised of 148 tornadoes, struck 12 central states of the USA on April 3 and 4, 1974.

Though tornadoes may occur in any month of the year in the USA but the highest frequencies of their occurrences are concentrated in three months of April, May and June (based on data from 1950 to 1997) which account for average number of tornadoes of 104, 171 and 161 per annum (table 12.8). Fortyeight years data (1950-1997) of frequencies of occurrences of tornadoes in the USA denote total occurrences to be 37,760 with mean annual average of 786 tornadoes (table 12.8). Besides the USA, tornadoes also occur in France, United Kingdom, China, Australia, eastern India etc.

4. Severity and Damage Scale of Tornadoes

A scale to assess the relative severity and damage of tornadoes was devised by **T. Theodore Fujita** in the late **1960s** on the basis of wind velocity and quantum of damage done by a tornado. This scale is popularly known as **Fuijita Scale**. It may be mentioned that the wind speed is not practically

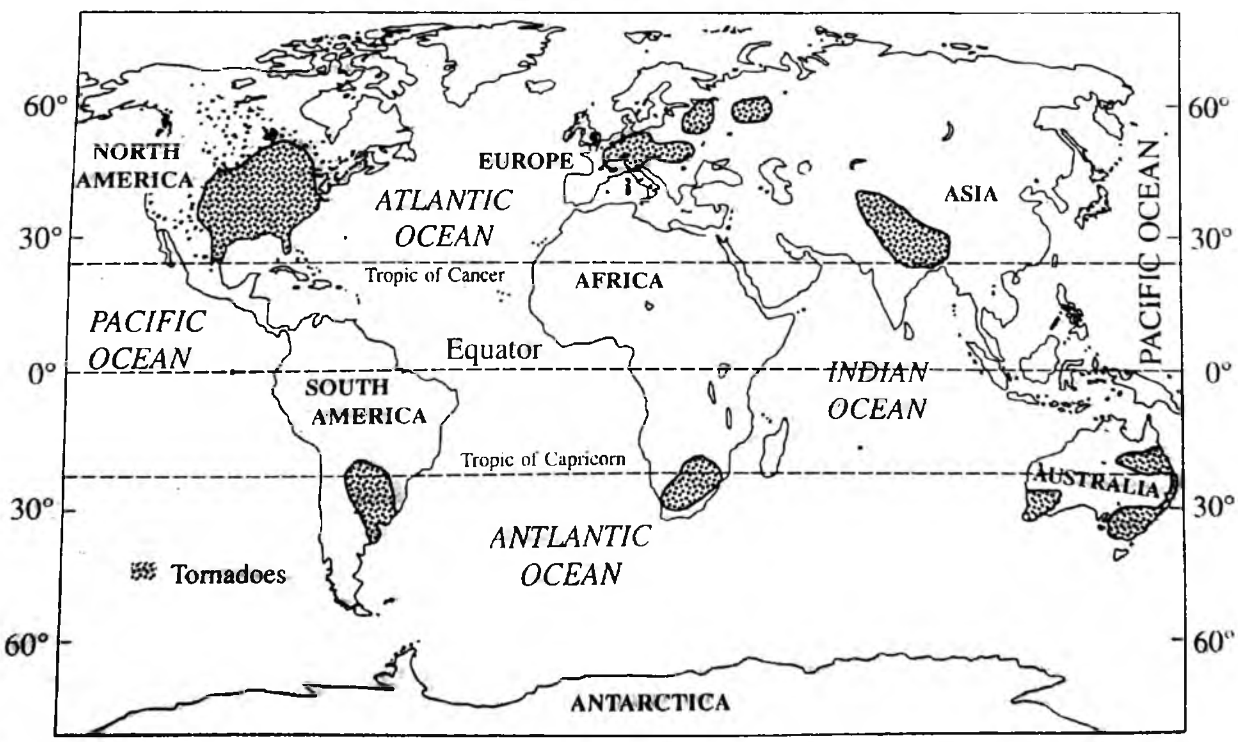


Fig. 12.5

Fig. 12.5 : Tornado areas of the world; source : based on and modified from McKnight, 1996

measured rather it is estimated after the tornado is over. Based on Fujita Scale tornadoes are divided into three major categories as follows :

1. **Weak tornadoes** are characterized by wind speed ranging between 64 km/hr to 179km/hr. These tornadoes are further divided into two subcategories on the basis of expected damage *e.g.* **category 0 : light damage,** branches of trees are broken, sign boards are damaged etc., wind speed from 64 km/hr to 115km/hr; **category 1** : wind speed ranging between 116km/hr and 179km/hr, **moderate damage,** trees are broken, windows of houses broken, broken parts whisked away.
2. **Strong tornadoes** are characterized by wind speed ranging between 180km/hr to 329km/hr, these are further divided into two subcategories *e.g.* **category 2** : wind speed between 180km/hr and 187km/hr, **considerable damage,** large trees are broken and uprooted, moving houses flown, weakly fixed building structures are damaged and removed; **category 3** : wind speed between 188km/hr and 329km/hr, **severe damage,** uprooted trees are carried away as tornado missiles, four wheeler and three wheeler automobiles are overturned and uplifted, roofs and walls of buildings are damaged and removed.
3. **Violent tornadoes** are characterized by very high wind speed ranging between 330km/hr and 509km/hr. These are further subdivided into 2 categories on the basis of wind speed and expected damage *e.g.* **category 4** : wind speed ranging from 330km/hr to 416km/hr, **devastating damage,** houses are destroyed, roofs, trees and automobiles are carried as **tornado missiles; category 5** : wind speed ranging between 417km/hr and 509km/hr, **incredible damage.**

The above types of tornadoes may be summarized as follows (adapted from Oliver and Hidore, 2003) :

(1) **Weak tornadoes**

category 0 : wind speed 64km/hr to 115km/hr damage category-light

category 1 : wind speed, 116km/hr to 179km/hr, damage category-moderate

(2) **Strong tornadoes**

category 2 : wind speed, 180km/hr to 187km/hr, damage category-considerable

category 3 : wind speed, 188km/hr-329km/hr, damage category-severe

(3) **Violent tornadoes**

category 4 : wind speed 330km/hr-416km/hr, damage category-devastating

category 5 : wind speed 417km/hr-509km/hr, damage category-incredible.

5. Tornado Hazards

Tornadoes are more common in the southern and eastern USA. The approach of tornadoes is heralded by dark and thick clouds in the sky resulting into complete darkness and minimum visibility and low air pressure. The wind blows with hyper velocity which causes cracks in the buildings. The corks of bottles suddenly open up automatically due to sudden change (lowering) of air pressure.

Tornadoes, though smallest in area of all the hazardous atmospheric storms, are very deadly to human lives and property. On an average, the annual toll caused by tornadoes in the USA includes damage to property worth 100,000,000 US dollars and 150 human deaths. The deadliest parts of tornadoes are **tornado misslies** (consisting of uprooted trees, their branches, roofs of buildings etc. which are carried away by the dynamic force of winds) which inflict great damage to buildings, other human structures, and human lives. A tornado, for example, at Lubbock (Texas, USA) in 1970 moved a long cylindrical fertilizer tank (3.35m × 12.5m in size with average weight of 11 tons for a distance of 1.21 km from its original place. It may be pointed out that a tornado becomes disaster only when its funnel of dark clouds moves by touching the ground through narrow column of swiftly moving wind. The **tornado outbreak** (occurrence of tornadoes in groups involving large numbers) of 60 tornadoes on February 19, 1884 struck the states of Virginia, North Carolina, South Carolina, Georgia, Alabama, Mississippi, Tennessee, and Kentucky between 10 A.M. and 12 midnight wherein the most terrific devastation was caused by violent wind storms ever experienced in the USA before this date. Total damages caused by these tornadoes included loss of property worth 3 to 4 million US dollars, death of 800 persons, injuries to 2,500 people, destruction of 10,000 buildings, homeless and destitute people numbering 10,000 to 15,000.

The following reporting in the news paper, the Washington Post, presents a vivid picture of the sad story of 1884 outbreak of tornadoes :

"The centre of the storm struck the outskirts of Rockingham with such fury that people were unable to escape from their houses. Buildings were blown into fragments. Some bodies were found under the timbers, other were carried by the wind 150 to 300 yards. A woman was found clasping to her breast an infant scarcely a month old; both were dead. The bodies of victims were terribly bruised and cut, presenting a ghastly appearance. The force of the wind was such that two millstones were moved 100 feet. Chickens and birds were picked clean, except the feathers on their heads." (Willimington (N.C.) Star in The Washington Post, 22 February, 1884).

The second important outbreak of tornadoes known as the Jumbo Outbreak comprised of 148 tornadoes struck 12 central states of the U.S.A. on April 3 and 4, 1974. The city of Xenia in Ohio state was worst affected by the tornado which destroyed 5 schools within the city. Like 1884 outbreak of tornadoes this outbreak also largely affected rural areas and avoided large cities. Total damage caused by these tornadoes in 12 US states included deaths of 300 people and injuries to 5,000 persons.

Table : 12.8 : Frequency of tornadoes and human causalities in the USA between 1950-1997

Months	Total number of tornadoes	Mean number of tornadoes	Total number of human deaths	Mean number of human deaths
January	716	15	106	2
February	975	20	274	6
March	2514	52	602	13
April	5002	104	1245	26
May	8185	171	883	18
June	7715	161	521	11
July	4509	94	63	1
August	2806	58	112	2
September	1829	38	75	2
October	1298	27	82	2
November	1398	29	149	3
December	810	17	124	3
Total	37760	—	—	—

Source : J.E. Oliver and J.J. Hidore, 2003

6. Forecasting of Tornadoes

The prediction of formation of tornadoes is very difficult because of its localized nature and very small size but violent nature, random distribution over space etc. The moment tornadoes are located after their formation their movements are tracked by radar system and the warning of their destination becomes possible but the time available is so short that destruction becomes inevitable destiny.

'The unpredictability and ferocity of tornadoes make protection and preparedness very difficult. Nevertheless, in the period that tornado forecast and warning services have been in operation in the U.S.A. the annual average number of fatalities seem to have decreased markedly' (J.E. Hobbs, 1980). According to G.P. Gressman (1969) the average number of annual deaths due to tornadoes is decreasing every year as average number of deaths between 1916 and 1952 was 200 per year but this figure was reduced to 120 between 1953-1968 because of improved warning systems. The fortyeight-year data of human casualities denote average annual death of only 70 people.Two methods of operational detection and tracking of tornadoes are in practice in the U.S.A. viz. (i) detection and tracking of tornadoes by weather surveillance radar, and (ii) prompt reports of visual sightings by competent observers. India has also set up more than 100 disaster warning systems and dying INSAT 1-B provided important information about the disastrous cyclone of May 9, 1990 which struck the Andhra coast. The advance monitoring and prediction of this disastrous cyclone at least a week before the final count down and its attack on the coastal districts of Andhra Pradesh saved thousands of people from sure death trap. People had sufficient time to move to safer places and thus warning systems contained human deaths which remained below 1000 mark (official figure being 598). In the absence of warning systems and ready response of inhabitants to evacuation programme this cyclonic storm being 25 times greater in intensity than the killer cyclone of 1977 (which caused 5500 deaths in Andhra Pradesh) might have caused unbelievable human deaths.

Recently **doppler radars** are used in the study of different aspects of tornadoes and their predication and warning. It may be mentioned that a mesocyclone takes 20 minutes time to develop into tornado and hence doplar radar predicts the arrival of a tornado at a particular locality 20 minutes in advance. The doplar radar also determines the speed and direction of tornado and hence it has now become possible to forecast the likely track of a tornado.

12.7 CUMULATIVE ATMOSPHERIC HAZARDS

Cumulative atmospheric hazards are those events which are caused due to cumulative effects of weather events which prolong for longer period of time ranging from a few weeks to several years depending upon the nature of weather events. For a example, any hot day may not become disastrous or hazardous but when very hot and dry days prevail for a few weeks in continuation, environmental hazards in the form of heat waves occurs which affect the environment and human lives, plants and animals. The persistence of exceptionally cold conditions for several days causes severe snowfall. A dry season a year may not be as much disastrous as continued dry seasons for several years. The perception and concept of drought vary from place to place and from one group of people to other group based on profession and occupation. In fact, drought occurs when there is appreciable decrease in rainfall from the average normal rainfall. Floods are still very severe environmental hazards which are related to atmospheric processes. Mississippi flood plains (U.S.A.) and the Ganga plains (India) are frequented by severe flood hazards. It may be pointed out that floods are not always hazards rather these are also boon because these bring rich fertile alluvial soils each time and thus increase agricultural productivity. The significant atmospheric cumulative hazards include floods, droughts, heat waves and cold waves.

12.8 FLOOD HAZARD

1. Meaning and Concepts

Flood simply means inundation of extensive land area with water for several days in continuation. Generally, floods are considered to be associated with rivers and people conceive floods as the outcome of accumulation of huge volume of water coming out of the rivers through overtopping of river banks during peak discharge period. In fact, flood is an attribute of physical environment and thus is a component of hydrological cycle of a drainage basin. It may be pointed out that flood is natural phenomenon and is a response to rainfall but it becomes hazard when it causes colossal loss to human lives and property. It is also important to note that floods are also aggravated by human activities and thus flood hazard is both natural as well as man-induced rather man-accentuated phenomenon. Floods are very often associated with alluvial rivers draining extensive alluvial and flood plains. About 3.5 per cent of the total geographical area of the world is covered by flood plains which house about 16.5 per cent of the total population of the world. The most notorious rivers of the world in terms of devastating floods and resultant damage to natural environment (riparian decay) and loss of human lives and property are the Ganga and its major tributaries such as the Yamuna, the Ramaganga, the Gomti, the Ghaghra, the Gandak, the Kosi, the Damodor, etc. (northern India), the Brahmaputra (north-east India), the deltaic segments of the Mahandi, the Krishna, the Godawari, the Tapi, the Narmada, the Luni, the Mahi etc. (all in India), the Mississippi and Missouri (U.S.A.), the Yangtze, the Yellow (China), the Irrawadi (Myanmar), the Indus (Pakistan), the Niger (Nigeria), the Po (Italy), the Euphratus and Tigris (Iraq) etc.

2. Causes of Floods

Since the floods of rivers are the responses of both natural and anthropogenic factors, the causes of floods of the alluvial rivers become highly complex and their relative importance varies from place to place. Among the natural factors which cause river floods, important are prolonged high intensity rainfall; meanderig courses of the rivers; extensive flood plains; break in slope in the long profiles of the rivers *i.e.* sudden change in channel gradient at the intervening zones of foothill slope of the mountains and upper end of the plains; blocking of free flow of the rivers because of enormous debris provided by landslides and due to volcanic eruptions; nature of river valleys and channels etc. Anthropogenic activities such as building activity and eventual urbanization, channel manipulation through diversion of its (of the river) course, construction of bridges, barrages and reservoirs, agricultural practices, deforestation, land use changes etc. by man invite several hazards in the river system viz. disastrous floods, landslides and slumping along the banks, massive erosion along the river banks causing large-scale riparian decay, shifting of channels and even of the river courses, silting of beds, deposition of sands, silts and clays in the flood plains etc. which pose a serious threat to human society and necessitate river regulation and flood control (Savindra Singh, 1983). The following causes may be held responsible for devastating floods of alluvial rivers. It may be pointed out that these factors should never be considered separately because it is the cumulative effects of several factors which ultimately cause severe floods.

(1) **Heavy rainfall** for long period in continuation is the root cause of river floods because immense volume of water either through high-intensity rainfall or large-scale snow-melt is the prerequisite condition for river floods. Heavy rainfall in the upper catchment areas of the concerned river causes sudden increase in the volume of water downstream. This causes overtopping of river banks by enormous volume of water and consequent inundation and flooding of flood plain areas. It may be pointed out that the occasional heavy rainfall resulting from strong rainstorms can cause severe floods only in those regions which are characterized by seasonal regime of rainfall or say seasonality of rainfall such as the regions of monsoon climate (rainfall during 4 wet summer months *e.g.* June to September), Savanna climate (rainfall during wet summer months), Mediterranean climate (rainfall during wet winter months) etc. because of the fact that the rivers maintain very low flow and low discharge of water during most part of the year and hence sudden torrential rainfall causes sudden increase in the volume of water which cannot be disposed off by the rivers immediately and thus the river banks are overtopped by the swelling water and instantaneous floods are caused.

The unprecedented flood of the Lower Damodar river in West Bengal due to torrential cyclonic rainfall of September 26-29, 1978 explains the impact of high intensity rainfall as a potent causative factor of floods. The severe cyclonic storm yielded heavy rainfall totalling 600 mm between September 26-29, 1978 in the upper catchment of the Damodar river (falling in Jharkhand, India) and 500 mm in its lower catchment (falling in West Bengal) thus giving an average amount of 550 mm within a 3-day period (September 27-29, 1978). It may be pointed out that the Damodar river is a controlled river through a series of dams and reservoirs on the main river and its tributaries such as Panchet dam, Maithan dam, Konar dam, Tilaiya dam etc. under the scheme of Damodar Valley Corporation (D.V.C.). The combined outflow of water from Maithan and Panchet dams was 16,000 cusecs (cubic feet per second) on September 23, 1978 and 10,000 cusecs on September 26, (upto the 6th hour), 1978 just before the outbreak of torrential rainfall from strong cyclonic storm centred in the upper catchment of the Damodar river. The torrential incessant rainfall resulted into enormous surface runoff which immediately reached the master stream and thereafter the reservoirs constructed behind the dams on the Damodar and its tributaries. Rapid pouring of enormous volume of water into the reservoirs caused quick rise in the level of reservoirs water and hence the discharge of outflow from the dams downstream had to be increased. Thus the outflow of water increased from 10,000 cusecs to 100,000 cusecs in the 24th hour of September 26 in response to the beginning of torrential rainfall in the upper catchment area. The discharge of outflow was noted on the next consecutive days as 160,000 cusecs on the 24th hour of September 27, 1978, 161,900 cusecs on the 3rd hour of September 28, 100,000 cusecs on September 29 and 60,000 cusecs on September 30, 1978.

Heavy rainfall also in the lower catchment having alluvial plains of West Bengal amounting to 500 mm within 3-day period and high discharge of water coming from upstream segment of the Damodar further augmented the discharge which was recorded as 379,800 cusecs on the 12th hour of September 27, 1978. This high discharge of water could not be accommodated in the valley of the Damodar in its lower reaches and hence devastating flood was generated which destroyed agricultural crops, caused heavy loss of human lives and property. High intensity rainfall giving average annual amount of 2500 mm in the plain area and 5000 mm in the hilly sector in Assam (India) causes frequent floods of high magnitude through the Brahmaputra river almost every year. High rainfall in the Himalayas and in the plains causes disastrous floods in the Himalayan rivers draining through the North India Plains or the Ganga plains.

(2) **Heavy spell of rainfall** in arid and semi arid areas where the rainfall is scant, low and infrequent causes flash floods because such areas have poor natural drainage systems and existing rivers and streams are unable to accomodate enormous volume of water caused due to huge volume of runoff resulting from high intensity rainfall during occasional rainstorms. For example, unprecedented rainfall of 836.4 mm between July 17, 1981 and July 21, 1981 in and around Jaipur city (Rajasthan, India : July 17-4.2 mm. July 18-235.8 mm, July 19-353.6 mm, July 20-228 mm, July 21-14.2 mm) caused flash floods because the chocking and blocking of lateral drainage from the hill through the dunes by human activity has resulted in a situation whereby this catastrophic runoff could not be eased out (H.S. Sharma, 1983).

(3) **Highly sinuous and meandering courses** of the rivers obstruct the normal discharge of water and thus the velocity is reduced which delays the passage of water resulting into stagnation of water. Consequently, the meandering valleys are immediately overflown and meander belts and loops are flooded.

(4) **Large-scale deforestation** in the upper catchments is perhaps the most important anthropogenic factor of the causes of the river floods. Large-scale deforestation effected by man for various purposes (such as for extension of agricultural land, for the supply of raw materials to the factories, for domestic uses as firewood, for commercial purposes etc.) decreases infiltration capacity of the cutover land and consequently increases surface runoff which helps tremendously in increasing the magnitude of floods. It may be pointed out that dense vegetation allows maximum infiltration of rainwater into the ground because rain drops are intercepted by forest canopy and thus reach the ground slowly in the form of **aerial streamlets** through the leaves, branches and stems of trees and hence infiltrates easily into the spongy soil layer, formed because of decomposition of fallen leaves (leaf litters). On the other hand, in the absence of forests and other vegetation covers raindrops strike the ground surface directly and in

case of heavy downpour the rainfall exceeds the limit of infiltration soon and thus maximum runoff is generated which reaches the rivers through rills, rivulets and streams and causes floods.

Increased surface runoff also accelerates the rate of soil erosion and thus increases the sediment load of the rivers. Increased sediment load causes siltation of river beds and filling of the valleys. This process results into gradual rise in the river beds and decrease in the cross sectional areas of the valleys and hence reduction in the water accommodating capacity of the river valleys. All these chain effects of deforestation and related increased surface runoff, increased soil erosion and decreased cross sectional areas of the valley not only cause floods but also increase the magnitude and dimension of floods. Large-scale deforestation in the Himalayas for the last one hundred years or so has resulted into phenomenal increase in the frequency, magnitude and dimension of floods in those rivers which have their source catchments in the Himalayas but extensive drainage areas in the alluvial Ganga plains such as the Ganga and its tributaries like the Yamuna, the Ramganga, the Gomti, the Ghaghra, the Gandak, the Buri Gandak, the Kosi etc. The extent of damages caused by swollen alluvial rivers and recurrent floods in the states of Uttar Pradesh, Bihar and West Bengal (India) is increasing every year.

(5) Increasing urbanization also helps in increasing the surface runoff and therefore dimension and magnitude of floods because extension in the puca ground cover through the construction of buildings, courtyards, roads, streets, pavements etc. reduces infiltration of rainwater significantly and increases surface runoff considerably which increases the volume and discharge of storm drains of urban areas. Thus the rainwater resulting from torrential rainfall is quickly disposed off through the city storm drains to nearby streams and thus the volume of river water is increased causing floods. Besides, obstruction of river flow due to bridges across the rivers, silting of river beds due to pouring of wastes and grabages from the nearby urban centres, gradual encroachment of human settlements towards the channels and lowlying areas, filling of 'nallas' (natural urban drains), construction of new roads and bridges etc. are also significant factors (related to urbanization) of floods which not only degrade the physical environment of the rivers and surrounding terrains but the recession of deluge also causes accumulation of human refuse, sewage materials, silts etc. bringing the epidemics and thus digrading the human environment in most of the riverine cities of alluvial regions of the developing countries in general and India in particular (Kanpur, Allahabad, Varanasi etc. located along the mighty Ganga river are burning examples of degradation of environment caused by recurrent floods of the Ganga river at frequent intervals).

(6) In India **valley side slopes of alluvial rivers** are ploughed down to the channel transverse to the channel or say transverse to the contours (inorder to dry out the moisture accumulated due to alluviation during floods) during 'rabi season' (winter cropping season) and the farms are never irrigated. After the crops are harvested, the ploughed fields are baked hot in the scorching sunlight of summer months with the result loose soils become extremely dry. These dried soils are soaked with water during first summer showers and are slumped into the river bed by overland flow. This slumping of moistened soils results in the gradual silting of river bed. On the other hand, the cultivation of valley-side slopes reduces the gradient of river banks. These two processes flatten the valley and thus reduces the water accommodating capacity of the river valley with the result the river takes very little time in attaining its bankfull capacity and afterward water spreads over the valley sides, inundates the low lying flood plains and helps in aggravating the flood situation.

(7) **Blocking of natural flow** of the rivers by landsides caused by earthquakes, other natural factors and anthropogenic factors and clearance of such blockades causes sudden severe flash floods in the downstream sections of the rivers. Similarly, breaches in the dams constructed across the river also cause devastating floods in the downstream segments.

3. Flood Hazards in the United States of America

Most of the countries of the world suffer from river floods in one way or the other but it would be out of place to discuss the floods of each country here. The flood hazards, therefore, of the most developed country *i.e.* the U.S.A. and one of the leading developing countries *i.e.* India are briefly discussed below.

The Mississippi and the Missouri rivers are most notorious rivers of the U.S.A. as regards flood havocs caused by them at regular intervals. The U.S. rivers which are known for severe floods and carry more than 300,000 cusecs (cubic feet per second) of water discharge during peak flood periods include Escambia and Tennessee rivers (Alabama state), Colorado river (Arizona), White, Red, Arkansas and Mississippi rivers (Arkansas), Eel and Klamath rivers (California), Savannah river (Georgia), Wabash river (Indiana), Neosho and Kansas rivers (Kansas) Ohio river (Kentucky), Atchafalaya river (tributary of Mississippi, Louisiana), Potomac river (Maryland), Missouri river (Missouri state), Delaware river (New Jersey), Miami river (Ohio), Arkansas river (Oklahoma), Willamette and Columbia rivers (Oregon), Tennessee river (Tennessee), W. Nueces, Llano, Little and Pecos rivers (Texas), Columbia river (Washington state), Potomac and Ohio rivers (West Virginia) etc.

The Mississippi, considered as vengeful monster as regards the flood havocs caused by it, draws its waters from a vast area spreading over 30 states of the country and thus its entire drainage basin accounts for 40 per cent of the total geographical area of the conterminus U.S.A. The river adopts a highly meandering course in the extensive flood plains. The magnitude of meandering of the Mississippi may be gauged from the fact that the straight air distance between Cairo (the confluence point of the Mississippi and the Ohio rivers) and its mouth in the Gulf of Mexico is 960 kilometres (600 miles) whereas the actual distance covered by the Mississippi is 2720 kilometres (1700 miles) and average channel gradient is about 3 cm per kilometre. Thus the meandering course and extremely low channel gradient and of course torrential rainfall through hurricanes and tornadoes in its extensive catchment area give the notorious character to the Mississippi river as 'both the sinuous course and low gradient of the Mississippi river so conspire to delay the passage of floods down its length that on occasion the river tops its banks and spreads in a broad sheet (of water) across the floodplain to inundate backswamps in a belt several miles wide' (A.N. Strahler and A.H. Strahler, 1976).

'In March 1927, the Mississippi river rose to the highest flood crest on record, inundation affected 18 million acres of land; thousands of families had to be evacuated from their homes. Deaths attributed to the flood numbered 313 persons; the damage in 1927 dollars was $ 300 million' (A.N. Strahler and A.H. Strahler, 1976). The Missouri, the Tennessee (tributary of the Ohio), the Ohio, the Arkansas, etc. contributed much of flood water to the Mississippi floods and therefore extensive control measures have been adopted to tame the Missouri, the Mississippi, the Arkansas, and the Tennessee rivers etc.

The heavy torrential rainfall accompanied by hurricanes is the major cause of flood hazards in the U.S.A. The flood hazards caused by hurricane Agnes in June 1972 in the south-eastern and eastern states of the U.S.A. very much tell the impact of atmospheric disturbances on the creation of devastating floods. The strong storm originating in the south-east of Florida struck the main land on June 19, 1972 and moved northward through the eastern coastal states of the U.S.A. to reach New Jersey on June 22, 1972. After remaining stationary from June 22 to 25 over north-eastern states (New Jersey, Pennsylvania) it moved eastward to dissipate after June 27 in the north Atlantic Ocean. This hurricane yielded rainfall between 150 mm to 230 mm in the southern states, 350 mm in Virginia, Maryland, and Delaware, 300 mm to 450 mm in the states of Pennsylvania and New York. This heavy amount of rainfall within a day or two caused severe floods in most of the Atlantic-bound rivers. For example, the Susquehanna river recorded its water level 4.?7m above its flood stage and the Ohio river (to meet the Mississippi in the south-west) at Pittsburgh reached 3.35m above flood stage. The worst affected rivers were the Susquehanna, Juniata, and the Schuylkill.

4. Floods in India

Most of the flood-prone and flood affected areas of the country are located in the northern parts mainly in the Ganga plains of the states of Uttar

Pradesh, Bihar and West Bengal. The flood hazards and disasters in Uttar Pradesh, Bihar and Andhra Pradesh combined together account for 62 percent of the total damages caused by flood hazards in the country. Table 12,.9 presents the statewise damages caused by flood hazards in India.

Table 12.9 : State-wise share of damages done by floods (in percentage) (average of 1971-78)

States	Share of damages (in percentage)		
Bihar	23.9	Rajasthan	4.5
Uttar Pradesh	23.8	Tamil Nadu	3.8
Andhra Pradesh	15.4	Haryana	3.2
West Bengal	7.0	Assam	2.1
Gujarat	5.7	Punjab	1.4
Orissa	4.5	Madhya Pradesh	1.3

Source : National Commission on Floods, 1980, Ministry of Energy and Irrigation, New Delhi.

It may be pointed out that there is constant inccrease in the frequency, intensity, spatial coverages (dimensions) and magnitude of damages of floods in India every year because of a bunch of causative factors such as rapid rate of deforestation in the source catchments of major rivers and their tributaries and consequent accelerated rate of soil erosion, increase in sediment load of rivers, siltation and rise of river beds and marked reduction in the water accommodating capacity of the river valleys; increasing urbanization, mushroom growth of settlements in the floodplains and even in the flattened (due to alluviation) valleys; encroachment of agricultural practices upon the valley sides and even down to the channels; construction of bridges, embankments and dikes etc.

'During recent years, both the frequency and intensity of floods have increased significantly. For example, compared to 1950-65, the average loss from floods got doubled in 1966-67 and went upto 3 times in 1971-75 and 5 times in 1976-78 showing a constant upward trend. According to another estimate, the loss caused by floods within two years (1976-78) remained more than 5 times as compared to earlier period of twelve years... As National Commission on Floods reports, the country suffers a damage of Rs. 1000 crores every year on this account and the figure is rising steadily. What is more, the total area subject to flooding has doubled from 20 million ha (hactare) in 1971 to 40 million ha in 1981' (J. Singh and D.N. Singh, 1988). Table 12.10 depicts the damages done by flood hazards in India during 20-year period (1953-75).

Table 12.10 : Magnitude of flood damage in India

Details of Damages	Average during 1953-1975	Annual Maximum Damages
Areas affected by floods	7.4 million hactares	1.372 million hactares
Cropped areas affected	3.1 million ha	7.6 million ha
Number of houses damaged	8,00,000	23,10,000
Number of cattle lost	50,331	270,000
Number of persons died	742	3,498
Total direc' losses	Rs. 2104 million	Rs. 8,850 million

Source : National Commission on Floods, Vol. I, Ministry of Energy and Irrigation, Govt. of India, 1980.

5. Flood Control Measures

Flood control measures include a series of steps to tame the menacing rivers such as (A) to delay the return of runoff resulting form torrential rainfall to the rivers; (B) to hasten the discharge of water; (C) to reduce the volume of water; (D) to divert the flow of water; (E) to reduce the impact of floods and above all (F) to forewarn the occurrence of floods.

It may be pointed out that the floods are natural phenomena and one cannot entirely get rid off them but their impacts can be minimised by man's technological skill, better warning systems and positive human response to flood warnings and various control measures adopted by the governments.

(A) The first and foremost step to control floods is to look into their basic cause which is perhaps the high intensity rainfall and resultant surface runoff. Man cannot stop high intensity rainfall and there is no need at all to interfere with natural processes. What man can do is to delay the return of surface runoff resulting from the high intensity rainfall to the rivers. This can be achieved by large-scale reforestation and afforestation in the hilly source catchment areas of those rivers which are notorious for their recurrent disastrous floods. The thick vegetal covers mostly of dense forests help in this regard in a number of ways viz. (i) forests delay the return of rainwater to the rivers because these intercept the falling raindrops and leaf litters and herbaceous ground covers hold waters; (ii) these encourage more infiltration of rainwater and therefore reduce, though marginally, amount of surface runoff; (iii) these significantly reduce soil erosion and hence reduce sediment load of the rivers; (iv) marked reduction in soil erosion and sediment load discourages siltation and hence reduction in the water accommodating capacity of the rivers etc. It is therefore apparent that making the hills, having the source of flood producing rivers, green through large-scale tree plantation can effectively reduce the frequency and dimension of floods.

(B) It has already been mentioned that too much bends and meander loops in the highly sinuous and meandering rivers retard the quick disposal of water. It is, therefore, advisable to straighten the sinuous and meandering courses of the rivers at some places (where meanders and loops have become extremely sharpened) by performing artificial cutoffs of individual bends or a series of bends so that the flood discharge may move downstream more rapidly and the water may be disposed off by the rivers quickly. Such devices are required to train the alluvial rivers because these rivers (like all of the alluvial rivers of the Ganga plains *e.g.* the Ganga, the Ramaganga, the Rapti, the Gomti, the Gandak, the Kosi etc.) develop highly meandering courses due to alluvial filled flat terrain. There are two main difficulties in the implementation of these control measures *e.g.* (i) the device requires huge money which may not be easily forthcoming in the developing countries and (ii) meandering is a natural process of alluvial rivers, if meanders are removed at some places the river may develop meanders at other places. The lower Mississippi river near Greenville (U.S.A.) was shortened in its length from 530km to 185 km between 1933 and 1936 to reduce flood crests. Similarly, the Missouri river (U.S.A.) was shortened in its length by 52 km between Sioux City and its confluence with the Mississippi in 1960 for flood control and navigation improvement.

(C) The volume of water during flood stage of a river may be reduced through a series of engineering devices such as construction of flood-control storage reservoirs. Such storage reservoirs impound enormous volume of water during flood period and thus these help in two ways *e.g.* firstly, these storage reservoirs reduce the volume of water of the rivers and secondly, these provide water for irrigation and drinking purposes. If the reservoirs are succeeded by huge dams, they also help in the generation of hydro-electricity.

Such flood-control reservoirs were constructed on Miami river in the state of Ohio (U.S.A.) as early as in 1913. A series of storage reservoirs were completed by 1921 and thus the scheme of the construction of storage reservoirs as effective flood-control measure became very popular in the U.S.A. The Tennessee basin of the U.S.A. was considered to be hell till 1933 because of perpetual waterlogging, recurrent floods, very high incidence of malaria, typhoid and tuberculosis, accelerated rate of soil erosion and increase in the infertility of the soils and wasteland. But the construction of a series of dams and reservoirs under the scheme of Tennessee Valley Authority (T.V.A.) since 1933 has not only controlled the recurrent floods and tamed the mad Tennessee river but has entirely changed the social and economic picture of the basin to such an extent that the basin once considered as 'hell and curse' is now considered as heaven.

The success of TVA attracted more countries to launch multi-purpose river projects for watershed management. The scheme was also implemented in India to check floods and for other purposes. The Damodar Valley Corporation (DVC), a multi-purpose river project, was launched on the line of TVA wherein 4 major dams and reservoirs have been constructed on the Damodar river and its tributaries such as the Barakar and the Konar rivers for water storage and flood moderation in the lower reaches of the Damodar river. Besides flood control, the DVC also generates hydroelectricity and provides water for irrigational purposes. 'The four dams namely Konar, Maithan, Panchet Hill and Tilaiya have a flood storage of 1603 million cubic metres and have been in operation since 1958 and have helped considerably in the moderation of floods in the Lower Damodar Region' (K.L. Rao, 1975). Similarly, the construction of Ukai Dam and Reservoir on the Tapi (Tapti) river has almost saved the lower reaches of the river and the town of Surat from the disaster of flood hazards. Many more examples may be cited to demonstrate the positive effects of storage reservoirs on flood control.

(D) Flood-diversion systems imply diversion of flood water in lowlying areas, depressions or artificially constructed channels bordered by artificial dykes so that the flood crests may be reduced and the flood magnitude may be decreased. For example, Ghaggar Diversion Schemes divert the water discharge of about 340 cumecs (cubic metres per second) before entering Rajasthan (India) into the depressions and in the areas between the sand dunes during flood period so that discharge of water in the main river (the Ghaggar) during flood stage may be kept within the safe limits.

(E) Embankments, dikes and flood walls are used to confine the flood water within the valley or say within a narrow channel. These engineering works include the building of artificial levees of earthen materials, stones or even concrete walls. Artifical bunds (levees) of mostly earthen materials have been constructed to protect many of the riverine cities and towns in the Ganga plains (such as Delhi, Allahabad, Lucknow etc.). Construction of dikes or artificial levees was practiced long ago in China, India etc. but there were several cases of breaches of earthen dikes and consequent more disastrous floods than natural floods. 'For example, dike failures in great flood on the Hwang Ho River (now Yellow River) in China in 1887 brought inundation to an area of 50,000 sq miles (130,000 sq km) and death by drowning to approximately one million persons' (A.N. Strahler and A.H. Strahler, 1976). Besides, protection to the towns and cities from floods by constructing dikes and other engineering structures such as revetments, artificial levees or earthen dikes are also constructed on either side of the river for longer distances to protect the floodplains from floods. For example, the Kosi flood Embankments running for 246 km are being used to check the westward shifting of the Kosi river (in Bihar, India) and to protect the fertile floodplains from recurrent floods and deposition of sands and coarse silts which used to render vast tracts of fertile lands unfit for cultivation. It may be pointed out that the Kosi river before the construction of flood embankments has shifted its course westwards by about 112 km. The 246 km long embankments on either side of the Kosi river have been kept wide apart about 12 to 16 km so that broad areas confined between the artificial walls (embankments/dikes) may serve as silt trap.

The Bagmati Flood Control Embankments running for a distance of 241 km and 290-km long embankments along the Mahananda river under Mahananda Embankment Scheme protect about 57,000 hectares and 160,000 hectares of floodplains respectively.

Stone spurs are also used to protect the towns, cities and other important places from severe erosion during and after the floods. Under the scheme of Dibrugarh Town Protection Works stone spurs, semi-permeable spurs, pile spurs, revetments and protective dikes of about 10 km length have been constructed to protect the town from floods and erosion by the Brahmaputra river. The Jalpaiguri Town Protection Works (India) include the construction of 16-km long embankments and the shifting of existing outfall of the Karala river into the Teesta river near Jalpaiguri by 6 km downstream.

(F) Flood Control Organisation and Flood Forecasting and Warning System in India: The Constitution of Central Flood Control Board in 1954 and the establishment of the State Flood Control Boards at state level have proved beneficial in adopting several flood control measures. The flood forecasting and warning system was started in India in 1959 to monitor the flood situation in the capital city of Delhi. Since then a network of flood forecasting and warning systems has been spread over the country to monitor the flood conditions of major river basins of the country. Thus the flood forecasting centres set up in various parts of India help in the forecasting of floods in the Ganga and its tributaries (*e.g.* Rapti, Gomti, Ghaghra, Yamuna, Burhi Gandak, Kosi, etc.), the Brahamaputra and its tributaries (*i.e.* Pagladiya and Burhi Dehing, Barak, Teesta), Subarnarekha, Damodar, Brahmani, Baitarni, Tapi, Narmada, Sahibi, Godavari, Ajoy, Betwa and other flood prone rivers. The flood forecasting centres collect data of rainfall and discharge rate, gauge level or flood level from various data recording centres in the jurisdiction of each flood forecasting centre and thus warn the inhabitants of particular river basin about the possible danger of floods much in advance.

12.9 DROUGHTS

Droughts are more deadly natural environmental hazards because these are directly related to one of the three basic requirements of any form of life (such as water, air and food) that is water and are indirectly related to food because crops and other plants and animals exclusively depend upon water. Droughts resulting from accumulative effects of water scarcity cause extensive and enormous damage to agriculture and natural vegetation and therefore cause famine and starvation of human and animal population of the regions concerned. The meaning and definition of droughts are difficult propositions because there are much variations in the viewpoints and perception of droughts from one region to another and from one group of people to another. 'Most people are reasonably well aware when a drought situation exists, but it is very difficult to find an overall acceptable definition of drought. It clearly involves a shortage of water, but can really be defined only in terms of a particular need. The most common view of drought is of rainfall deficiency, but the links between rainfall and the water which becomes available to meet a demand are complex. Therefore, definition of a drought relates not only to water needs but also to the complex set of factors involved to supply that need through the hydrological cycle' (J.E. Hobbs, 1980).

It may be pointed out that increased dryness for prolonged period causing drought conditions is related to the amount of rainfall, its departures from normal average annual value and local demand of water for various purposes. It is not the amount of total annual rainfall which matters for drought or wet conditions rather it is the regularity and irregularity of rainfall which matters more. For example, a more persistent and reliable amount of 200 mm of annual rainfall may not be the cause of concern of the agriculturists in dry region because their agricultural activities would be adapted to this meargre amount of rainfall but the receipt of only 200 mm of annual rainfall for a few years in continuation or even in a single year in those areas which receive normal annual rainfall of 500 to 800 mm may cause crop failure and hence disastrous drought condition may prevail. According to C.E. Hounam et al. (1975) 'The agriculturist or pastoralist, especially in the direr regions, has assessed the nature of local rainfall and, through years of long and sometimes bitter experience, has learned to adapt his operations to the rainfall characteristics of the area.' 'In other words, drought is related to the failure of the usual rains at a particular time, since most activities using water will be geared to that which is normally available' (J.E. Hobbs, 1980).

It is, thus, obvious that rainfall is the main parameter for the determination of droughts but 'rainfall values, however, have limitations as drought indicators, so many definitions and indices incorporate other parameters such as evaporation, humidity, air temperature, solar radiation, wind, soil moisture, streamflow and plant conditions (J.E. Hobbs, 1980). The following are a few drought definitions based on the parameters of precipitation :

(i) **C.G. Bates (1935)** : Annual precipitation is 75 per cent or less of normal precipitation and monthly precipitation is 60 per cent or less of normal monthly precipitation.

(ii) **BRO (British Rainfall Organization, 1936)—absolute drought** : when there are atleast 15 consecutive days with less than 0.01 inch of rainfall per day. **Partial drought** : when there are at least 29 days having mean rainfall of 0.01 inch or less. **Dry spell** : when 15 consecutive days receive less than 0.04 inch of rainfall per day.

(iii) **J.C. Hoyt (1936)**—Annual and monthly rainfall less than 85 per cent of normal rainfall.

(iv) **V.A. Conard (1944)**—Period of 20 or more consecutive days without 0.25 inch precipitation in 24 hours (during March-September).

(v) **D.A. Ramdas (1950)**—When rainfall for a week is half normal or less.

(vi) **A.J. Henry (1960)**—21 days or more when rainfall is 30 per cent or less of average rainfall. Extreme droughts occur when rainfall is less than 10 per cent of average rainfall for 21 days or more.

Most of the aforesaid definitions of droughts do not have any relevance in India and in many of the tropical and sub-tropical countries because here agricultural practices are associated with distinct seasonal water regime. Failure of monsoonal rainfall in India and adjacent countries adversely affects 'kharif crops' and causes drought conditions. According to Indian Meteorological Department (IMD) drought is defined as a situation occurring in any area when the mean annual rainfall is less than 75 per cent of the normal rainfall. IMD has further classified droughts into two broad categories viz. (i) **severe drought** when the deficiency of rainfall exceeds 50 per cent of the normal rainfall, and (ii) **moderate drought** when the deficiency of rainfall is between 25 per cent and 50 per cent of the normal rainfall.

Impact of Droughts

As referred to earlier, droughts affect all types of life-form in the biospheric ecosystem because both plants and animals directly depend on water. Any shortage of water supply adversely affects them. Thus, the impacts of prolonged droughts include ecological, economic, demographic and political aspects. Prolonged drought conditions in a given region change the biotic component of the natural ecosystem because (i) some species of plants and animals perish as they cannot withstand extreme drought conditions; (ii) some animals migrate to other places and hence there is marked decrease in the population of certain animal species; (iii) some animals die of hunger and starvation; (iv) there is stiff competition for food due to scarcity created by drought among the animals which result in the elimination of weaker animals etc. The most significant ecological impact of prolonged drought is natural control of plant and animal populations.

The **economic impact** of droughts includes economic losses due mainly to marked decrease in agricultural production, livestock yield and even industrial production because of short supply of water. **Demographic impact** of drought includes depopulation of regions/areas and temporary migration of affected people and animals. Many of the people of Sahelian region of tropical Africa have left the region because of persistent drought conditions. There is frequent migration of people from drought affected areas of Rajasthan, Gujarat, Maharashtra and Andhra Pradesh in India. Due to prolonged severe droughts for four consecutive years (1984-to 1987) in Gujarat and Rajasthan a large number of people temporarily shifted to Uttar Pradesh and Bihar together with their cattle though most of the people sold out their cattle at much lower prices due to total dearth of fodder. **Political significance** of extreme drought conditions includes the change of political power due to acute shortage of foodgrains caused by crop failure due to droughts (*e.g.* Mr Khurschev had to step down from power in the former USSR because he had to purchage wheat from the western world) and increase in the dominance of the USA, Canada etc.

on drought affected poor countries because they have to depend on those developed countries which have surplus food supply. Even the fate of state and central governments of India depends on the nature and mercy of monsoon rainfall. The idea of impacts of droughts on human activities may be had from the detailed discussion of a few case studies of drought affected areas as given below.

(1) **Sahel Region** : The region extending between hot and dry desert areas of the Sahara in the north and the Savanna region in the south and running from the western part of Africa through Mauretania, Senegal, Mali, Upper Volta, Niger, Nigeria, Chad, Uganda, and Ethiopia in the east is called **Sahel Region** or **Sub-Sahara Region**. The drought zone of the Sahel is a tropical grassland and is characterized by a **feast** and **famine climate** wherein the life of nomadic herders and grain farmers exclusively depends upon rainfall received during a short rainy season. The growth of grasses depends upon rainfall. Even the people of Sahel depends for their drinking water upon groundwater which is replenished through rainfall. Prolonged drought results in the depletion of groundwater and hence acute scarcity of drinking water. This region is very often frequented by severe droughts which cause extensive damage to flora and fauna and humans. The recent severe drought began in 1968 and continued upto 1975. The drought became acute during 1971 and 1972 and its cumulative effects became so disastrous that it became a **human catastrophe** by 1974. The prolonged drought for 7 years in continuation resulted in the depletion of subsurface water reserve and drying of water holes (trapped water in sands and gravels of stream beds) and low wells. The nomadic herders were compelled to sell out their cattle which could survive due to water shortage in the beginning of the drought and thus they became refugees and collected in special camps near the cities and towns to get small packets of foodgrains donated by other countries of the world. Inspite of relief measures coming from over the world thousands of people of the Sahel region died of hunger and starvation, thirst and diseases. About 5 million cattle were claimed by severe Sahel drought. About 50,000 people in Ethiopia alone died of starvation, malnutrition and diseases. The drought condition still persists in Ethiopia and millions of children are suffering from malnutrition and diseases.

(2) **Australia** : Drought is very common natural phenomenon in Australia. The Australian droughts are both frequent in recurrence and widespread in spatial coverage. A few case histories of droughts would certainly reveal the magnitude of Australian droughts. The worst drought started in 1895 and continued upto 1902. The adverse impacts of this prolonged droughts included sharp fall in the number of sheep from 106 million sheep in 1891 to only 54 million in 1902 and 50 per cent decrease in the number of cattle (from 14 million cattle in 1891 to 7 million in 1902). Several enormous dust storms submerged many fences under thick cover of huge amount of soils and sands, the city of Melbourne was drenched (on November 21, 1902) with dust, several towns in the interior part could not see the sun on that day (November 21, 1902) because of thick layer of dusts in the air, railway lines at many places were buried under thick deposits of loose soils and sands. Severe hazardous droughts again occurred during 1911-1916 and 1919-1920. Thus the three phases of severe droughts viz. (1) 1895-1903; (iii) 1911-1916 and (iii) 1919-1920 resulted in marked decrease in the agricultural land which was increased substantially after 1866. It may be pointed out that favourable rains during 1860's and 1870's led to phenomenal increase in the cropped area as the cultivated lands were extended from more favourable coastal areas to the inland marginal areas. The cropped land in the south-east Australia increased 6 times between 1866 and 1900 but the aforesaid three consecutive phases of severe droughts forced the farmer to retreat towards the favourable coastal areas. The recent severe droughts in Australia include two widespread dry spells in 1965-66 and 1967-68 which caused decrease in the farm gross national product by 20 per cent.

(3) The aforesaid examples of droughts are related to those areas which are already rain deficient regions and droughts are very common features but there are other areas where there is no problem of large-scale droughts. In such areas a drought causes serious problems of various sorts. The example of 1975-76 drought in U.K. reveals this fact. The twelve-month period (from May 1,

1975 to April 30, 1976) recorded less than 60 per cent of normal annual precipitation. The dry conditions continued for further 4 months *i.e.* from May, 1, 1976 to August 1976. This prolonged dry spell resulted into acute shortage of supply of water for domestic and industrial purposes as the reservoirs could not be filled up to their capacities. There was also substantial fall in agricultural production as wheat, barley, oats and potato productions in England and Wales fell by 22, 12, 12 and 13 to 40 per cent respectively. The total loss to agricultural production amounted to more than 500 million pounds. The gravity of the 1975-76 drought may be gauged from the fact that the government appointed a Drought Minister to handle the problems arising out of the drought.

(4) **India** : Since monsoon climate and associated rainfall is very much deceptive, irregular and uncertain, and hence nearly most parts of the country are affected by drought and floods in one way or the other. For example, Rajasthan is a chronic drought-prone area but heavy rainfall during the first two weeks of July 1990 (exceeding 500 mm a day) caused severe floods in most parts of Rajasthan. The chronically drought affected areas of the country include 67 districts where drought affects 25 per cent of the total cropland and 12 per cent people of India. This zone, worst affected by severe droughts, includes larger tracts in the states of Rajasthan, Gujarat, Haryana, Maharashtra, Karnataka, Andhra, Pradesh and southern Uttar Pradesh. The severe drought-prone areas of India are divided into 3 zones viz. (i) Desert and semi-arid regions spread over an area of about 600,000 km^2 and form a rectangular tract which stretches from Ahmedabad to Kanpur (to form eastern and southeastern border), from Kanpur to Jullundur (to form north-eastern and northern boundary) and from Jullundhar to Rann of Kutch along the western international border. The region is characterized by low rainfall ranging between 350 mm and 750 mm per annum but the extreme western desert areas receive even less than 350 mm of annual rainfall. This zone includes whole of Rajasthan and Gujarat, western and south-western parts of Punjab, most of Haryana, south-western part of Uttar Pradesh and narrow strip along the western and north-western border of Madhya Pradesh. There is little impact of droughts in Punjab and Haryana because sufficient irrigational facilities are available but the areas having no irrigational facilities are the worst drought-affected and famine areas of the country.

(ii) The second chronic drought-prone zone forms a rectangular tract which spreads over the rainshadow areas of the Western Ghats. In fact, this zone is situated to the east of the Western Ghats and extends in a width of 300 km. It includes south-western Andhra Pradesh, eastern Karnataka (east of Western Ghats) and south-western Maharashtra (east of Western Ghats). This region covers 370,000 km^2 of area and is characterized by highly erratic mean annual rainfall of less than 750 mm.

(iii) Besides the aforesaid two broad zones of severe droughts, there are some scattered pockets of droughts in the country such as Tirunelveli district located to the south of Vagai river, Coimbatore area, Palamau area of Jharkhand, Purulia District of West Bengal, Kalahandi region of Orissa etc. The scattered pockets of drought-prone areas cover about 100,000km^2 of area.

The Ministry of Agriculture has identified drought affected areas in the country on the basis of rainfall distribution, frequency of occurrence of drought and percentage of irrigation. On the other hand, the Irrigation Commission has demarcated drought prone areas on the basis of rainfall and and irrigation in the region concerned. Thus according to the Irrigation Commission those areas are drought affected areas which have less than 1000 mm of mean annual rainfall, 20 per cent or more of the years do not receive even 75 per cent of this annual amount of rainfall and where irrigated areas are less than 20 per cent of the cropped areas.

Drought Control Measures

Unlike floods, forewarning is not possible in the case of droughts, though computer-based study of numerous climatic and meteorological parameters may provide some idea about the nature and pattern of precipitation in the ensuing year. Even the amount of air moisture and precipitation may be increased through anthropogenic activities such as afforestation. The usual practice prevalent in most of the country to combat droughts is to provide relief measures to drought affected people. Such measures are also necessary because these provide immediate reliefs to the affected people. Besides, there should be long-term measures to ameliorate the severity of droughts. Such measures include afforestation to increase the content of air moisture, to increase the amount of precipitation, to increase the rate of infiltration of rainwater and hence the replenishment of groundwater and rise of water table; introduction of dry farming techniques to reduce the dependence of farming on rainwater; checking of desertification or deseart spread; introduction of water conservation schemes; development of horticulture and pastures; revitalisation of Drought-Prone area Programmes (DPAP); construction of reservoirs, digging of wells etc.

12.10 IMPORTANT DEFINITIONS

Annualr belt : The band surrounding spiral bands of a tropical cyclone, characterized by low relative humidity, weak cloudiness, little rainfall is called annular band or belt.

Baguio : Tropical cyclones in Philippines are called baguio.

Cloud burst : Sudden localized heavy downpour with cloud thunder and lightning associated with thunderstorms is called cloud burst.

Disaster : Disaster is sudden adverse extreme event which causes great damage to human society as well as plants and animals. Disasters occur rapidly, instantaneously and without making any discrimination. For example, the violent earthquake with 8.9 on Richter scale which occurred on December 26, 2004 in the Indian Ocean off the coast of Sumatra, generated 10m high tsunami, claimed thousands of human lives in India, Sri Lanka, Thailand, Indonesia etc.

Down burst : Strong downward movement of air (down draught) in strong thunderstorm associated with heavy precipitation through dense cumulonimbus cloud is called downburst.

Easterly waves : The migratory wavelike tropical disturbances (cyclones) associated with trade winds are called easterly waves.

Extreme events : Those events or accidents, whether caused by natural processes or by human factors, which occur very rarely, are called extreme events.

Fujita scale : The scale to assess the relative severity and damage of tornado, devised by T.T. Fujita, is called Fujita scale.

Hurricanes : Tropical cyclones in the Caribbean Sea and the USA are called hurricanes.

Hurrican waves : The waves caused in the oceans due to ferocity of hurricanes are called hurrican waves which are generally from 3m to 6m in height.

Storm surge : The storm surge or tidal surge refers to unusual rise in sea level caused by very low atmospheric pressure and the stress of strong gusty winds associated with tropical cyclones.

Taifu : Tropical cyclones in Japan are called taifu.

Tornadoes : Tornadoes are funnel shaped very violent rotating system of air wherein the air from the ground having lowest pressure is sucked by the upper air and is suddenly uplifted causing convective instability.

Tornado outbreak : The occurrence of several tornadoes in groups is called tornado outbreak.

Tornado missiles : The materials of different nature like uprooted trees, roofs of buildings, small cars etc. carried by tornadoes are called tornado missiles.

Typhoons : Tropical cyclones in China are locally called as typhoons.

13

CLASSIFICATION OF CLIMATES

The climatic conditions vary considerably both horizontally and vertically over the globe due to a host of variables and hence the identification of such variations is required to determine groups of similar characteristics of climate. The climatic classification thus involves the groupings of identical weather and climatic characteristics in terms of insolation and temperature, atmospheric circulation and pressure, humidity and precipitation and their influences on vegetation, soil and fauna, of different regions of the world. The classification of climates also seeks answers of two questions, namely (i) what should be the spatial scale for a definite climatic region? and (ii) what should be approach to the classification? Thus, the scheme of classification of world climates involves two aspects, namely (1) size of areal (spatial) units (spatial scale), and (2) methodology of classification i.e. approaches to climatic classification. Before attempting a few established schemes of climatic classification, these two aspects need brief discussion.

13.1 SPATIAL SCALES FOR CLIMATIC REGIONS

As already discussed in the 1st chapter of this book there are spatial variations in the combinations of elements of weather and climate (insolation and temperature, air pressure, humidity and precipitation etc.) which are responsible for variations in climatic types in the world. The study of weather and climatic elements in an area having uniform conditions of these elements is called **regional climatology** wherein the size of areal unit grades from vegetable gardens and crop fields to villages, cities, forest covers, deserts, mountains, plains, countries and even to continents. It is thus evident that the spatial unit of a climatic region varies from micro spatial scale (e.g. vegetable garden and cropfield) to macro scale (e.g. a continent or part thereof). Based on spatial scale of areal unit M.M. Yoshino has divided the world climates into four principal types e.g. (1) **micro climate**,(2) **local climate**, (3) **mesoclimate**, and (4) **macroclimate.**

1. Microclimate

Microclimate refers to the climatic conditions of the smallest spatial unit having a horizontal extent from one meter to 100 meters and vertical extent from the ground surface to 100 meters upward such as a vegetable garden, a single cropfield, a single household, the area around a tree etc. (other details have been given in chapter one of this book).

2. Local Climate

The local climate comprising a few microclimatic areas covers such spatial unit which has horizontal extent from 100 meters to 1000 meters and vertically extends from ground surface to 1000 meters wherein horizontal differences in climatic conditions are given more importance than vertical differences.

3. Mesoclimate

The mesoclimate incorporates several local climatic areas horizontally extending from 100 meters to 20 km and has vertical extent from the ground surface to the altitude of 6 kilometers. Topographically mesoclimatic area is homogeneous which is characterized by similar physical controls of weather and climate e.g. the Ganga delta, the middle Ganga plain, Konkan coastal plain, Malabar coast, Tamil Nadu plain, Rewa plateau, Tarai region of Uttar Pradesh, Godavari delta, Sardar Sarovar area etc. It may be mentioned that in the beginning spatial scale was used to determine the areal units for mesoclimatic studies but recently the scales of atmospheric motions are given more emphasis and the study of mesoscale meteorological phenomena involving atmospheric motions like severe atmospheric storms (supercyclones, severe tornadoes and hurricanes), land and see breezes, mountain and valley winds, precipitation in a physical unit, heat wave areas, cold wave areas etc. has gained currency with the advancement in obtaning updated meteorological data through advanced weather satellites and radars.

4. Macroclimate

Macroclimate, also known as **geoclimate** or **geographical climate,** covers largest area of all the other three types of regional climate as referred to above. It covers the horizontal distance of more than 20 km (it may be several hundred kilometers) and vertically it extends from the ground surface to more than 6 kilometers. Thus the macroclimatic area may cover even the entire continent or a large country like the USA, China, Russia, Brazil, India etc. (but there are further spatial variations in climatic conditions even in a single macroclimatic region). It may be mentioned that during the study of macroclimatic region which comprises several mesocalimatic regions averages of atmospheric circulation patterns over longer period of time are considered to determine the general characteristics of the concerned region while small scale (in terms of time and space both) patterns of atmospheric motions are ignored.

13.2 APPROACHES TO CLIMATIC CLASSIFICATION

The approaches to the classification of world climates depend on the nature of parameters which are selected to determine the identical combinations of climatic elements worldover and the objectives and viewpoints of the persons involved in such classification. Generally, two basic climatic parameters of temperature (mean monthly and mean annual) and precipitation (both monthly and annual averages) became the basis of climatic classification schemes of early scientists mainly the botanists (more specifically plant physiologists) and geographers (mainly biogeographers, more specifically plant geographers). Such classification was based on relationship between vegetation, and temperature-humidity as it was conceived that the vegetations of a particular area or region were the function of temperature and humidity conditions of that area. The climatic types, thus, were based on the types of vegetation and were named after plants associations such as equatorial rainforest climate (evergreen trees), savanna climate (the region having coarse grasses and scattered dwarf trees on the margins of the tropics having seasonal rainfall-i.e. in summer season), taiga climate (having coniferous evergreen forests of the subarctic regions of North America and Eurasia), tundra climate (having vast treeless almost ice covered plains of arctic regions of North America and Eurasia) etc.

It may be mentioned that the basis of influences of climate on vegetation types and their distribution is still used for the classification of climates into major climate types, but it requires besides vegetation response to climate, other responses to climate to make the classification of world climates more scientific and elaborate e.g. human response to climate, effects of climate on denudational processes (rock weathering and erosion), climatic effects on soils and pedogenesis, requirements of water, temperature and humidity by agricultural crops etc. It appears from the above description that the effects of climates on vegetation, soils and pedogenesis, rock weathering, agricultural crops, human health, geomorphological processes etc. are determined on the basis of observed information and data. Thus the classification of world climates based on observed effects of climate on the above mentioned aspects is called **empirical classification** and the approach is called **empirical approach.**

On the other hand, some scientists have attempted to classify the world climates on the basis of causes of variations in climates and hence occurrence of different types of climates. Thus the classification of climates on the basis of causes of climatic variations and their explanations is called **genetic classification** and the method adopted is called **genetic approach**. The third method of classification of world climates involves the inclusion and analysis of numerical meteorological data obtained through modern techniques of weather satellites and radars. Such classification is called **numerical classification**.

It is thus evident that there are three approaches to the classification of world climates, namely (i) **empirical approach,** (ii) **genetic approach,** and (iii) **numerical approach,** and the classifications based on these approaches are called (1) **empirical classification,** (2) **genetic classification,** and (3) **numerical** or **quantitative classification** of world climates.

13.3 EMPIRICAL CLASSIFICATION

As stated above the empirical system of classification of world climates involves the consideration of the effects of climate on several environmental phenomena such as types and distributional patterns of vegetation, soils and soil forming processes, geomorphological processes, rock weatherng, human beings (human health and physical growth), agricultural crops etc.; and the numerical data of such observed effects. Since the empirical classification is primarily based on experiments, observations and data coming therefrom, and hence it is more consistent, stable and standard system of classification of world climates. Two such systems devised by Koppen and Thornthwaite are most widely known and are still relevant. So, the schemes of the classification of world climates involving empirical bases by Koppen and Thornthwaite are elaborated as follows :

1. Koppen's Classification

The German botanist and climatologist Wladimir Koppen presented descriptive scheme of the classification of world climates first in 1900 based on vegetation zones of French plant physiologist Candolle presented in 1874. He revised his scheme in the year 1918 wherein he paid more attention to monthly and annual averages of temperature and precipitation and their seasonal distribution. He again modified his scheme in 1931 and 1936. Koppen's original scheme was modified in 1953 by Geigger-Pohi and the revised scheme known as Koppen-Geigger-Pohi's scheme of classification of world climates was published. It may be pointed out that the classification of Koppen is more popular because it is quantitative in nature as numerical values of temperature and precipitation have been used in delineation of boundaries of different climatic types. The climates have been named on the basis of alphabets and climates have been determined on the basis of formulae and hence the classification has become difficult to memorise because each alphabet has definite and specific meaning.

Koppen used the following five major vegetation zones of the world as identified by Candolle in 1874 :

1. **Megathermal zone** represents such plants which depend on high temperature and humidity (and rainfall) throughout the year and hence there is no winter season. The plants are evergreen. The temperature of coolest month remains above 18°C. The megathermal zone has the dominance of equatorial (tropical) rainforests having well developed vertical 5 strata.
2. **Xerophytic zone** represents such plants which thrive in hot and arid conditions. Such plants have suitable characteristic features to withstand extreme aridity. Here evaporation exceeds precipitation. The xerophyte plants have their own moisture conserving devices such as long roots, thick barks, waxy leaves, thorns and little leaves so that they may avoid evapotranspiration and consequent loss of moisture from them.
3. **Mesothermal zone** represents mesotherm group of vegetation wherein plants are

adapted to moderate temperature and precipitation. The temperatures for the coldest month are below 18°C but above –3°C while the average temperature of the warmest month is 22°C.

4. **Microthermal zone** represents such plants which can survive in the region having temperature of the coldest month below –3°C but the average temperature of the warmest month remains above 10°C but below 22°C. Boreal deciduous and steppe vegetations are termed as microtherms.
5. **Hekistothermal zone** represents such plants which thrive on almost permanently ice covered arctic and polar areas, say tundra region. There is perfect relationship between vegetation and condition of moisture in the soils. The characteristic lithosols of this zone (tundra biome) support only lichens and mosses.

It may be mentioned again the Koppen was convinced that there was perfect relationship between plant groups and climates and hence he used five vegetation zones of Candole (e.g. megatherms, mesotherms, xerophytes, microtherms and hekistotherms) as the basis of classification of world climates on the belief that the distribution of natural vegetation was the best indicator of the total picture of climate of a region concerned. Based on these five vegetation zones he divided the world climates into five principal types and designated them by capital alphabets A, B, C, D, and E.

(1) A Climate represents humid tropical climates characterized by winterless season, warm and moist conditions throughout the year and mean temperature always above 18°C.

(2) B Climate represents dry climates where evaporation exceeds precipitation and there is constant water deficit throughout the year.

(3) C Climate represents humid mesothermmal or middle latitudes warm temperate climates having mild winters, average temperatures of the coldest and warmest months beings between 8° to 18°, and 22°C respectively.

(4) D Climate includes humid microthermal or cold forest climates characterized by severe winters, average temperatures of coldest and warmest months being below –3°C and above 10°C respectively.

(5) E Climate includes polar climates characterized by summerless season, average temperature of the warmest month below 10°C.

Besides these capital letters, Koppen has used the following small (lower) letters in his scheme for specific meaning.

f = precipitation throughout the year, average temperatures of the coldest month being more than 18°C, minimum precipitation of 6 cm in every month of a year

m = monsoon climate, short dry season, average precipitation in driest month less than 6 cm.

w = winter dry season

s = well defined summer dry season .

Koppen has divided 5 major climatic types into 11 subtypes on the basis of seasonal regimes of precipitation and nature of aridity and coldness.

1. Tropical Rainy Climates (A Climates)

A or tropical rainy climate is that where the temperature of the coldest month is above 18°C. On the basis of periodicity and regime of precipitation this type has been further divided into 4 sub types.

(i) **Af climate** : humid tropical climate, precipitation in the driest month more than 6cm, seasonal distribution of precipitation more or less uniform throughout the year, very low daily range of temperature.

(ii) **Aw climate** : tropical humid and dry climate, winter dry season (w), precipitation of at least one month less than 6cm, high temperature throughout the year.

(iii) **Am climate** : monsoon climate, one short dry season but sufficient annual precipitation and thus wet ground throughout the year, dense forest, precipitation of at least one month less than 6cm. The boundary between Aw and Am climates is demarcated on the basis of annual precipitation and the precipitation of the driest moth as per formula given below :

a = 3.94 - r/25

where a = precipitation of driest month

r = annual precipitation

If the precipitation of the driest month of a place is less than the value of a, it will be Aw climate, if it is more than the value of a, it will be Am climate.

Example = If the annual precipitation of a place is 50 inches, then Am/Aw boundary would be = 3.94 - 50/25 = 1.94 inches. If the precipitation of the driest month of that place is 2 inches (this should be always less than 2.4 inches, otherwise it would be Af climate), it would be Am climate. On the other hand, if the precipitation of the driest month of that place is 1.8 inches, it would be Aw climate.

(iv) **As climate :** dry summers, rarely found.

The aforesaid Af, Am and Aw climatic types as identified by Koppen are generally similar to equatorial rainforest climate (Af), monsoon climate (Am), and savanna climate (Aw) respectively. Koppen has further identified finer details in A climates and has used the following lower letters to indicate them.

w'	maximum precipitation in autumn
w"	two seasons of maximum precipitation separated by two dry seasons
s	dry summers
i	difference of temperature of the warmest and the coldest month less than 5^0C.
g	hottest season preceding precipitation

2. **Dry climates (B climates) :** evaporation exceeds precipitation, precipitation not sufficient to maintain permanent stable water table of groundwater. B climates are divided into two types on the basis of annual temperature and the rainiest month of the year e.g. (i) dry desert climate (BW), and (ii) semi-arid or steppe climate (BS). The boundary between BW and BS climates is determined on the basis of the following formula :

$$r = \frac{0.44t - 8.5}{2}$$

where

r = annual precipitation (inches)

t = temperature (^{0}F)

If the annual precipitation of a given place is more than the value of r, the climate of that place will be BS but if it is less than r, the climate will be BW. For example, if the temperature of a place is 80^0F, the annual value of precipitation for dividing boundary between BS and BW climates will be 13.3 inches as given below:

$$r = \frac{0.44 \times 80 - 8.5}{2} = 13.3 \text{ inches}$$

B climates are further differentiated on the basis of annual temperature. When the mean annual temperature is more than 18^0C (64.4^0F), the climate is indicated by h letter but if the mean annual temperature is less than 18^0C, it is indicated by k letter. Thus, B climates are divided into the following four sub types:

(i) BWh	tropical desert climate, average annual temperature more than 18^0C ($64,.4^0$F)
(ii) BSh	tropical steppe climate, mean annual temperature above 18^0C
(iii) BWk	middle latitude cold desert climate, mean annual temperature below 18^0C
(iv) BSk	middle latitude cold steppe climate, mean annual temperature below 18^0C

Koppen has identified further details in B climates and has used the following letters to indicate them :

k	mean annual temperature below 18^0C
h	mean annual temperature above 18^0C
a	summer dry, three times more precipitation in the wettest month of winter season than the driest month of summer season
w	winter dry, 10 times more precipitation in the wettest month of summer season than the driest month of winter season
n	minimum fog

(3) **Humid mesothermal or warm temperate rainy climates (C climates) :** average temperature of the coldest month above 3^0C but below 13^0C, precipitation in all seasons. Based on seasonal distribution of precipitation C climates have been divided in to 3 climatic types :

(i) **Cf climate :** precipitation throughout the year, precipitation more than 1.2 inches in the driest month of summer season. This climate represents Western Europe type of climate. This is further divided into two second order sub-divisions e.g. Cfa (humid subtropical) and Cfb (marine west coast type)

(ii) **Cw climate :** dry winter, 10 times more precipitation in the wettest month of summer season than the driest month of winter season. This represents China type of climate.

(iii) **Ca climate :** dry summers, three times more precipitation in the wettest month of winter season than the driest month of summer season, precipitation of the driest month of summer season less than 1.2 inches. This represents Mediterranean type of climate.

Koppen has identified further minor details in C climates and has used a few explanatory small letters as given below :

a warm summers, temperature of the warmest month above 22°C (71.6°F).

b cold winter, temperature of the warmest month below 22°C.

c cold short summer season

i,n,g, = as explained above.

(4) **Humid microthermal** or **cold snow forest climates** or **humid cold climates (D climates) :** temperature of the coldest month below-3°C (26.6°F) but of the warmest month above 10°C (50°F), ground surface covered with snow for several months of a year. This climate has been divided into three types.

(i) **Df Climate :** humid cold climate, no dry season. This is further divided into (a) Dfa (long warm summers, continental), (b) Dfb (long and cool summers), and (c) Dfc (short and cool summer-subarctic).

(ii) **Dw Climate :** humid cold climate, dry winters, further divided into (a) Dwa- continental climate with long cool summer, (b) Dwb-cool short summer (sub-arctic type), and (c) Dwc-cold winters. d = temperature of the coldest month −38°C or below-38°C, f, a, w, b, c as explained above.

(5) **Polar climates (E climates) :** temperature of the warmest month less than 10°C (50°F), further divided into (i) ET and (ii) EF climates.

(i) **ET climate-tundra climate,** temperature of the warmest month below 10°C but above 0°C.

(ii) **EF climate-**permanent snow field, temperature in all months below O°C.

Evaluation of Koppens's Scheme

Koppen used two easily measurable weather elements e.g. temperature and precipitation as the basis for statistical parameters for the delineation of different climatic regions. In fact, temperature and precipitation are most widely and most frequently used effective weather elements as representatives of the effects of climatic controls. His scheme of climatic classification is primarily based on the relationship between floral types and their characteristics, and climatic characteristics of a given place or a region. He also paid due consideration to the loss of moisture through evaporation as he included effective precipitation, which depends on the rate of potential evapotranspiration, in his scheme. It may be pointed out that it is not the total annual precipitation which matters more for vegetation community rather it is the effective precipitation (amount of precipitation which is actually available to plants) which is more important for flora. Koppen's scheme appealed more to geographers because the scheme recognized association between vegetation types and climatic types. Besides, this scheme is descriptive, generalized and simple and hence it was widely acclaimed.

Inspite of several merits as referred to above the Koppen's scheme also suffers from some serious drawbacks. Koppen gave undue significance to mean monthly values of temperature and precipitation in his scheme of climatic classification and neglected other weather elements such as precipitation intensity, amount of cloudiness and number of rainy days, daily temperature extremes, winds etc. He made his scheme more descriptive and generalized and ignored the consideration of causative factors of climate. He did not include the characteristics of different airmasses in his classification. The use of different letter symbols to indicate different climatic types and their secondary and tertiary subtypes makes the scheme very difficult to memorise.

Further, it has not been commonly agreed that the vegetation types closely correspond to climatic types i.e. some scientists are still skeptical about complete relationship between vegetation distribution and climate distribution. A few scientists are also of the view that the boundaries between different climatic types have been very rigidly determined which is not justifiable as there are a lot of fluctuations in temperature and precipitation from year to year at a particular place. Inspite of above mentioned drawbacks of Koppen's system of empirical approach to the classification of world climates, the merits of his scheme still score over demerits and is widely used as general system of classificatory schemes of world climates.

2. CLASSIFICATION BY THORNTHWAITE

C.W. Thornthwaite, an American climatologist, presented his first scheme of classification of climates of North America in 1931 when he published the clamatic map of North America. Later he extended his scheme of climatic classification for world climates and presented his full scheme in 1933. He further modified his scheme and presented the revised second scheme of classification of world climates in 1948. His scheme is complex and empirical in nature.

1931 Classification

Like Koppen, Thornthwaite also considered natural vegetation of a region as the indicator of climate of that region. He accepted the concept that the amount of precipitation and temperature had paramount control on vegetation but he also pleaded for inclusion of evaporation as important factor of vegetation and climate. This is why Thornthwaite used two factors, e.g. **precipitation effectiveness** and **temperature effectiveness,** for the delimitation of boundaries of different climatic regions.

(I) Precipitation Effectiveness

Precipitation effectiveness or precipitation efficiency refers to only that amount of total precipitation which is available for the growth of vegetation. He used precipitation efficiency ratio for the calculation of this amount of water available to vegetation. Precipitation efficiency ratio (P/E ratio)_is calculated by dividing total monthly precipitation by monthly evaporation and precipitation efficiency index (P/E index) is derived by summing the precipitation efficiency ratios for 12 months of a year. Since it is difficult to obtain data of evaporation for every centre and hence Thornthwaite suggested the following formulae for the calculation of precipitation efficiency ratio and index.

$$P/E\ Ratio = 11.5\ (r/t - 10)^{10/9}$$

$$P/E\ Index = \sum_{i=1}^{12} 11.5(r/t - 10)^{10/9}$$

where

r = mean monthly rainfall in inches

t = mean monthly temperature in ^{0}F

He identified **5 humidity zones** on the basis of P/E Index and boundary values for the major vegetation zones.

Humidity zones	Vegetation	P/E Index
A (Wet)	Rainforest	127
B (Humid)	Forest	64-127
C (Subhumid)	Grassland	32-63
D (Semiarid)	Steppe	16-31
E (Arid)	Desert	<16

Thornthwaite further subdivided each humidity zone into 20 subhumidity zones on the basis of seasonal distribution of precipitation.

1. Ar	5. Br	9. Cr	13. Dr	17. Er
2. As	6. Bs	10. Cs	14. Ds	18. Es
3. Aw	7. Bw	11. Cw	15. Dw	19. Ew
4. Ad	8.Bd	12. Cd	16. Dd	20. Ed

Where r = adequate rainfall in all seasons

s = rainfall deficient in summer

w = rainfall deficient in winter

d = rainfall deficient in all seasons

(II) Thermal Effectiveness

He believed that temperature had important contribution in the growth of vegetation. He, thus, devised an index of **thermal efficiency or temperature effectiveness,** expressed by positive departure of monthly mean temperatures from freezing point, and suggested the following formulae :

(i) Thermal Efficiency Ratio

$$T\text{-}E\ Ratio = (t - 32)/4$$

(ii) Thermal Efficiency Index

$$T - E\ Index = \sum_{i=1}^{12} (t - 32)/4$$

Where t = mean monthly temperature in °F. It is apparent that T-E Index is the sum of thermal efficiency ratios for 12 months. On the basis of T-E index Thornthwaite divided the world into 6 temperature provinces :

Temperature Province	T-E Index
A' - Tropical	127
B' - Mesothermal	64-127
C' - Microthermal	32-63
D' - Taiga	16-31
E' - Tundra	1-15
F' - Frost	0

Thus, on the basis of precipitation effectiveness, thermal efficiency, and seasonal distribution of rainfall there may be 120 probable combinations and hence climatic types on theoretical ground but he depicted only 32 climatic types on the world map as given below:

1. A A'r — tropical wet climate with rainfall adequate in all seasons
2. A B'r — mesothermal wet climate with adequate rainfall in all seasons
3. A C'r — microthermal wet climate with adequate rainfall in all seasons
4. B A'r — tropical humid climate with adequate rainfall in all seasons
5. B A'w — tropical humid climate with rainfall deficient in winter
6. B B'r — mesothermal humid climate with adequate rainfall in all seasons
7. B B'w — mesothermal humid climate with rainfall deficient in winter season
8. B B's — mesothermal humid climate with rainfall deficient in summer season
9. B C'r — microthermal humid climate with adequate rainfall in all seasons
10. B C's — microthermal humid climate with rainfall deficient in summer season
11. C A'r — tropical subhumid climate with adequate rainfall in all seasons
12. C A'w — tropical subhumid climate with deficient rainfall in winter season
13. C A'd — tropical subhumid climate with rainfall deficient in all seasons
14. C B'r — mesothermal subhumid climate with adequate rainfall in all seasons
15. C B'w — mesothermal subhumid climate with rainfall deficient in winter season
16. C B's — mesothermal subhumid climate with rainfall deficient in summer season
17. C B'd — mesothermal subhumid climate with rainfall deficient in all seasons
18. C C'r — microthermal subhumid climate with rainfall in all seasons
19. C C's — microthermal subhumid climate with rainfall deficient in summer season
20. C C'd — microthermal subhumid climate with rainfall deficient in all seasons
21. D A'w — tropical semiarid climate with deficient rainfall in winter season
22. D A'd — tropical semiarid climate with rainfall deficient in all seasons
23. D B'w — mesothermal semiarid climate with rainfall deficient in winter season
24. D B's — mesothermal semiarid climate with rainfall deficient in summer season
25. D B'd — mesothermal semiarid climate with rainfall deficient in all seasons
26 D C'd — microthermal semiarid climate with rainfall deficient in all seasons
27 E A'd — tropical arid climate with rainfall deficient in all seasons
28 E B'd — mesothermal arid climate with rainfall deficient in all seasons
29. E C'd — microthermal arid climate with rainfall deficient in all seasons
30. D' — taiga type climate
31. E' — tundra type climate
32. F' — permanently snow-covered polar climate

1948 Classification

After making sizeable modifications Thorthwaite presented his modified scheme of climatic classification in 1948. Though he again used previously devised three indices of precipitation effectiveness, thermal efficiency and seasonal distribution of precipitation in his second classification but in different way. Instead of vegetation, as done in 1931 classification, he based his new scheme of climatic classification on the concept of **potential evapotranspiration** (PE) which is in fact an index of thermal efficiency and water loss because it represents the amount of transfer of both moisture and heat to the atmosphere from soils and vegetation (evaporation of liquid or solid water, and transpiration from living plant leaves) and thus is a function of energy received from the sun. It may be pointed out that potential evapotranspiration is calculated (and not directly measured) from the mean monthly temperature (in ^{0}C) with corrections for day length (i.e. 12 hours). The PE (Potential Evapotranspiration) for a 30-day month (a day having only the length of sunshine i.e. 12 hours) is calculated as follows :

$$PE \text{ (in cm)} = 1.6\,(10t/I)^a$$

where PE = Potential Evapotranspiration

I = the sum for 12 months of $(t/5)^{1.514}$

a = a further complex function of I

t = temperature in ^{0}C

Thornthwaite developed four indices to determine boundaries of different climatic types e.g. (i) moisture index (Im), (ii) potential evapotranspiration or thermal efficiency index (PE), (iii) aridity and humidity indices, and (iv) index of concentration of thermal efficiency or potential evapotranspiration.

(i) **Moisture Index (Im)** : Moisture index refers to moisture deficit or surplus and is calculated according to the following formula:

$$Im = (100S - 60D)/PE$$

where Im = monthly moisture index

S = monthly surplus of moisture

D = monthly deficit of moisture

The sum of the 12 monthly values of Im gives the **annual moisture index**.

$$\text{Annual Moisture Index} = \sum_{i=1}^{12}(100S - 60D)/PE$$

(ii) **Thermal Efficiency Index** : Thermal efficiency is simply the potential evapotranspiration expressed in centimetres as referred above. It is, thus, apparent that the thermal efficiency is derived from the PE value because PE in itself is a function of temperature. The method of the calculation of PF is given above.

(iii) **Aridity and Humidity Indices** : These indices are used to determine the seasonal distribution of moisture adequacy. These are calculated as follows :

Aridity Index = in moist climates annual water deficit taken as a percentage of annual PE becomes aridity index.

Humidity Index = in dry climates annual water surplus taken as percentage of annual PE becomes humidity index.

(iv) **Concentration of thermal efficiency** refers to the percentage of mean annual potential evapotranspiration (PE) accumulating in three summer months.

On the basis of **moisture index** (IM) Thornthwaite identified 9 moisture or humidity provinces.

Moisture Index	Humidity province
(1) 100 and above	A perhumid
(2) 80 to 100	B_4 humid
(3) 60 to 80	B_3 humid
(4) 40 to 60	B_2 humid
(5) 20 to 40	B_1 humid
(6) 0 to 20	C_2 moist subhumid
(7) -33.3 to 0	C_1 dry subhumid
(8) -66.7 to -33.3	D semiarid
(9) -100 to -66.7	E arid

On the basis of **thermal efficiency** (potential evapotranspiration) 9 thermal provinces were recognized.

Thermal Efficiency Index (cm)	Thermal Province (Type)
(1) 114 and above	A' Megathermal
(2) 99.7 to 114.0	B'_4 Mesothermal
(3) 85.5 to 99.7	B'_3 Mesothermal
(4) 71.2 to 85.5	B'_2 Mesothermal
(5) 57.0 to 71.2	B'_1 Mesothermal
(6) 42. 7 to 57.0	C'_2 Microthermal
(7) 28.5 to 42.7	C'_1 Microthermal
(8) 14.2 to 28.5	D' Tundra
(9) Below 14.2	E' Frost

On the basis of summer concentration of thermal efficiency the world was further divided into 8 provinces :

Summer Concentration of Thermal Efficiency (%)	Type
(1) below 48.0	a'
(2) 48.0-51.9	b'
(3) 51.9-56.3	b'_3
(4) 56.3-61.6	b'_2
(5) 61.6-68.0	b'_1
(6) 68.0-76.3	c'_2
(7) 76.3-88.0	c'_1
(8) above 88.0	d'

On the basis of seasonal moisture adequacy 2 major and 10 subclimatic types are identified-

Moist Climates (A,B,C_2)		Aridity Index
(1) r	little or no water deficit	0 to 10
(2) s	moderate summer deficit	10 to 20
(3) w	moderate winter deficit	10 to 20
(4) s_2	large summer deficit	above 20
(5) w_2	large winter deficit	above 20
Dry Climates (C_1,D,E)		**Humidity Index**
(6) d	little or no water surplus	0 to 16.7
(7) s	moderate surplus	16.7 to 33.3
(8) w	moderate surplus	16.7 to 33.3
(9) s_2	large winter surplus	above 33.3
(10) w_2	large summer surplus	above 33.3

The climate of a place, thus, is determined by combining the aforesaid elements of the climatic classification e.g. moisture index, thermal efficiency index, summer concentration of thermal efficiency, and seasonal moisture adequacy (aridity and humidity indices). Thus the climate of a place is represented by four letters. For example-A A' a' r climate = Perhumid (A) megathermal (A') climate with summer concentration of annual thermal efficiency (PE in cm) of less than 48 per cent (a') and little or no water deficit (r) etc. On the basis of above indices the classification system becomes so complex due to large number of climatic types that it becomes difficult to represent them cartographically.

Evaluation of Thorthwaite's Schemes

In many aspects the 1931 classification scheme of Thornthwaite was almost similar to Koppens' scheme because both had a few common points e.g. (i) Like Koppen's scheme his scheme is also empirical as well as quantitative as the boundaries of different climates are determined on the basis of quantitative parameters derived from precipitation and temperature, (ii) Vegetation is made as the basis for the identification of climatic zones, (iii) Various letter combinations are used to designate different climatic types etc. The Thornthwaites's scheme differs from the Koppen's scheme in that the former used two indices of precipitation efficiency and thermal efficiency for differentiation of different climatic types but the delimitation of climatic boundaries on the basis of these two indices becomes difficult and vague. Moreover, the Thornthwaite's scheme yielded the number of major climatic types (32) three times greater than Koppen's climatic types. Like Koppen's scheme Thornthwaite's scheme also became popular among zoologists, botanists and geographers but it was not appreciated by meteorologists and climatologists because this scheme did not include the causative factors of climates into the classification of world climates in different types. This scheme also suffers from a serious problem of non-availability of the data of evaporation for all the places. Thus, the lack of adequate climate data makes it difficult for the precise demarcation of climatic boundaries.

Though 1948 scheme of climatic classification of Thornthwaite was thoroughly revised and modified and was based on 4 important indices of moisture index, thermal efficiency or potential evapotranspiration index, seasonal moisture adequacy (aridity and humidity indices), and summer concentration of thermal efficiency but no world map of different climatic types could be prepared. It may be pointed out that it becomes very difficult to cartographically represent a large number of climatic types identified quantitatively on the basis of aforesaid indices. Moreover, the data of potential evapotranspiration are not available for all the places for a worldwide classification of climates. The complex empirical formulae divised by Thornthwaite require regular data but these are not always forthcoming. They also involve a lot of calculations for determining the climatic type of a particular place. This is why his scheme could not get more popularity and recognition.

13.4 GENETIC CLASSIFICATION

Genetic classification of world climates is based on the causes of climatic variations and hence the genesis of different types of climates. The classification also involves explanations and interpretations of causal factors of different climatic types. Generally, two approaches are more significant, e.g. (1) approach based on identified physical determinants of climates, and (ii) air mass approach. It may be mentioned that genetic classifications being more descriptive and having less precisely determined boundaries between two climate types, could not become popular and hence could not be widely used.

Oliver-Hidore's Classification (Air Mass Model)

J.J. Hidore presented a genetic classification of world climates based on air mass dominance in the year 1969. He divided the globe into nine environments on the basis of (i) seasonal patterns of radiant energy, and (ii) seasonal patterns of precipitation. If we look into this scheme, it is evident that Hidore also used temperature, in one way or the other, and precipitation regimes as bases of his classification. In place of temperature radiant energy has been used as an effective variable by Hidore. Each of the nine environments, as determined on the basis of seasonal patterns of radient energy and precipitation, has been taken as a climate type, which has same seasonal characteristics of either temperature or moisture.

The four major air masses, namely maritime tropical (mT), continental tropical (cT), maritime polar (mP) and continental polar (cP), have been used for the identification of 9 climates. Oliver and Hidore (2003) have divided the world climates into 3 major groups and nine climate types. Each major group consists of 3 climate types. This scheme has been illustrated by the following figure (13.1) drawn by Oliver and Hidore.

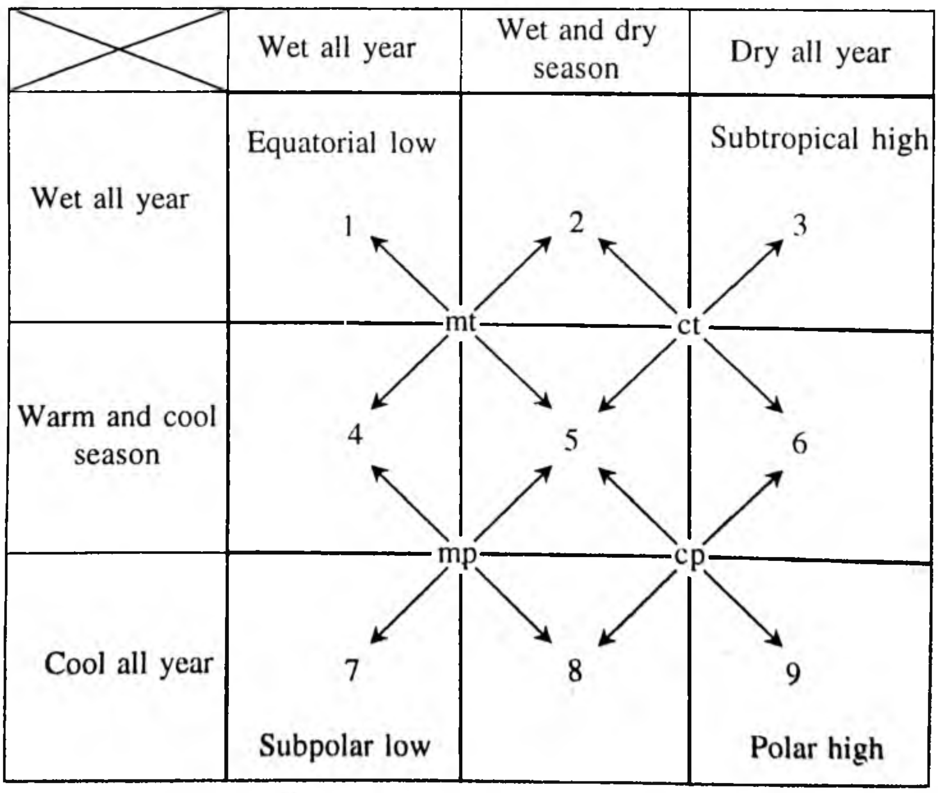


Fig. 13.1 : Schematic presentation of nine basic types of world climates. After : J.E. Oliver and J.J. Hidore, 2003.

Out of these 9 climate types and their regions four types, numbering 1, 3, 7 and 9 (figs. 13.1 and 13.2) are characterized by almost absence of any seasonal variation in radiant energy (temperature), or moisture content in the year. 'Each of the four systems (climate types, fig. 13.2) is influenced

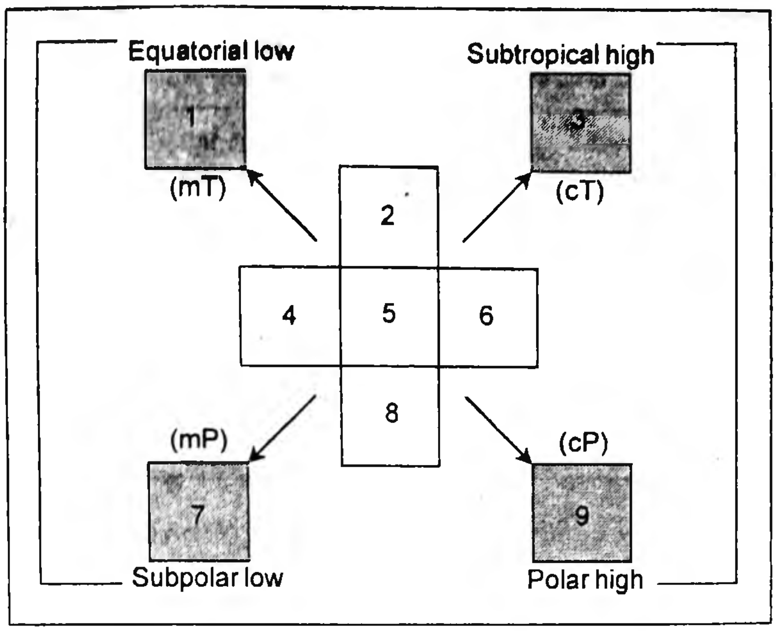


Fig. 13.2 : Four climatic regions numbering 1,3, 7 and 9 have little or no seasonal variation in temperature and moisture. Each of four climates is dominated by single air mass and is found in the core area of single semipermanent pressure system as outlined above. After : Oliver and Hidore, 2003.

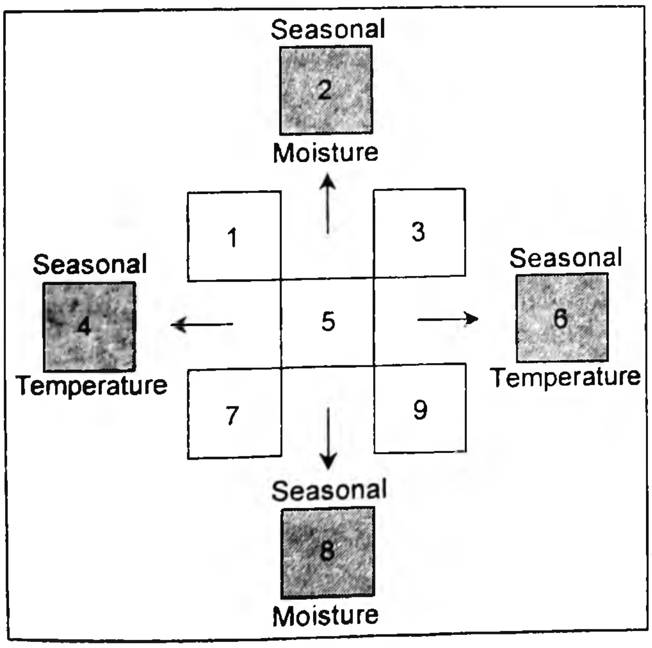


Fig. 13.3 : Climates nos. 4 and 6 are characterized by seasonal variations in temperature, nos. 2 and 8 by seasonal variations in moisture and the remaining no.5 is dominated by all the four major air masses and has middle latitudinal location. After : Oliver and Hidore, 2003.

primarily by one kind of air mass and each is associated with one of the four semipermanent pressure zones in the atmosphere' (Oliver and Hidore 2003) e.g. equatorial low pressure system, subtropical high pressure system, subpolar low pressure system, and polar high pressure system.

The four climate types (numbering 2, 4, 6 & 8) out of remaining five climate types (numbering 2, 4, 5, 6 and 8) are characterized by seasonal variations in either radiant energy (i.e. temperature) or moisture content in the air, or both. Climate nos. 4 and 6 are characterized by pronounced seasonal variation in temperatures i.e. warm and cool seasons, while the other two (nos. 2 and 8) climate types have marked seasonal variations in moisture content in the air, i.e. wet and dry seasons. The characteristics of climate numbering five in figs. 13.1, 13.2 and 13.3 depend on the influences of all the four major air masses and is marked by maximum seasonal variations.

Oliver and Hidore, based on their above model of air mass classification of world climates, have divided the world climates into 3 major groups and 9 climate types as follows (it may be mentioned that Oliver and Hidore model of classification of world climates is popularly known as **Air Mass Model**) :

	Wet ⟵⟶ Dry			
Hot	Tropical wet (equatorial)	Tropical wet and dry	Tropical desert	Group I
↕	Midlatitude wet	Midlatitude summer or winter dry	Midlatitude desert	Group II
Cold	Polar wet	Polar wet and dry	Polar desert	Group III

Fig. 13.4 : Climate types according to Air Mass Model : After Oliver and Hidore, 2003.

	Climate types	**Air mass control**
Group I	Tropical air mass dominated climates	
	1. tropical wet climate	maritime tropical (mT) air masses
	2. tropical wet and dry climate	maritime tropical (mT) and continental tropical (cT) air masses in wet and dry seasons respectively
	3. tropical dry climate	continental tropical air mass dominates
Group II	**Tropical air mass (in summer) and polar airmass (in winter) dominance seasonally**	
	4. mid-latitude wet climate	maritime tropical airmass in summer and maritime polar air mass in winter
	5. mid-latitude wet and dry climate	
	5 S summer dry climate	cT/mP air masses
	5 W winter dry climate	mT/cT air masses
	6. mid-latitude dry climate	cT/cP air masses sesonally
Group III	**Polar air masses-dominated climates**	
	7. polar wet climate	maritime polar (mP) air mass dominance
	8. polar wet and dry climate	seasonally dominated by mP/cP air masses
	9. polar dry climate	dominated by cP air mass

Source : adapted from Oliver and Hidore, 2003.

Oliver and Hidore have also depicted 9 climatic regions on the world map (fig. 13.5) which is reproduced in fig. 13.5.

They have further opined that each climate type as mentioned above may be divided into subdivisions on the basis of suitable criteria. As is evident from fig. 13.4, they have identified 3 major climate types e.g. tropical climates, mid-latitude climates, and polar climates. These major groups have been further subdivided as follows :

(1) **Tropical climates**

(a) tropical wet climate

(b) tropical wet and dry climate

(c) tropical dry (desert) climate

(2) **Mid-latitude climates**

(a) wet-hot summer climate

(b) wet-cool summer climate

(c) summer dry climate

(d) winter dry climate

(e) dry climate (all seasons)

(3) **Polar climates**

(a) wet climate

(b) we and dry climate

(c) dry climate

(4) **Mountain climate** (not described and subdivided)

13.5 COMPOSITE CLASSIFICATION

Composite classification of world climates is based on the common bases of both empirical and genetic approaches wherein observed data of climatic parameters and causes of the genesis of different climatic types are used for the classification. The main purpose of such classification is to present simplified and realistic picture of climates so that these can be easily understood and used for different purposes. The scheme of classification of world climates by G.T. Trewartha falls under this category of classification.

Classification of G.T. Trewartha

G.T. Trewartha, an American climatologist, made several revisions and modifications in the scheme of climatic classification of Koppen since 1930s and ultimately presented his simple scheme of climatic classification having a blending of both empirical and genetic schemes of classification of world climates. In fact, Trewartha's basic aim was to present a simple generalized and unambiguous scheme of the classification of world climates so that the major climatic types at world level could be easily and realistically identified and cartographically represented on world map. Thus, Trewartha's scheme is a compromise between purely empirical and genetic methods of climatic classification. He was fully convinced that the schemes should not be cumbersome and complex as were the schemes of Koppen and Thornthwaite. He was also opposed to produce large number of climatic types on the basis of statistical and quantitative parameters. That is why he recognized only a limited number of major climatic types. According to him, if required, several second and third-order subdivisions may be added within each major climatic type. Like other scientists he also made precipitation and temperature as the basis for his scheme of climatic classification. He identified 6 major climatic types of first order at world level and designated them as A,B,C,D,E,F, climates out of which B climates were determined on precipitation criteria while others were determined on the basis of temperature criteria.

1. Tropical Humid Climates (A Climates)

A climates or tropical humid climates are found in those low latitudes on either side of the equator which are characterized by high temperature and adequate rainfall throughout the year and absence of winter season. On the basis of variations in precipitation A climates are subdivided into (i) Af, (ii) Aw, and (iii) Am climates, (1) **Af climate** is tropical wet climate which extends upto 5^0 to 10^0 latitudes on either side of the equator and is characterized by adequate rainfall throughout the year. This is also known as tropical rainforest climate. There is no winter season as it is characterized by uniformly high temperature all the year round.

(ii) **Aw climate** is a tropical wet and dry climate characteried by uniformly high temperature throughout the year but there are more than two dry months. This climate is also known as **savanna climate** which is dominated by dry trade winds or subtropical anticyclones during winter season and by equatorial westerlies and intertropical convergences during summer season.

(iii) **Am climate** is monsoon climate which receives more thnn 80 per cent of annual rainfall during four summer monsoon months.

2. Dry Climates (B Climates)

The boundaries of B (dry) climates have been determined on the basis of precipitation variations. They extend from the outer boundary of A climates to the middle latitudes. B climates are characterized by high evaporation, loss of moisture through evapotranspiration exceeding the annual receipt of water gain from precipitation, large annual and daily ranges of temperature, extreme seasonal temperatures, very low and highly vari-

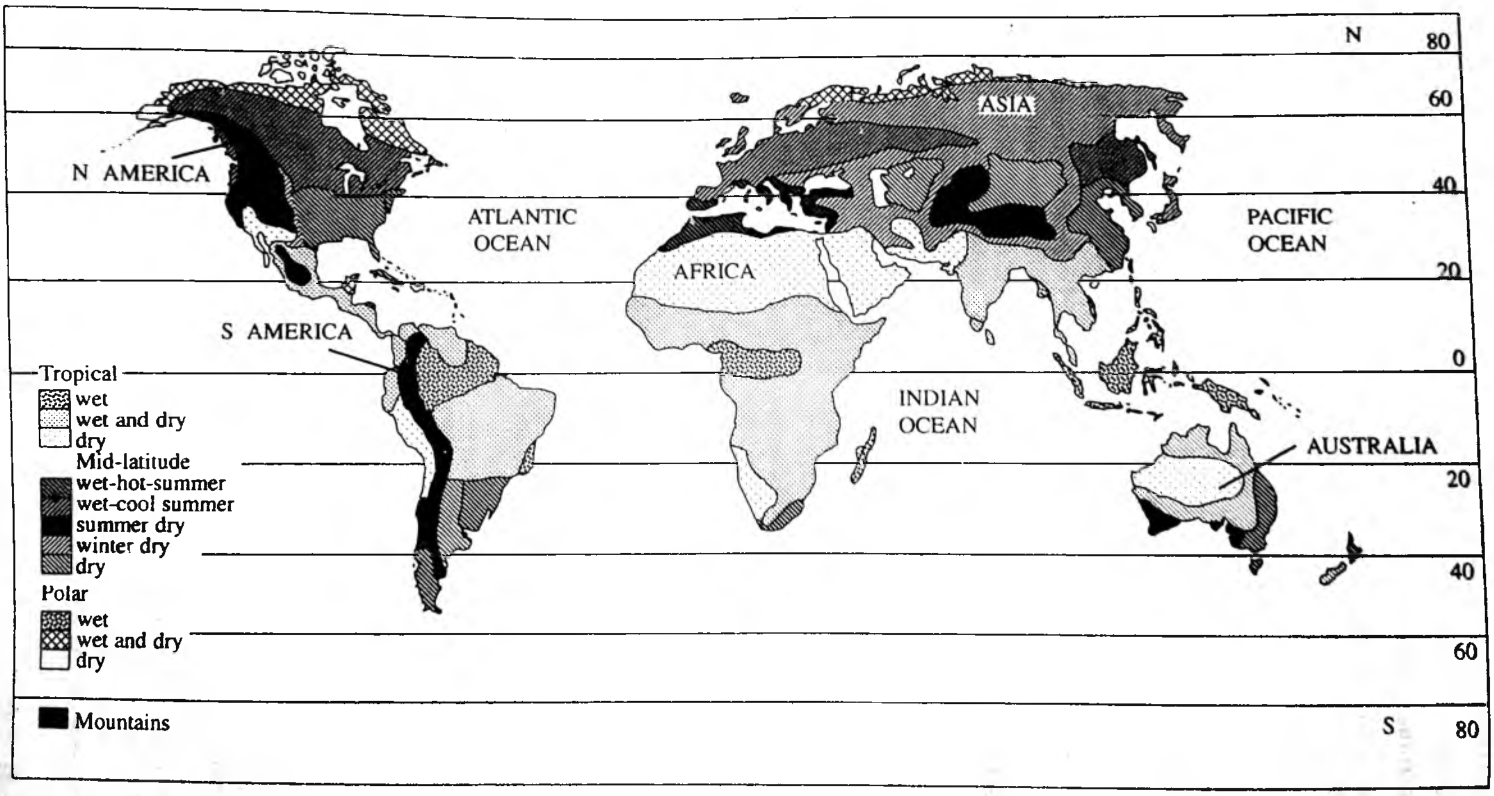


Fig. 13.5 : Climatic regions of the world according to Air Mass Model of Oliver and Hidore, 2003.

able annual precipitation, extremely low relative humidity, abundant sunshine and clear sky.

On the basis of aridity and annual average precipitation B (dry) climates have been divided into two climatic types e.g. (i) **arid** or **desert climate**-BW climate, and (ii) **semi-arid** or **steppe climate**-BS climate. On the basis of temperature variations arid (BW) and semiarid (BS) climates have been divided into 4 climatic types as follows :

(i) BWh climate	tropical-subtropical hot desert climate
(ii) BWk climate	middle latitudes or temperate and boreal cold dry climate
(iii) BSh climate	tropical-subtropical steppe or semiarid climate
(iv) BSk climate	middle latitudes or temperate and boreal steppe climate

The boundary between hot dry and cold dry climates is determined on the basis of 32^{0}F (0^{0}C) isotherm of the coldest month. Tropical-subtropical dry (BWh) and steppe (BSh) climates are dominated by dry trade winds and subtropical anticyclones resulting into constant dry conditions. At least 8 months of a year record average temperature above 10^{0}C. On the other hand, temperate cold dry (BWk) and cold steppe (BSk) climates are located on the leeward sides of the mountains in the interior of the continents and are dominated by cold anticyclones during winter season.

3. Middle Latitudes Wet Climates (C Climates)

The isotherm of 18^{0}C of the coldest month forms the equatorward boundary of C climates. On the basis of seasonal distribution of precipitation C climates are divided into 3 types e.g. (i) Cs climate (subtropical subhumid climate with dry summer, also known as Mediterranean climate), (ii) Ca climate (subtropical humid climate), and (iii) Cb climates (middle latitude marine climate). Cs climate, located on the western sides of the continents on the tropical margins of the middle latitudes, is affected by subtropical anticyclonic conditions in summers and by wet westerlies in winters. Ca climate (Cfw of Koppen), located on the eastern sides of the continents, receives precipitation in all seasons but summer months receive more rainfall than winter months (this climate is known as China type of climate). Cb climate is affected by westerlies throughout the year.

4. Microthermal or Temperate Climates (D Climates)

These climates are found in the areas of high middle latitudes which are affected by westerlies in summers and by polar winds in winters. The poleward and equatorward boundaries are determined by average temperatures of 10^{0}C for 4 months in the case of the former and for 6 months in the case of the latter. On the basis of temperature variations 'D' climates have been divided into 4 types e.g. (i) **Da climate** (continental humid climate with temperature of the warmest month above 25^{0}C), . (ii) **Db climate** (continental humid climate with temperature of the warmest month below 22^{0}C). (iii) **Dc climate** (subpolar climate, short summer season), and (iv) **Dd climate** (temperature of the coldest month less than –38^{0}C).

5. Boreal Climate (E Climate)

Boreal climate is located in the higher middle latitudes and is characterized by short and cool summer season, long and very cold winter season, very short frost free season, one to three months of a year having average temperature of 10^{0}C or more etc.

6. Polar Climate (F Climate)

Summer season is absent. Polar winds dominate throughout the year. These climates are found in the northern hemisphere only. No month of the year records average temperature above 10^{0}C. On the basis of temperature variations 'F' climates are divided into (i) **tundra climate** (Ft climate) and (ii) **icecap climate** (Ff climate).

Departures From Koppen's Classification

The Trewartha's scheme of climatic classification registers the following departures from the scheme of Koppen.

(1) In B climates Koppen used isotherm of 18^{0}C average annual temperature to differentiate the boundary between hot dry and cold dry (h/k boundary) climates while Trewartha used an

isotherm of 32°F (0°C) of the coldest month for the determination of h/k boundary.

(2) Koppen used the isotherm of -3°C (26.6°F) temperature of the coldest month for determining boundary between B and C climates while Trewartha selected isotherm of 32°F (0°C) for the purpose.

(3) Koppen divided C climates on the basis of seasonal distribution of precipitation into 3 types e.g. (i) Cs (summer dry), (ii) Cw (winter dry), and (iii) Cf (no dry season) but Trewartha divided C climates into (i) Cs, (ii) Ca, and (iii) Cb types.

(4) Koppen divided D climates on the basis of precipitation into (i) Dw and (ii) Df types while Trewartha divided them on the basis of summer temperature into (i) Da, (ii) Db, and (iii) Dd types.

Evaluation

As stated earlier Trewartha's scheme of climatic classification is very simple, unambiguous and a mixture of both empirical and genetic methods of climatic classification . It uses only two weather elements i.e. precipitation and temperature and avoids vigorous statistical and mathematical calculations in determining climatic type of a place and demarcating boundaries between two different climatic types. This scheme also includes the effects of land and water surfaces on the climate of an area. Trewartha's scheme became more popular among geographers because of its simplicity.

13.6 IMPORTANT DEFINITIONS

Concentration of thermal efficiency : The percentage of mean annual potential evapotranspiration accumulating in three summer months has been defined as the concentration of thermal efficiency by Thornthwaite.

Empirical classification : The classification of world climates based on observed meteorological data and observed effects of climates on vegetation, soils and soil forming processes, rockweathering, agricultural crops, human beings etc. is called empirical classification.

Genetic classfication : The classification of world climates on the basis of causes of climatic variations, genesis of different climates and their explanation is called genetic classification.

Geoclimate : Geoclimate, also known as ecoclimate or geographical climate or macroclimate involves the consideration of climatic characteristics of very large area covering a horizontal distance of more than 20 kilometers (it may be several hundred kilometers) and vertically extending from the ground surface to more than 6 kilometers upward in the atmosphere.

Hekistotherms : Hekistotherms represent such groups of plants which thrive on almost ice covered arctic and polar areas, say tundra. There is perfect relation ship between vegetation and soil moisture.

Megatherms : Megatherms represent such plants which thrive on high temperature, high humidity and precipitation throughout the year e.g. equatorial rainforests.

Mesotherms : Mesotherms represent such groups of plants which depend on moderate temperature and precipitation, e.g. plants in Miditerranean climate.

Microtherms : Microtherms represent such plants which can survive in the region having temperature of the coldest month below -3°C but the average temperature of the warmest month remains above 10°C but below 22°C, e.g. boreal deciduous and steppe vegetation.

Moisture index : Moisture index refers to moisture deficit or surplus in an area.

Precipitation effectiveness : Precipitation effectiveness or precipitation efficiency refers to only that amount of total precipitation which is available for the growth of vegetation.

Xerophytes : Xerophyte represents such groups of plants which thrive in hot and arid climate and can withstand extreme aridity, e.g. vegetation of hot dry deserts.

14

CLIMATIC TYPES AND BIOMES

Generally, world climates are divided into 3 major groups, as discussed in the preceding chapter, namely (1) tropical climates, (2) middle latitudes climates, and (3) polar and highland climates. These major groups of climates have been subdivided into several types of second and third orders by different scientists on different bases. These have been explained in much details in the preceding chapter. This chapter includes the consideration and description of well established and commonly agreed climatic types wherein each climate type has been discussed involving the following aspects : location, temperature, air pressure and winds, precipitation (cloudiness, distribution, rainfall regime, variability of rainfall), and effects of climate on natural vegetation. Besides, characteristic features of biomes associated with definite climatic type and region have also been described. **Biome** is, in fact, a large natural ecosystem wherein we study the total assemblage of plant and animal communities. According to I.G. Simmons (1982) 'the most extensive ecosystem unit which it is convenient to designate is called biome'. Though a biome is studied in terms of its plants and animal communities but it also conforms with a definite distributional patterns of soils and climates. The world is divided into three major groups of biomes, namely (1) tropical biomes, (2) temperate biomes, and (3) tundra biomes. These are further divided into 10 biomes of second order and 21 biomes of third order (table 14.1)

It may be mentioned that while describing the characteristic features of climatic type the discussion of its biome characteristics is not required at all. Here, the characteristics of biomes associated with particular climates have been discussed only to demonstrate the influences of climates on plants and animals and interactions between abiotic and biotic components of the ecosystems. It may also be pointed out that the description of a biome includes discussion on location, climatic characteristics, vegetation, animals, and anthropogenic modification of a biome but here, while discussing biome, the description of location and climatic characteristics have been omitted as these have been included in the description of climatic types.

Table 14.1 : Types of Biomes

Biomes of the First Order (based on climatic zones)	Biomes of the Second Order (based on vegetation)	Biomes of the Third Order
1. TUNDRA BIOME	(i) Arctic Tundra Biome	
	(ii) Alpine Tundra Biome	
2. TEMPERATE BIOME	(i) Boreal Forest Biome (Taiga forest Biome)	(a) North American Biome
		(b) Asiatic Biome
		(c) Mountain Forest Biome
	(ii) Temperate Deciduous Forest Biome	(a) North American Biome
		(b) European Biome
	(iii) Temperate Grassland Biome	(a) Russian Steppe Biome
		(b) North American Prairie Biome
		(c) Pampa Biome
		(d) Australian Grassland Biome
	(iv) The Mediterranean Biome	(a) Northern Hemispheric Biome
		(b) Southern Hemispheric Biome
	(v) Warm Temperate Biome	
3. TROPICAL BIOME	(i) Tropical Forest Biome	(a) Evergreen Rainforest Biome
		(b) Semi-evergreen Forest Biome
		(c) Deciduous Forest Biome
		(d) Semi-deciduous Forest Biome
		(e) Montane Forest Biome
		(f) Swamp Forest Biome
	(ii) Savanna Biome	(a) Savanna Forest Biome
		(b) Savanna Grassland Biome
	(iii) Desert Biome	(a) Dry or Arid Desert Biome
		(b) Semi-arid Biome

14.1 EQUATORIAL CLIMATE OR TROPICAL RAIN FOREST CLIMATE (Af)

Location

Equatorial type of climate, also known as **tropical rainforest wet climate** or simply Af climate, is located upto 5^0 to 10^0 latitudes on either side of the equator (fig. 14.1) but at some places it extends upto 15^0-25^0 latitudes mainly along the eastern margins of the continents. This climatic zone is subjected to seasonal shifting due to seasonal shifting of pressure and wind belts consequent upon the northward and southward migration of the sun. The equatorial climate is characterized by two major properties e.g. (i) uniformly high temperature throughout the year, and (ii) uniformly adequate rainfall throughout the year received through convective mechanism. The equatorial climate is found in the following localities-(i) the Amazon Basin in South America, (ii) the Congo Basin in Africa, (iii) Guinea coast in Africa, (iv) much of the Indo-Malaysian Region mainly in Java, Sumatra, Borneo, Malaysia, Singapore and New Guinea, (v) Philippine Islands, (vi) eastern central America (parts of Panama, Coastarica, Nicargua, Honduras, Guatemala etc.), some islands in the Caribbean Sea, western Columbia and eastern Madagascar.

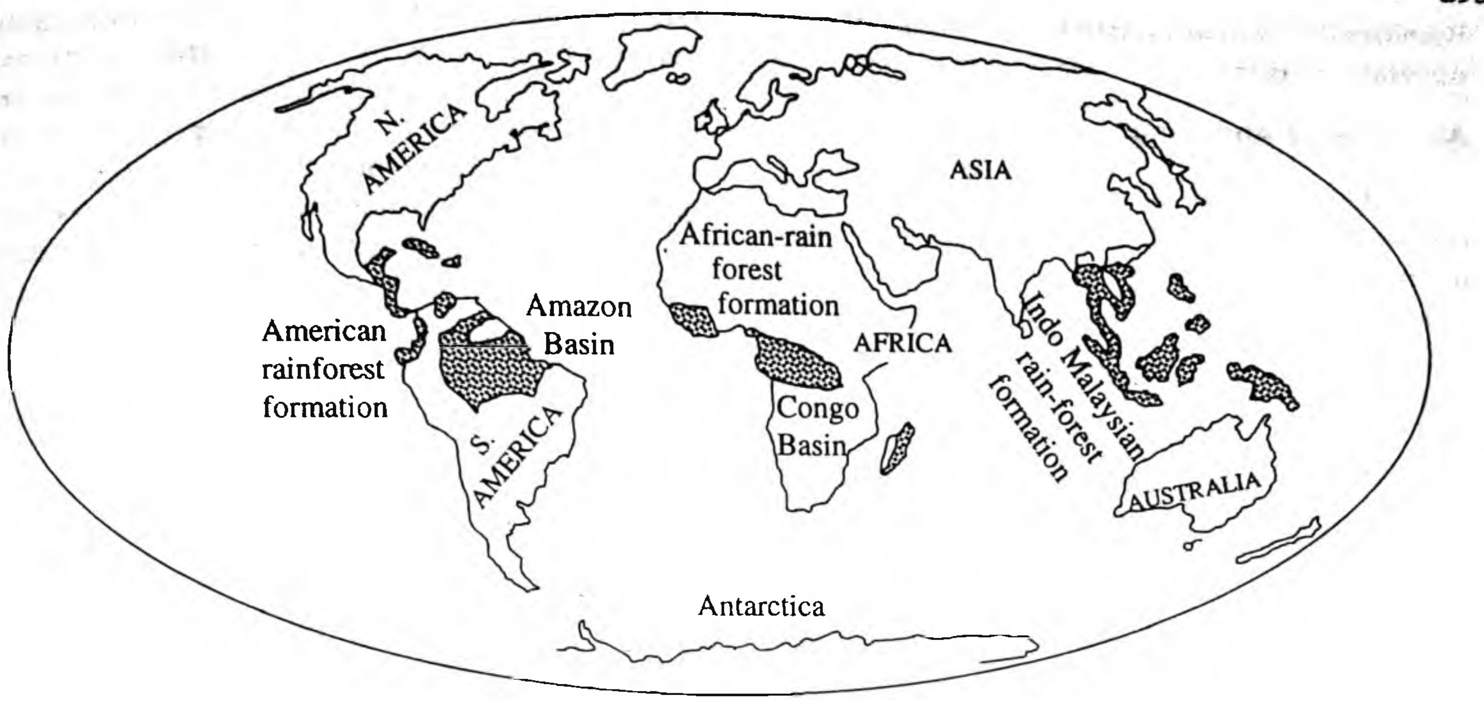


Fig. 14.1 : Location of equatorial rainforest (Af) Climate.

Temperature

Since mid-day sun is almost overhead throughout the year and there is little difference between the lengths of day and night during the year and hence the equatorial region receives maximum amount of insolation which causes uniformly high temperature throughout the year as the average monthly temperature is always more than 18°C. The mean monthly temperature of most of the places ranges between 24°C and 27°C. Mean annual temperature is around 20°C but the maximum temperature of the year touches 30°C. The mean annual range of temperature of island areas ranges between 0.5°C and 1°C but other areas record annual ranges of temperature between 2°C to 3°C. The annual range of temperature of Iquitos (located in Peru falling in the Amazon Basin, 4°S of the equator) is 2°C. Similarly, Akassa (located at the mouth of the Niger River, Africa) records annual range of temperature of 2°C but Para records less than 2°C as annual range of temperature. The annual range of temperature becomes minimum over the oceans. For example, Jaluit, located on Marshall Island in the central Pacific Ocean records annual range of temperature of only 0.4°C. Thus, uniformly high temperature of the equatorial regions, though lower than the temperature of the hot desert climate, becomes unpleasant and injurious to human beings because of its uniformity and monotony.

The daily range of temperature varying between 5°C and 10°C is usually far greater than the annual range of temperature. Usually, mid-day temperature rises to 29°C-34°C and comes down to 21°C-24°C during nights. Thus, relatively low nocturnal temperature becomes uncomfortable to local people. This is why nights of the equatorial regions are called **winter of the tropics.** The annual range of temperature of Bolobo of the Belgian Congo is 1°C but the daily range becomes 9°C. Belam city records daily maximum and minimum temperatures as 32.8°C and 20.1°C respectively thus registering diurnal range of 12.7°C. Similarly, Santaram of the Amazon Basin records 35.5°C and 19.5°C as maximum and minimum daily temperatures and thus diurnal range of temperature becomes 16.0°C. The daytime temperature becomes oppressive and unbearable due to high relative humidity, weak air circulation, bright sunlight etc. The inhabitants of the equatorial regions are so used and habitual to uniformly high temperatures throughout the year that they feel immediately even a slight fall in temperature. They feel cold if temperature falls below 20°C and they burn wood to ward off relative cold (though there is no winter season).

Air Pressure And Winds

Thermally induced low pressure belt develops around the equator due to uniformly high temperature throughout the year but the pressure gradient is so low that strong air circulation is not possible. Thus, the equatorial region lies in the belt of calm and doldrum characterized by light and variable winds. The surface air is heated, becomes light and moves upward thus forming convective currents. On the ground surface the winds uniformly spread laterally due to more or less uniform air pressure. The discontinuous belt of doldrums characterized by equatorial westerlies is found along the equator. The convergence of trade winds coming from the subtropical high pressure belt forms intertropical convergence (ITC) which is associated with atmospheric disturbances (cyclones). The winds become strong with thunderstorms. Strong winds give temporary relief from sultry weather. Temperature is lowered due to arrival of Harmattan winds in the nights in the Guinea coast and thus the pleasantly cooling effect of Harmattan gives comfort to human bodies. Sea breezes penetrate upto 48-96 km inland in the coastal areas and thus brings pleasant weather through their cooling effects. This is why coastal areas in the equatorial regions are comparatively better suited for living than the interior areas.

Precipitation

Equatorial regions receive rainfall throughout the year and thus there is no dry season. Average annual rainfall exceeds 200 cm to 250 cm. Even the driest month of the year receives rainfall more than 6 cm. Iquitos (Peru), Akassa and Ocean Island receive 261 cm, 366 cm and 213cm of rain per annum respectively. Though most of the rainfall occurs through convective mechanism but wherever mountain barrier becomes effective the amount of rainfall increases substantially. For example, annual rainfall reaches 1000 cm in the foothill zone of Cameroon Mountain in Africa. Most of the annual rainfall in the equatorial region is received in the form of convectional rainfall (see types of rainfall in chapter 9). The strong daily vertical convective mechanism due to intense heating of ground surface because of high amount of insolation, horizontal convergence of trade winds forming intertropical convergence, a fairly large number of atmospheric disturbances (cyclonic storms) and thunderstorms yield heavy rainfall daily throughout the equatorial regions.

Distribution : inspite of high rainfall throughout the year there is no uniform spatial distribution of rainfall in all parts of equatorial climatic region. Though no month goes dry but definitely some months of the year receive more rainfall than the other months. Thus, the months having more rainfall are called **wet months** while the months receiving less rainfall are known as **less wet months.** If the temporal distribution of rainfall in the equatorial regions is considered carefully it appears that there are two periods of maximum rainfall and two periods of minimum rainfall in a year. Normally, April and November receive maximum rainfall but the period of maximum rainfall varies spatially. For example, Lagos receives maximum rainfall in May, June and July amounting to 100 cm whereas October records 25cm of rainfall.

Cloudiness : equatorial climate is characterized by fairly large amount of cloudiness throughout the year. Generally, cumulus type of clouds dominates daily weather conditions. On an average, there is about 60 per cent cloudiness daily. The maximum amount of cloudiness is found between 3 and 4 P.M. daily because of maximum convective activity during this period but the sky is generally clear in the morning and at night. Though daily period of cloudiness is less in comparison to high middle latitude areas dominated by temperate cyclones but there is strong heavy downpour due to convective mechanism and resultant convectional rainfall.

Rainfall regime : equatorial rainfall is convectional in character wherein there is daily heavy downpour from cumulo-nimbus clouds. The sky is usually free from clouds in the early morning. As the sun rises above the horizon, the amount of insolation received at the ground surface increases and hence air temperature also increases accordingly. Air is heated, becomes light and moves upward and thus becomes unstable which causes convectional system. The ascending air cools at dry adiabatic lapse rate (10°C per 1000m) and the air soon becomes saturated and condensation level is reached. Clouds are formed. In the beginning they are cumulus and few in number but as the day advances, humidity increases due to increasing evaporation, the clouds are thickened and darkness increases. By afternoon the whole sky becomes overcast with thick cumulo-nimbus clouds. Thus, heavy rain starts with lightning and cloud thunder. As the day draws towards evening the rain becomes slow and weak and it completely stops by evening, clouds are cleared and weather becomes pleasant for some time. The aforesaid mechanism is repeated daily. Some time, this rhythmic daily mechanism is interrupted as rains continue uninterruptedly for several days. Continuous rains for 40 hours have been reported in Ivory Coast (Africa). The most characteristic feature of equatorial rainfall is that it is usually associated with strong thunderstorms as about 75 to 150 rainy days are associated with them.

Variability of rainfall : inspite of very high mean annual rainfall there is temporal variability in the amount of rainfall and this variability is more than the variability of temperature. The crops grown in this climatic region are such that they require more moisture and thus the year having little less than average annual rainfall is termed as a drought year because the crops are damaged. Though the word drought is unfamiliar in equatorial climatic region but some times brief drought conditions are created. There is also variability of rainfall within a year. For example, Belem (in the Amazon Basin) receives average annual rainfall of 239 cm and March receives more rainfall than other months. March has 28 rainy days against 10 rainy days in November. It may be concluded that rainfall in equatorial rainforest climate is adequate enough to support field crops and luxurious dense forests. Most of the rains is intercepted by forest canopy and thus reaches ground surface slowly in the form of aerial streamlets through leaves, branches and stems of trees and thus there is maximum infiltration of rainwater. Recent clearance of rainforests in equatorial regions in general and in Amazonia in particular has converted once forest-convered surface into a bare ground surface which is subjected to accelerated rate of soil erosion due to daily heavy rains.

Effects of Climate on Natural Vegetation

The tropical rainforest or equatorial climatic region accounts for the largest number of plant species and luxuriant growth of natural vegetation due to high temperature and high rainfall throughout the year. The climatic region is characterized by broad-leaf evergreen dense forests comprising valuable trees such as mahogany, rosewood, coconut, palm, avony, cincona, plaintain, bamboos, wild rubber, sandal wood etc. The number of tree species is so large and their diversity is so great that one hectare of land in the equatorial region accounts for 40 to 100 species. It may be pointed out that tree species account for 70 per cent of the total plant species of the tropical evergreen forests. **Creepers** or **climbers** are the second important members of the rainforests. The creepers comprising (i) climbers of lower strata, (ii) long woody climbers known as **'lianas'**, and (iii) **epiphytes** are so circuitous and highly irregular in form that it becomes difficult to find out their actual length. "They ramble through the forest, scaling the highest emergent trees and frequently looping down to the ground and then ascending further sections of the forest" (Furely and Newey, 1983). The climbers so greatly bind several trees and plants together that the accessibility in the forest cover becomes almost zero.

The vertical stratification of vegetation community consists of 5 layers or strata viz. (i) **first** or **top layer** or **dominant layer** representing the canopy of tallest trees (30 to 60m in height), (ii) **second layer** or **co-dominant layer** (25m to 30m in height), (iii) **third layer** of smaller trees (12m to 20m in height), (iv) **fourth layer** of shrubs (5m in height), and (v) **ground layer** of herbaceous plants and ferns.

14.1.1 TROPICAL RAINFOREST BIOME

The location and climatic conditions of rainforest biome has already been described in the previous section 14.1, while dealing with equatorial or tropical rainforest climate. Here only species (vegetation and plants) characteristics, ecosystem productivity and human interactions are discussed.

Plant Community and Structures

The tropical evergreen rainforest biome accounts for the largest number of plant species. Though there is almost uniformity and similarity in the life forms and the structure of the plants in all parts of this biome but there is much variation in the composition of plant species. There are numerous species of plants in the various parts of the tropical evergreen rainforest biome. For example, 6000 to 7000 species of flowering plants in the western Africa (Congo Basin); 20,000 species of flowering plants but quite different from the western Africa in Malaysia; 40,000 species of flowering plants in Brazil and 2000 species of flowering plants in Panama Canal Zone have been identified. It will be virtually impossible to present all the species of plants by names if all the species of plants of the tropical evergreen rainforest biome become known to the botanists. There is close relationship between evergreen nature of plant communities and temperature and moisture conditions of equatorial rainforest climate wherein high temperature and abundant rainfall throughout the year support luxuriant growth of plants and the competition among the plant communities to receive sunlight has been responsible for full stratification of vegetations in this biome.

Tree is the most significant member of the tropical evergreen forests. The number of tree species is so large and their diversity is so great that one hectare of land in the equatorial region accounts for 40 to 100 species of trees. It may be pointed out that tree species account for 70 per cent of the total plant species of the tropical evergreen rainforests. **Creepers** or **climbers** are the second important floral members of the rainforests. These belong to the category of **vines** and range in form from fine string-like stems to massive cable-like forms. These creepers are so circuitous and highly irregular in form that it becomes difficult to find out their actual lengths. 'They ramble through the forest, scaling the highest emergent trees and frequently looping down to the ground and then ascending further sections of the forests. In the constant struggle for light, climbers have developed this mechanism for reaching the high insolation areas with the investment required for a large supporting biomass' (P.A. Furely and W.W. Newey, 1983). The climbers, thus, so greatly bind several trees and plants together that the accessibility in the forest cover becomes almost zero. This typical structural form of the tropical evergreen rainforest has also affected the form of animal life (to be discussed in the succeeding section). It may be pointed out that the tropical rainforests account for 90 percent of all climbing species.

Climbers are divided into two major groups as presented by P.W. Richards (1952) e.g. (i) climibers of the lower strata of the forests include herbaceous plants and (ii) long woody climbers known as **lianas** are found in all strata (right from the ground stratum to the uppermost stratum of forest canopy) of the forests. Lianas are the most significant members of the climbers or creepers. The lianas are characterized by thickly woody stems of 20 cm diameter or even more, longer lengths upto 240 m or even more and large crowns of numerous leaves sometimes resembling the crowns of trees. Besides, (iii) a third type of tropical climbers has been also identified i.e. the **epiphytes** which do not have their roots on the ground surface, rather these are evolved on the trunks, stems, branches and leaves of trees, shrubs and herbs, climbers etc. The epiphytes live in almost all the strata or layers of the forests and they do not require climbing ability as they grow upward and reach the uppermost canopy of the forest in search of sunlight. These epiphytes provide certain habitats to micro-organisms such as planarians, earthworms, snails, woodlice, millipedes, centipedes, termites, ants, grasshoppers, earwigs, scorpions, snakes, tree frogs, lizards and host of insect larvae.

It may be pointed out that the aforesaid two major members of the tropical rainforest biome viz. trees and climbers are autotrophic green plants which manufacture their own food through the process of photosynthesis but there are other numerous parasite and saprophyte plants in this biome.

Vertical Stratification

The vertical stratification of vegetation community means the composition of plant assemblages from the soil surface or ground surface to the upper most forest canopy. Thus, the different strata of the vertical profile of plant community in a given region represent different layers of habitat of different plant groups. 'Stratification results from competition between species for favourable locations which, in turn, exerts control over micro-climate and other factors affecting the habitats of plants and animals' (P.A. Furley and W.W. Newey, 1983). There are five layers or strata from the ground surface to the uppermost canopy of the tropical evergreen rainforests out of which three upper layers consist of trees.

(i) **First** or **top layer (stratum)** represents the uppermost canopy of the tallest trees of the forests. The top surface of the uppermost stratum is like an umbrella but the level of the top surface is not uniform, rather it is discontinuous and wavy in character. This layer receives maximum amount of sunlight and intercepts the rain drops. The height of the topmost layer ranges between 30 m and 60 m. This layer is also called as **dominant layer.**

(ii) **Second layer** is formed below the first and uppermost layer of the forest canopy at the height of 25m to 30m. It is also called as the **codominant layer** or the **second dominant layer.** The upper crown of this layer is mopshaped.

(iii) **Third layer** is formed of lower and smaller trees, the crown of which is the height of 15-20 m from the ground surface. The trees of this layer have a typical characteristic of their leaves in that they (leaves) are much larger than the leaves of the aforesaid first two layers because of the fact that these larger leaves can trap more sunlight which is very low in this layer.

(iv) **Fourth layer** represents the shrub layer which is below the aforesaid three layers. This layer is not continuous rather it is fragmented and sporadic in nature. This layer also includes the saplings but these are not permanent members of this layer because after growing they reach the upper layer. This **herbaceous** or **shrub layer** also includes some pygmy (dwarf or stunted plants and trees) trees but of less than 5-m height. The crown of this layer is usually 5m from the ground surface.

(v) **Fifth** or **lower ground layer** represents the plants growing at the ground surface but seldom gains height of more than a metre or two. This layer is dominated by herbaceous plants and fern. These herbaceous plants do not form dense cover and have fewer species because the absence of light does not allow much growth of herbaceous plants.

Animal Life

There are some unique characteristics of animals of the tropical evergreen rain forest biome which are not observed in other biomes e.g. (i) There is regular growth of plants throughout the year and therefore there is regular and constant supply of abundant food for the animals, with the result they have not to migrate for food. In other words, the animals of the tropical evergreen rainforest biome are least mobile. (ii) The forest is full of animal activities throughout 24 hours i.e. throughout day and night because animals of different species live in the various vertical strata of the forests. Some animals are active during day time while others are active during nights. It is very unique but interesting feature of the rainforests that there is always hue and cry which makes this biome alive.

It may be pointed out that the vertical stratification of the rainforests which are themselves the outcome of climatic conditions of the biome, has largely affected the life-forms of animals living in the different layers (strata) of the forests. Most of the animals are **arboreal** (tree living) and thus they have been provided additional feature by the nature to climb the trees like claws, adhesive pads, fingers, toes and several clinging mechanisms. Some animals have developed the ability to glide in the air e.g. fox, tree frogs, squirrels, tree snakes etc. The ground animals have to pass through the dense and thick covers of trees, shrubs and climbers and thus they have acquired special qualities to make their ways through the forests viz. (i) mammals have generally larger and sturdy bodies so that they can move by pushing thickets of plants away. Such animals include chimpanzee, gorilla, bison, African elephant, ocapi, leopard, numerous genera of pigs etc. (ii) Some ground animals are very small in size but are very much mobile and clever so that they can pass through dense vegetation. (iii) The third category of ground animals includes hidden small organisms belonging to the group of cryptozoic animals. Such organisms live beneath stones, logs, dead branches of trees, parts of trees, litters of leaves etc.

The number, density and diversity of animals in the tropical evergreen rainforest biome increase from the ground layer towards increasing strata (layers) upward because of the fact that food supply also increases upward from the ground stratum due to increasing trend of sunlight in the same direction. It may be remembered that the green plants manufacture their food through the process of photosynthesis which requires sufficient amount of sunlight. It is obvious that the vertical stratification of the rainforest has given birth to well organized vertical stratification of animals. J.L. Harison (1962) has identified the following strata of animals and their important members from the uppermost stratum to the ground stratum:

(i) **Upper air animal community** : The upper surface of the canopy of the topmost stratum of the rainforest is dominated by insectivorous birds and bats but a few species are also carnivores. These birds belong to the category of fast flying species such as Asian falconet, swifts, seviftlet etc.

(ii) **Main canopy animal community** includes those birds and fruit bats which live in the canopy of the tallest trees forming the uppermost stratum. The important animals of the topmost canopy of the Amazonian rainforest are toucans, parakeets, barbets, cotingas, curassows, bill birds etc. A few small mammals, such as squirrels, herbivorous monkeys etc. are also found in the topmost stratum.

(iii) **Middle-zone flying animal community** includes mostly flying birds and insectivorous bats.

(iv) **Middle-zone climbing animal community** : The animals of this zone have various climbing mechanisms and they reach the topmost stratum through the stems and branches of trees and climb down to the ground stratum. These belong to both categories of carnivorous and herbivorous animals. Squirrels and civets are the important members of rodents which belong to the category of mammals. The binding circuitous and criss-crossing networks of various types of climbers facilitate easy movement of these climbing animals through all the vertical strata. These creepers also provide ideal habitats for these animals.

(v) **Large ground animal community** includes mostly animals but there are also some birds in the ground stratum. These animals have large but sturdy bodies and lack in climbing qualities and mechanisms. The herbivorous large animals are few in number, important being mouse, deer and cassowaries. Numerous members of pig family feed on roots, tubers and bulbs. It may be pointed out that the largest animals of the tropical rainforests are smaller in size than their counterparts in other open forests and grasslands because here the ground animals have to pass through dense vegetation cover and therefore they have been provided relatively smaller bodies but with great power and strength so that they can make their ways through dense forest. For example, the forest elephants of the rainforest biome are much smaller in size than the bush elephants and savanna elephants.

(vi) **Small ground animal community** includes small animals and micro-organisms. Most of these animals are insectivorous such as Argus pheasant, peacocks and numerous types of fowl such as Guinea fowl.

Ecosystem Productivity

The **primary productivity** of the tropical rainforest biome is the highest of all biome types of the world. It may be pointed out that the rainforest biome represents only 13 per cent of the total geographical area of the world but this biome accounts for 40 per cent of the total **net primary productivity** of the world. The average net primary production of this biome is 5000 dry grams per square metre per year. Wood constitutes the largest share of the total biomass and net primary production. There is maximum competition among the various members of vegetation communities of the tropical evergreen rainforest biome to get light.

Thus it is obvious that the plant species of almost similar characteristics and features can survive in this competition. This is the reason that inspite of largest number of plant species in this biome they have more or less similar life-forms.

The maximum ecosystem productivity is because of availability of sufficient sunlight and humidity (water) throughout the year. It may be remembered that these two are the primary requirements for photosynthesis by green plants. It is thus apparent that two basic parameters of high mean monthly temperature (radiant energy) and rainfall is fully reflected in the luxuriant growth of tropical evergreen rain forests and their maximum primary productivity

Human Interactions

The human interaction with tropical (equatorial) rainforest biome has not been harmonious rather it has been and is exploitative and destructive. Man has started to damage this biologically richest ecosystem through his economic activities. A sizeable portion of Amazonian rainforests has already been damaged through mining activity and industrial and agricultural expansion. The construction of large dams and reservoirs on the Amazon and its tributaries at the cost of rich forest cover has upset the ecological balance of the area. The powerful elite society and even the local Brazilean government is not paying any attention to the mass movement of the local aborigins against mass felling of trees.

14.2 TROPICAL MONSOON CLIMATE (Am)

Location

Monsoon climate is generally related to those areas which register complete seasonal reversal of wind direction and are associated with tropical deciduous forests but there are some departures from this close relationship and near correspondence between the regions of monsoon climate and tropical deciduous forests. Monsoon climate is found in the zone extending between 5^0 and 30^0 latitudes on either side of the equator (fig. 14.2). In fact, this zone comes under the domain of trade wind belt which experiences seasonal shifting due to northward and southward migration of the sun. Onshore winds blow for six months from warm tropical oceans towards the continents and offshore winds blow for another six months from land to the sea. The areas of monsoon climate are divided in the following categories.

(1) **True monsoon areas** include India, Burma (Myanmar), Pakistan, Bangladesh, Thailand, Combodia, Laos, North and South Vietnam, southern China, Philippines, and northern coastal area of Australia.

(2) **Areas of monsoonal tendencies or pseudo-monsoons** are found along the south-west coast of Africa including the coasts of Guinea, Sierra Leone, Liberia and Ivory Coast; eastern Africa and western Madagascar (Malagasy).

(3) **Areas of monsoon effects** include north-east coasts of Latin America e.g. east Venezuela, Guyana, Surinam, French Guyana, and north-east

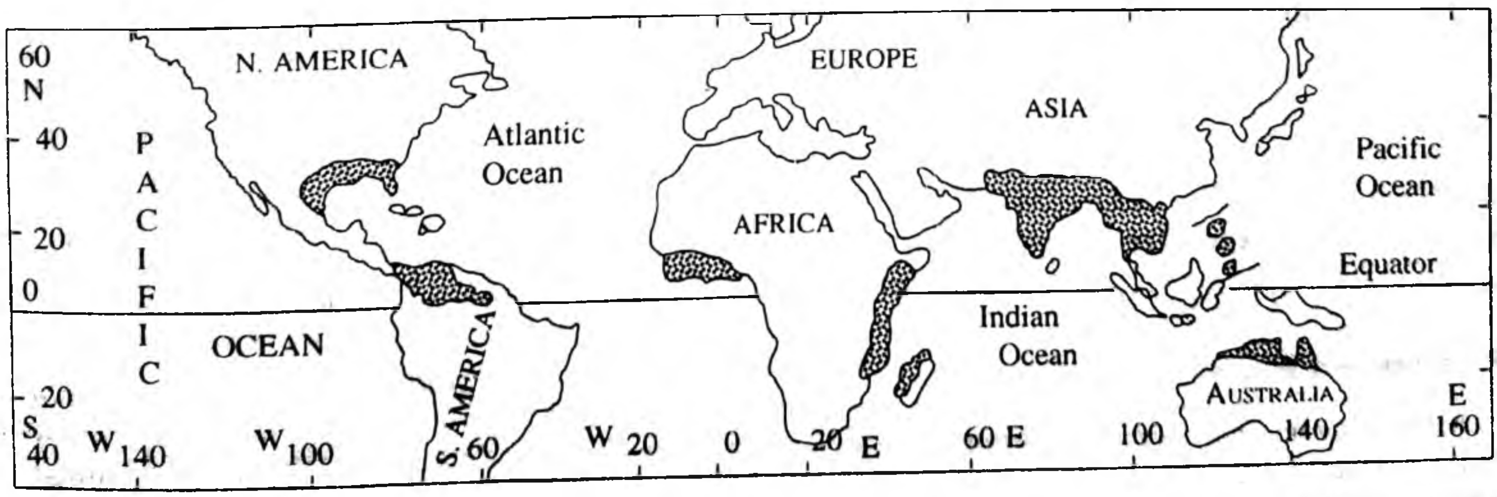


Fig. 14.2 : Distribution of monsoon climate areas.

Brazil. Besides, Puerto Rico and Dominican Republic in the Caribbean Island also enjoy mild monsoonal effect.

(4) **Areas of modified monsoon** are found in parts of central America and south-east USA.

Temperature

Though mean annual temperature is fairly high but summer and winter seasons are sharply differentiated due to northward (summer solstice) and southward movement of the sun (winter solstice). There are three main seasons in a year in Indian Subcontinent and surrounding monsoonal areas e.g. (1) dry warm summer season (March to June), (2) humid warm summer season (July to October), and (3) dry winter season (November to February). Average temperature of warm dry summer months ranges between 27°C and 32°C but maximum temperature ranges between 38°C and 48°C during May and June. Warm humid summer months record average temperatures ranging between 20°C and 30°C. The mean temperature during day in winter months varies from 10°C to 27°C. Annual range of temperature ranges between 2°C and 11°C and is controlled by nearness or remoteness of the sea (i.e. distance from the sea), continental and latitudinal influences. For example, annual range of temperature increases inland (5.3°C at Rangoon, 11°C at Mumbai, 18.4°C at Allahabad, 20.2°C at Agra). Similarly, diurnal range of temperature is low in the coastal areas but it increases inland. Diurnal range of temperature is much higher in dry summer season than in other seasons. For example, in the Ganga plains of India maximum temperature during day time may go as high as 44°C to 48°C and the minimum temperature during nights may come down as low as 20°C to 25°C, thus registering diurnal range of 23°C to 24°C. The temperature during May and June becomes exceptionally high due to prevalence of hot winds locally known as loo.

The monthly average temperatures for 3 representative areas of monsoon climate are shown in table 14.2 e.g. Kolkata (India, true monsoon region), Dakar (Senegal, pseudo monsoon region), and Darwin (Australia, true monsoon region).

Table 14.2 : Monthly average temperature and rainfall for tropical monsoon climate

Months	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Kolkata, India													
Tem. (°C)	20	23	28	30	31	30	29	29	30	28	24	21	27
Rainfall (mm)	13	24	27	43	121	259	301	306	290	160	35	3	1582
Dakar, Senegal													
Tem. (°C)	21	20	21	22	23	26	27	27	28	28	26	25	24
Rainfall (mm)	0	2	0	0	1	15	88	249	163	49	5	6	578
Darwin, Australia													
Temp (°C)	28	28	28	28	27	25	25	26	28	29	29	28	28
Rain (mm)	341	338	274	121	9	1	2	5	17	66	156	233	1562

Source : Based on Oliver and Hidore, 2003

Air Pressure and Winds

Monsoon areas are affected by high and low pressure systems due to winter and summer seasons respectively. In fact, there is complete reversal of pressure gradients over Asiatic landmass because of northward and southward migration of the sun and consequent differential heating of the continent and adjoining oceanic areas. Due to southward migration of the sun after 23 September (autumnal equinox) high pressure centres are developed on the landmass of Asia during winter season while low pressure is developed in the southern Indian and Pacific Oceans, with the result pressure gradient is developed from land areas to the oceanic areas resulting into the outflow of surface winds from high pressure centres of the land areas towards oceanic low pressure areas. This wind system having north-east direction is called **winter monsoon** which is nothing more than the reestablished north-east trade winds which are displaced during summer season due to northward shifting of intertropical convergence (ITC) because of northward migration of the sun. These offshore winds are generally dry because they come from over the land areas but wherever they pass over the oceanic areas, they pick up moisture and yield rainfall when effectively obstructed. For example, north-east monsoon winds while passing over the Bay of Bangal pick up moisture and give rainfall in the coastal regions of Tamil Nadu during winter season. The pressure system is completely reversed during summer season when the sun registers northward migration after 21 March and becomes almost vertical over tropic of Cancer on June 21. Thus, thermally induced low pressure develops due to very high temperature over huge landmass of Asia. These low pressue centres are further intensified due to northward movement of intertropical convergence (ITC) upto 20^0 to 35^0N latitudes while high pressure centres are developed over southern Indian and Pacific Oceans, with the result sea to land pressure gradient is steepened and onshore winds are generated. These onshore winds are the south-west or summer monsoon winds which are moist as they pass over the sea surfaces.

According to the advocates of the concept of **thermal origin of monsoon** the north-east or winter monsoons and south-west or summer monsoons are originated due to differential heating of landmasses and oceanic areas during summer and winter seasons and resultant thermally induced high and low pressure areas. According to them the summer and winter monsoons are south-east and north-east trade winds. In fact, the south-east trades while crossing over the equator during summer season due to northward shifting of pressure belts caused by northward migration of the sun becomes south-westerly in direction according to **Ferrel's law.** Since these winds come from over the ocean, they become moist and give rainfall. According to the advocates of the **dynamic origin of monsoon** the belt of doldrums and North-Intertropical Convergence (NITC) are drawn over south and south-east Asia during summer season due to northward migration of the sun and thus **equatorial westerlies** of the belt of doldrums are also established over south and south-east Asia and thus they become south-west monsoons. The tropical disturbances (cyclones) associated with the intertropical convergence (ITC) yield copious rainfall. For detailed discussion on the origin of monsoon see chapter 7.

Precipitation

Monsoon regions receive most of their annual rainfall through cyclonic and orographic types of rains though convective mechanism also yields some rainfall. On an average, the average annual rainfall is around 1500 mm but there are much variations in the temporal and spatial distribution. Some times, a few areas receive less than 500mm of mean annual rainfall. Even the temporal distribution of rainfall within a single year is highly variable because more than 80 per cent of mean annual rainfall is received within 3 wet months of summer season (July, August, and September). Thus, the rainy season records much surplus water whereas dry winter and summer seasons have marked deficit water because dry seasons receive less than 25 mm of rainfall per month. There is maximum evaporation during warm dry summer months which results in desiccation of soils and marked reduction in soil water. This seasonal regime of annual rainfall gives deciduous character to the vegetations which shed their leaves during the transitional period between winter and summer seasons.

Most of the annual monsoonal rainfall is received through moisture laden south-west monsoon winds which come from over the ocean surface. The outbreak of monsoon generally occurs in India around mid-June. When these moisture laden monsoon winds strike the mountain barriers they give copious rains. This is why the western coastal plains of India receive more than 2500 mm of annual rainfall because the Arabian Sea Branch of monsoon winds are obstructed by the Western Ghats and hence they are forced to ascend and soon become unstable and saturated. The leeward sides of the mountains fall in rainshadow region because descending winds are adiabatically warmed and thus become stable and dry. This is why Mangalore, located on the windward side of the Western Ghats receives 2000 mm of annual rainfall whereas Bangalore, located on the leeward side receives only 500 mm of annual rainfall.

The eastern coast of Tamil Nadu and Andhra Pradesh receives much rainfall during winter season through north-east monsoons as they while passing over the Bay of Bengal, pick up sufficient moisture and yield rainfall. January and February are generally driest months in India but the Ganga plains receive some rains from westerly disturbances or temperate cyclones coming from Mediterranean Sea.

Variability of rainfall in terms of both amount and duration is the characteristic feature of monsoon climate. Secondly, monsoonal rainfall is basically cyclonic in character.

14.2.1 MONSOON DECIDUOUS FOREST BIOME

The location, distribution of monsoon climate and climatic characteristic features of monsoon deciduous forest biome have been described in section 14.2.

Plant Community and Structure

The number of plant species is less in the tropical deciduous forest biome than the tropical evergreen rainforest biome. Since the density of plants is also lower in this biome than the rainforest biome and hence there is comparatively less competition among the plants for getting sunlight. The height of most of the trees ranges between 12m and 30m. There are four strata or layers in the vertical structure of the tropical deciduous forests. The uppermost and the second strata consist of trees, the third stratum is formed by shrubs whereas the last and the fourth stratum or the ground stratum represents herbaceous plants.

Most of the trees are deciduous but the shrubs of the third stratum are evergreen. The trees are characterized by thick girth of stems, thick, rough and coarse bark and large hydromorphic leaves or small, hard xeromorphic leaves. The large hydromorphic leaves enable the tree to trap more and more rainfall during wet seasons but these large leaves are shed in dry periods to conserve moisture whereas small and hard xeromorphic leaves enable the trees to withstand dry weather and water deficiencies.

Though there are numerous climbers mainly **lianas** and **epiphytes** but their numbers are far less in the tropical deciduous forest biome than the tropical evergreen rainforest biome.

Sal (Shorea robusta) and teak trees of Indian deciduous forests form forest canopy but its shape is not like umbrella or cauliflower as is the case with the forest canopy of the rainforest biome. Bamboo is another important member of the Indian deciduous forest. Besides, there are numerous trees, climbers, shrubs and grasses which have spatial variations from one region of the tropical deciduous forest to the other region.

Animal Life

It may be pointed out that various dimensions of animal community of any habitat/ecosystem/biome including the number of species, their population and density, their life-forms and various activities, reproduction and various types of biological interactions and above all species diversity largely depend on the composition and structure, richness or poorness, total biomass etc. of vegetation communities of the concerned biome. It is a significant ecological principle that more the development of stratification of the vertical structure of the vegetation community of a biome and greater the number of plant species, the more will be the number of animal species, their total population and species diversity. This ecological principle holds good in the case of tropical evergreen rainforest biome as discussed earlier. But there are comparatively lesser number of animal species in the monsoon deciduous forest biome than the rainforest biome because of comparatively less developed vertical strata and hence less diversification of animal species.

The seasonal character of vegetation community in terms of dense vegetation cover, full development of leaves and their evergreen form during rainy months (wet summer season, July to September) and shedding of leaves, drying of herbaceous plants etc. during dry season mainly during dry warm season has affected and determined the seasonal behaviour of animal communities particularly breeding and migrating behaviour. In other words, the seasonal character of the monsoon deciduous forests has been responsible for the seasonal regime in the breeding and reproduction and migration of animals. For example, birds in east Africa breed twice during the two different seasons of a year. Indian dogs generally breed once a year mainly at the end of wet monsoon season (during October-November).

The animals of the tropical and sub-tropical dry deciduous forest biome range from very small animals (micro-organisms) to very large-bodied animals like elephants, horses, hippopotamus, ganda or rhinos, lions, forest buffalo together with a large population of birds of several species. This biome represents the largest number of domesticated mammals because of the development of agriculture. This biome also carries the largest number of human population of the world.

Man and Monsoon Deciduous Forest Biome

The tropical and sub-tropical monsoon deciduous forest biome is one of the most disturbed ecosystems of the world. The forests have been adversely affected by both natural and anthtropogenic processes. There are numerous cases of frequent forest fires every year kindled by either natural processes such as lightning or anthropogenic factors such as inadvertent actions of man (throwing of burning ends of 'bidi' or cigarettes by the herdsmen in the forests) or advertent and intentional actions of man (such as clearing of forests through deliberate burning for agricultural purposes under **jhum cultivation** which is very much prevalent in India) and large-scale grazing. The forests of the monsoon deciduous forest biome have been so rapidly destroyed within the last 50 years or so through the rapacious utilization of forest resources for commercial and industrial purposes and large-scale clearance through mass felling of trees for agricultural land that the vegetation cover has shrunk to a very critical size.

The rapid rate of deforestation has led to the initiation of several ecological and geological problems. Several species of precious animals have now become endangered species because of destruction of their natural habitats. For example, lions and tigers and even elephants have become endangered species in India partly because of deforestation and partly by mass hunting of these animals. Similarly, Indian rhinos are facing extinction because of their mass killing. The lions of Gir forest of Gujarat of India together with other animals like leopards, spotted deer, sambhar deer, Indian gazelle, nilgai, antelope, wild boar etc. are now endangered species because of enormous destruction of the Gir Forest Ecosystem. The rapid rate of deforestation in the monsoon lands mainly in India has caused accelerated rate of soil loss through rill and gully erosion, siltation of river beds and consequent recurrent severe floods in the alluvial rivers.

14.3 TROPICAL WET-DRY CLIMATE (Aw) SAVANNA CLIMATE

Location

The word **savanna** has been used for different meanings by various scientists e.g. the word **savanna region** has been used by the climatologists to indicate a particular type of climate i.e. tropical wet-dry climate (Aw climate of Koppen) as **savanna climate,** while the botanists have used the word savanna for a typical type of vegetation community of tropical regions characterized by the dominance of grasses. This climate is also called as **Sudan type of climate.** Savanna type of climate is located between 5^0-20^0 latitudes on either side of the equator (fig. 14.3). Thus, savanna climate is located between equatorial type of climate (Af) and semi-arid and subtropical humid climate. In other words, this climate is located between equatorial low pressure belt or rain producing intertropical convergence and subtropical high pressure belt. The most characteristic areas of savanna climate include the Llanos of Orinico Valley including Columbia and Venezuela, the Guiana Highlands, the Campos of Brazil (south central parts), and Paraguay in South America; hilly areas of Central America; southern part of Zaire, Angola, Zambia Mozambique, Tanjania, Uganda, and Central Rhodesia, all to the south of the Congo Basin, and central Nigeria, southern Kenya and Uganda, Central African Rupublic, Dahomey, Togo, Chad, Ghana, Ivory Coast and eastern Guinea in Africa; northern Australia and some areas of India (**the savanna of India is not the original and natural vegetation cover rather it has developed due to human interference with the original forest cover resulting into the development of widespread man induced grasslands).**

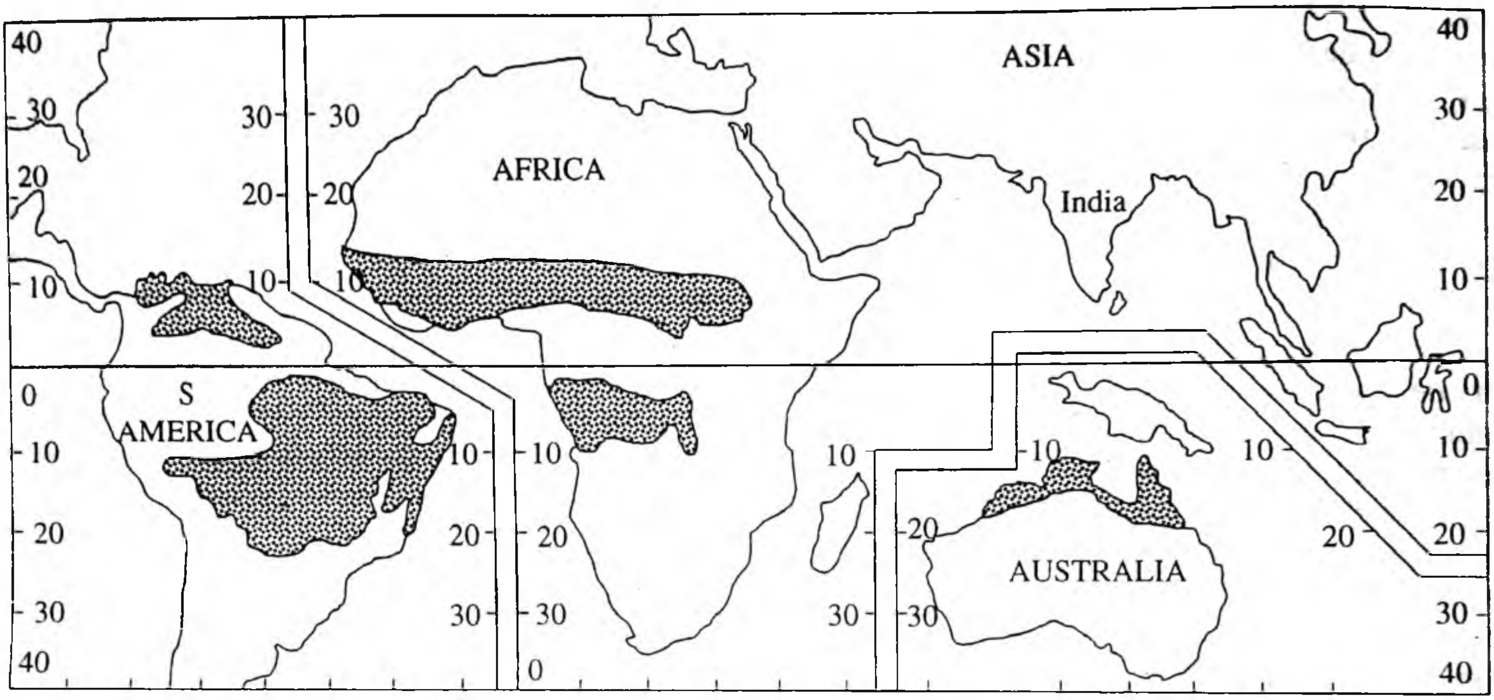


Fig. 14.3 : Location of Savanna climate.

Temperature

The Savanna climate is characterized by distinct wet and dry seasons, mean high temperature throughout the year (ranging between 24⁰C and 27⁰C), and abundant insolation. Temperature does not fall below 20⁰C in any month of the year. Thus, Savanna climate is similar to equatorial climate as regards temperature but the annual range of temperature ranging between 3⁰C and 8⁰C is greater than in the equatorial climate. There are three main seasons on the basis of the combination of temperature and humidity (though on an average there are only two seasons as referred to in the beginning but the dry season is further divided into warm dry season and cold dry season on the basis of temperature). (1) **Cold dry season** is characterized by high day temperature ranging between 26⁰C and 32⁰C but relatively low temperature during nights, usually 21⁰C. (2) **Warm dry season** is characterized by almost vertical sun's rays, high temperature ranging between 32⁰C and 38⁰C due to abundant insolation. (3) **Warm wet season** receives between 80-90 percent of total annual rainfall and thus records relatively lower temperature than warm dry season.

Air Pressure and Winds

The regions of Savanna climate are affected by low and high pressure systems in a year. Due to northward migration of the sun during summer solstice (21 June) the equatorial low pressure belt and doldurm are shifted northward and thus Savanna climate comes under the influence of **Inter Tropical Convergence** (ITC) which is associated with atmosperhic disturbances (cyclones) which yield rains. Due to southward migration of the sun during winter solstice (22 December) **Savanna** climatic zone comes under the influence of subtropical high pressure belt and thus anticyclonic conditions dominate the weather and bring dry conditions. The descending stable winds under anticyclonic conditions cause dry weather. Besides, the coastal areas are affected by local winds and sea breezes. Eastern coasts are influenced by trade winds. Strong and high velocity tropical cyclones dominate the weather conditions during warm season. It is apparent that the Savanna type of climate is induced due to the introduction of wet summer and dry winter seasons because of northward and southward migration of the sun respectively. Since the Savanna climate is located between equatorial wet and tropical dry climates and hence there is gradual variation in weather conditions away from the equator as the aridity increases poleward.

Rainfall

The average annual rainfall ranges between 100cm and 150cm but there is much pronounced variation in the spatial distribution of mean annual rainfall in different parts of Savanna climate mainly because of two factors viz. (1) distance from the equator, and (2) the nature of topographic features. For example, the Savanna region of Brazil, locally called as **Cerrado** having the average absolute relief of 1300m AMSL, records mean annual temperature and mean annual rainfall of 20^{0}C-26^{0}C and 75cm-200cm respectively. The **Llanos** of Columbia is characterized by mean annual rainfall of 200cm-400cm (near Andes Mountain), mean annual temperature of 22^{0}C, and maximum temperature of 32^{0}C. The Indian Savanna is characterized by the highest temperature (being 45^{0}C-48^{0}C in May and June) and lowest temperature (being 5^{0}C or even less during the month of January) of all the Savanna regions of the world and the mean annual rainfall well below 150cm, 80 to 90 per cent of which is received during a brief period of 3 months (July to September).

Since the Savanna climate is a transitional belt between humid equatorial and dry tropical climates and hence there is much variability in the amount and duration of rainfall at the wet (equatorward) and dry (poleward) boundaries. There is copious rainfall in the equatorward margins because of convergence of surface winds and convective mechanism of ascending unstable winds but at the poleward margins near-dry climate (BWh) is found and rainfall significantly decreases due to descending air and anticyclonic conditions. Here mean annual rainfall becomes as low as 25 cm. As the Intertropical Convergence (ITC) moves northward due to northward migration of the sun, thunderstorms begin to develop by March and the amount of rainfall increases in the following months. The Intertropical Convergence reaches its northernmost limit by August. Thus, rainfall continues to increase upto August and most of rains are received through tropical cyclones and thunderstorms. Rainfall decreases due to southward shifting of ITC and dry trade winds are re-established after November resulting into dry weather conditions. It is apparent that the period of wet weather decreases while that of dry weather increases as the distance from the outer limit of the equatorial climate increases. The amount of mean annual rainfall also decreases from east to west. Savanna climate is also characterized by high variability of rainfall as there may be so heavy and abundant rainfall in a particular year that floods are caused while the following years may receive so little rainfall that drought conditions prevail.

14.3.1 SAVANNA BIOME

The location, distribution and climatic conditions of Savanna biome have been discussed in the preceding section 14.3. Here, only vegetation community, animal community and man's impacts on savanna biome are discussed.

Vegetation Community

Though the general characteristics of typical Savanna vegetation are trees and grasses but the Savanna biome is, no doubt, dominated by grasses. The Savanna vegetation community has developed layered structure wherein three distinct layers have clearly developed.

(i) Ground layer (stratum) : is dominated by various types of grasses and herbaceous plants. The grasses, the most dominant vegetative member of the Savanna biome, are generally coarse, stiff and hard and of course perennials having the height of 80 cm but very long grasses reach up to 350cm

(3.5m) in height. The African elephant grass attains the enormous height of 500cm (5m). The leaves of these grasses are almost flat which are shed during dry season but they are regenerated during wet season. The Savanna grasses are usually tufted in structure and form. It may be pointed out that not all the grounds are continuously covered by Savanna grasses, rather there are frequent open patches which are devoid of grasses. The root systems of the Savanna grasses consist of lateral dense network of fine branches which penetrate into the depth of 2.5m in the soil cover. The important genera of the Savanna grasses are Hyparrhenia (elephant grass), Panicum, Pennisetum, Andropogon and African species Imperata cylindrica. The grasses bear deserted look during dry warm summer season but they become lush green again during humid summer season.

(ii) Middle layer consists of shrubs and very stunted woody plants.

(iii) Top or canopy layer is formed by trees of various sorts. The general characteristics of trees depend on the availability of water and moisture and therefore there is a great taxonomic variety of Savanna trees which are usually 6.12m in height. The Savanna trees have developed various unique characteristics to cope with the dry conditions of this biome. For example, there are a few species of trees which have developed such mechanisms which help them to reduce evapotranspiration from their leaves during warm dry season and enable them to remain green even during dry season of deficient water supply. On the other hand, there are such tree species which cannot withstand dry conditions and therefore they shed their leaves and bear the characteristics of deciduous trees. The roots of the Savanna trees have also developed according to the environmental conditions as they are very large which can penetrate into the soil and ground up to the depths from 5m to 20m so they can obtain water from groundwater even during dry season when the groundwater table falls considerably. The smaller plants and many herbaceous plants have special kinds of root systems characterized by root tubers and swellings so that they may preserve water which may be used by the plants during dry season, because the roots of these plants seldom reach the depth of more than 20cm in the soils and the coarse soils up to this depth become dry during dry season.

The trees form flattened crown or canopy but they are very sparsely distributed. Several branches come out from the stems which are mixed up with the middle layer. Some of the Savanna trees are fire resistant (**pyrophytic**) as they have thick bark and thick bud-scales. The Savanna biome is characterized by the monotony of tree species as there are very few tree species per unit area as compared to the tropical rainforest and tropical monsoon deciduous forest biomes. For example, baobab is the only significant tree from Tanzania to Senegal and the Savannas of Ivory Coast and Sudan are dominated by palm trees. The important tree species are Isoberlinia, the baobab and dom palm in African Savannas; species of Eucalyptus such as E. Marginata and E. Calophylla in Australia; pine in Honduras etc.

The net primary productivity ranges from one place to another place depending on the nature of tree densities. The mean net primary productivity of the Savanna biome is 900 dry grams per square meter per year but there is great spatial variation in the productivity as it ranges from 1500 dry grams per square meter per year in the **closed savanna** (dominated by tress and shrubs) to a minimum of 200 dry grams per square meter per year in the desert scrub Savanna.

On the basis of the proportion of trees and grassland and the structure of the vegetation the Savanna biome may be divided into the following four types (P.A. Furley and W.W. Newey, 1983):

(i) **Woodland savanna** is dominated by trees and shrubs which form dense upper canopy. This Savanna is, thus, also called as **closed savanna.** Inspite of comparatively closed upper tree canopy of the topmost layer, enough sunlight reaches the ground surface to support ground cover of herbaceous plants. There is more or less general absence of **epiphytes** but some climbers having their roots in the ground are present.

(ii) **Tree savanna** represents relatively open vegetation cover in terms of trees, and shrubs which are sparsely distributed. The ground cover is dominated by grasses. No tree canopy is developed.

(iii) **Shrub savanna** is represented by treeless vegetation which is dominated by grasses at the ground layer and shrubs at the second layer. Infact, shrub Savanna is two layered vegetation where the topmost layer is formed of shrubs and the ground cover consists of grasses.

(iv) **Grass savanna** is characterized by general absence of trees and shrubs and over dominance of dense grasses. The grass cover is not continuous, rather it is separated by intervening patches of grassless areas.

The frequent fires, both natural and anthropogenic (intentional annual burning of grasses by man), are common features of all the aforesaid Savanna biomes. Though many organic materials are destroyed due to annual burning of grasses by man, regular fires in Savanna grasslands are very important ecological processes because these favour regeneration of grass every year, mineralisation of leaf litter and regulation of fauna. 'Thus, fire appears to be a normal part of the Savanna biome and one of the major factors in its nature—Savanna (is) a delicate balance of the outcome of climate, soils, vegetation, animals and fire, with fire as the key agent whereby men have created the biome; as it now stands this biome in Africa cannot be regarded as climatic climax but as a product of human activity' (I.G. Simmons, 1982).

No doubt, frequent burning of grasses by man has been responsible for the evolution of a few fire-resistant species of trees and grasses such as Imperata spp (a type of grass).

Animal Community

It may be pointed out that animal communities of different Savanna areas of the continents show a wide range of species diversity because of the fact that (i) different Savanna areas have developed differently in different environmental conditions during various stages of evolution, and (ii) the degree of human interference has greatly varied in different Savanna regions. The availability of food during different seasons depends on the environmental conditions. Since there is maximum growth and development of vegetation during wet summer season and almost barren ground during dry summer season and hence there is abundance of food during wet season but there is marked scarcity of food during dry season. This seasonal regime of the availability of animal food has largely affected animal community in the Savanna biome. Secondly, hunting of animals by man has also adversely affected them. Inspite of these limiting factors the Savannas are capable of supporting a very diverse fauna.

The African Savanna accounts for the largest number and the greatest variety of grazing vertebrate mammals in the world. For example, the East African Savanna carries 40 species of very large herbivourous mammals such as African buffalo, zebra, giraffe, elephants, many types of antelopes, hippopotamus etc. of which even 16 species graze together in the same habitat. On the other hand, the South American and Australian Savannas do not have large number of grazing mammals similar to the African Savanna but great variety of birds like those of the African Savanna is invariably found. The Australian Savanna is dominated by **marsupials** (typical mammals of South American and Australian origin having pouch in their bodies to keep and feed their offsprings). There are at least 50 species of kangaroo in the Australian Savanna which greatly vary in size ranging from very large red kangaroo (1.5m tall) to very small species of wallaby (only 30 cm in height). The large grazing mammals of the South American Savannas include deer and guanaco. Besides, toucans, parrots, nightjars, kingfishers, doves, finches, parakeets, wood peckers are also found in large number in the South American Savannas.

It may be pointed out that relatively less denser cover of vegetation in the Savanna biome provides maximum mobility to the animals and thus the Savanna grasslands have been responsible for the origin and evolution of great number of large mammals (like elephant, giraffe, zebra, ganda, hippopotamus, antelopes etc.) and birds such as courses, bustards, game birds, ostrich, and several non-flying birds like emu.

There is complete correlation and correspondence between the structure and seasonal regime of the Savanna vegetation and invertebrate animals. The invertebrate animals include insects (such as flies-diptera, locusts, grasshoppers, termites-Isopetra, ants and arthropods (like spiders, scorpions etc.) which are found profusely in the various parts of the Savanna regions. The density of oligachaete worms, spiders and insects in the Guinea Savanna of tall grasses of the western Africa is 50,000 to 60,000 per 300 square meters of area during dry season but the density of these organisms increases to 1,00,000 during wet season because of regeneration of dense cover of green grasses. The rainy season is characterized by the dominance of smaller animals (such as springtails, ants, earwigs, cockroaches, small crickets, carabid beetles etc.) whereas the larger invertebrates dominate during dry season like locusts, grasshoppers, mantids and crickets.

It may be pointed out that inspite of large number and great variety of animals of invertebrate and vertebrate categories (ranging from micro-organism-like insects to very large bodied animals like giraffe and elephants) there is no competition for food among the animals in the Savanna biome because of the fact that the animals of this biome have developed typical feeding habits and mechanisms according to the characteristics of the vegetation. For example, giraffe uses the top layers of the trees and shrubs through his exceptionally long neck, zebra lives on the leaves of shrubs and the head of tall grasses, wildbeasts graze the grasses of medium height whereas the gazelles (deer family) depend on short grasses. It appears that there is close correspondence between the vertical stratification of the vegetation community and feeding habits of the animals of the Savanna region. Thus, the Savanna biome is characterized by the development of grazing succession which enables the animals of various species and sizes to live in the same habitat without having much competition among themselves for food.

There is also wide range of variation in the seasonal mobility of the ungulate animals (animals having hoofs) and thus the seasonal variability of the animal mobility has also discouraged competition among the animals for food. Based on seasonal characteristics of mobility A.F. Lamprary (1964) has divided the animals of the Savanna biome into the following 5 categories.

(i) Animals with little or no seasonal movement, e.g. giraffe, Grant's gazelle, hartebeest etc.

(ii) Animals having partial movement during dry season, e.g. impala

(iii) Animals having partial movement during wet season e.g. warthog, dikdik, waterbuck, rhino etc.

(iv) Animals migrating during dry season, e.g. buffalo, zebra, wild beest, eland, elephant etc.

(v) Animals used to passage migration e.g. buffalo, zebra, elephant etc.

Ecosystem Productivity

The East African Savanna is the richest of all the other Savannas in terms of total animal population. 'Where a rich fauna still exists, as in East and Central Africa, it may achieve a yearlong vertebrate biomass of 100×10^5 kilogram per hectare live weight' (I.G. Simmons, 1982). The average **net primary productivity** (NPP) of the Savanna biome is 900 dry gram per square meter per year whereas the total net primary productivity of all the Savannas of the world is 13.5×10^9 tons per year. The termites are very significant animals of the Savanna biome because they help in decomposing the organic matter and in recycling the nutrients. According to an estimate (I.G. Simmons, 1982) the biomass of termites in Ivory Coast is 12kg per hectare and these consume 30kg of cellulose per hectare per year and rearrange several dozen tons of soils every year.

Man and the Savanna Biome

The impact of man in the Savanna biome right from the evolution of human races in the various parts of the present-day Savannas to the present-day technologically advanced society has been so immence that the very nature and the characteristics of Savanna grasslands are the outcome of the continued man's interferences with the original natural environmental conditions particularly natural vegetation and related micro-climates. The regular burning of vegetation generates lush green grasses during wet season which support large number and variety of grazing animals but simultaneously this routine annual practice reduces the number of large animals feeding on the leaves of trees because frequent fires are not conducive for luxuriant growth of trees.

The rapidly increasing human population for the last 50 years or so has put enormous strain on the natural Savanna grasslands because a vast area of the original grasslands has been converted into agricultural fields to grow more food crops to feed the teeming millions. The rapid rate of expansion in the agricultural lands under the new scheme of green revolution has further been responsible for the shrinkage of natural Savanna grasslands. Further more, enormous increase in the number of domesticated animals has greatly damaged the grasslands. In nut shell, the impact of human activities has resulted in the shrinking of the areas of grasslands and reduction of natural vegetation which have caused shortage of food supply to the animals. All these have ultimately adversely affected the animal communities. Consequently, the number of animal species and their total population are gradually decreasing.

14.4 TROPICAL-SUBTROPICAL HOT DESERT CLIMATE (BWh) (SAHARA TYPE OF CLIMATE)

Location

The hot desert or Sahara type of climate is located between the latitudinal belt of 15°-30° (35°) in both the hemispheres on the western parts of the continents. This climate is found in (1) Africa—the Namib and Kalahari deserts of coastal Angola and southwest Africa, interior Botswana and South-Africa, and Sahara desert; (2) Asia-Thar deserts of India and Pakistan, Arabian deserts, Iranian desert; (3) South America-Acatama desert of coastal Peru and Chile; (4) Mojave and Arizona deserts of south-western USA; (5) Australia-Great Sandy Desert, Great Victoria Desert and Tanami Desert (fig. 14.4). This climate is characterized by annual aridity, and subsiding warm air masses of the subtropical anticyclones. The following reasons are held responsible for the genesis of perpetual

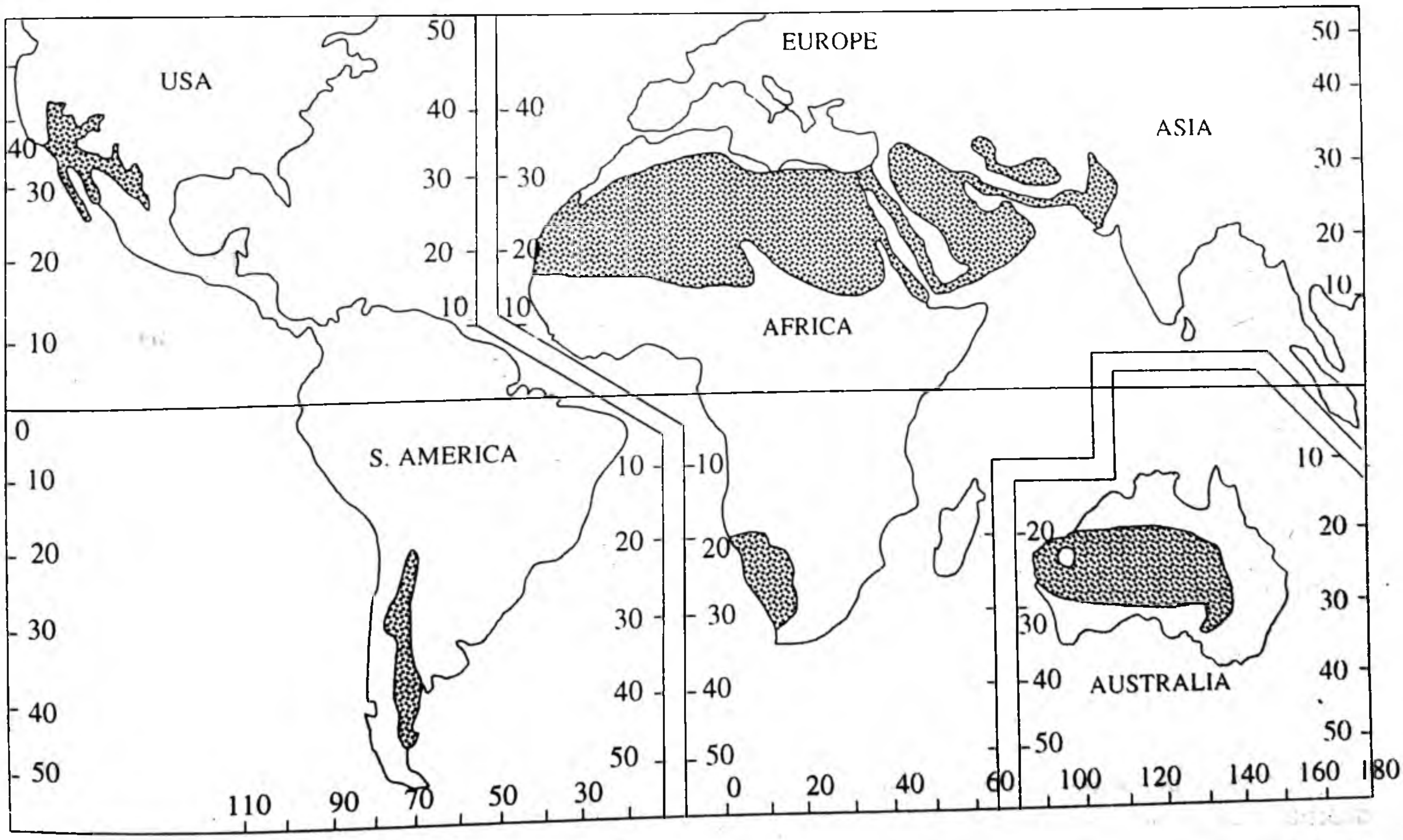


Fig. 14.4 : Location of tropical-subtropical hot dry desert climate-Sahara type of climate.

aridity of the tropical-subtropical hot desert climate: (i) Temperate cyclones do not reach these areas. (ii) Intertropical Convergence (ITC) also does not influence these areas because of their distant location from the equator. (iii) The trade winds spend most of their moisture through rainfall in the eastern margins of the continents and as they reach the western margins of the continents they become dry and hence are unable to give rainfall. (iv) Due to anticyclonic conditions winds descend from above and hence they are warmed adiabatically with the result their moisture retaining capacity increases resulting into marked decrease in relative humidity. (v) Subtropical high pressure system causes divergence of surface winds which is antagonistic to rainfall. (vi) The ground temperature is so high that raindrops, if formed at all, are evaporated before they reach the ground surface.

Temperature

On the basis of annual distribution of temperature two distinct seasons are recognized e.g. summer season and winter season. Average temperature during summer season ranges between 30°C and 35°C but maximum temperature exceeds 40°C during mid-day. The temperature of 40°C to 48°C is very common at noon during summer months. The western part of Great Australian Desert records temperature above 40°C for 64 days in continuation and above 32°C for 150 days in continuation but temperature falls at nights giving much relief to the people. Phoenix of Arizona (USA) records more than 30°C at noon but temperature falls to 24°C in the nights. Azizia has recorded the highest temperature of 58°C (136.4°C) so far. Similarly, exceptionally very high temperature of 56.4°C (134°F) has been recorded in the Death Valley of Californian desert (USA). Daytime mean temperature during winter season ranges between 15.5°C and 21°C but some times it reaches 27°C but at nights temperature falls to 10°C.

It is, thus, apparent that both annual and diurnal ranges of temperature are high in the tropical-subtropical 'hot' desert climatic areas. Generally, annual range of temperature ranges between 17°C and 22°C while daily range varies from 22°C to 28°C. Some times, daily range of temperature exceeds 40°C. Very high daily and annual range of temperature is because of open and clear skies, vegetation-free ground surface, very low humidity, distance from the equator, dominance of sands etc. It may be pointed out that in the absence of clouds and moisture maximum insolation is received at the ground surface. Loose sands are soon heated and thus ground temperature soon shoots up. Again there is rapid loss of heat from the sandy surface through outgoing longwave terrestrial radiation at nights due to clear sky and completely dry condition (total absence of moisture in the air) resulting into considerable fall in night temperature. This mechanism causes very high daily range of temperature. It may be remembered that blankets are needed in the nights in hot desert areas due to very high difference in daytime and night temperatures even during summer seasons. Tripoli recorded highest and lowest temperatures of 91°F and 31°F respectively on December 25, thus registering a daily range of 60°F.

Pressure and Winds

Poleward areas of the regions of hot desert climate are affected by divergent air circulation and anticyclonic conditions because they fall in the belt of subtropical high pressure. The winds become stable and dry because they descend from above and are heated and thus there prevails dry condition. The north-east trades (northern hemisphere) become dry when they reach the western parts of the continents in the latitudinal zones of 15°-35°. Some local low pressure centres are formed during summer season and thus a few local but weak cyclonic storms are produced. The upper air anticyclonic conditions do not allow the winds of these local storms to rise. Heat waves dominate in summer season thus making human life very difficult. The extensive deserts of Sahara and Australia become ideal source regions for the development of tropical continental airmasses.

Rainfall

Rainfall in tropical desert climate is so low and variable that it becomes difficult to determine average annual rainfall as it never comes true. The various sources put the annual average of rainfall between 25 cm and 37.5 cm but these figures are highly misleading because there are so many such areas where not even a single drop of rain is received for several years in continuation. Thus, the annual average rainfall is considered to be less than 12 cm. Most of Sahara receives less than 12 cm of mean annual rainfall. Cairo of UAR (3.0 cm), Lima of Peru (5 cm), William Creek of Australia (13.3. cm), Yuma of Arizona (USA, 8 cm), Toloth in S.W. Africa (5.6 cm) etc. receive very low mean annual rainfall. Northern parts of Chile some times do not receive any drop of rains for 5 to 10 years in continuation. The equatorward relatively more humid areas, however, receive 50 to 75 cm as mean annual rainfall. Most of the rains is of convectional type due to local heating. Some times, occasional storms give heavy downpour within few hours causing flash floods. For example, 85 cm of rainfall was recorded within two days in Doorbazi of Rajasthan whereas its mean annual rainfall is only 12.5 cm. Such occasional catastrophic rainfall causes flash floods resulting into choking of storm drains, destruction of human settlements, silting and choking of canals and destruction and disruption of means of transport and communication. Such heavy rainfall is not useful at all as all of the rainwater are disposed off quickly through surface runoff and the remaining water is evaporated due to high temperature.

Skies are generally free from clouds and thus sun's rays reach the ground surface without being reflected throughout the year and hence the tropical desert climatic regions receive sufficient bright sunshine all the year round. The Sonoran Deserts of the USA and Mexico receive more than 75 per cent and 90 per cent sunshine during winter and summer seasons respectively. Most parts of Sahara Desert are characterized by 1/10 cloudiness in December and January and 1/30 cloudiness from June to October. It is, thus, apparent that the ground surface is more or less always baked in the sun. Some times, dark cumulo-nimbus clouds are formed, thunderstorms with cloud thunder and lightning are experienced but still there is no rain because raindrops are evaporated before they reach the ground surface. The average relative humidity ranges between 10 to 30 per cent.

Natural Vegetation

Hot desert type of climate is not conductive for vegetation growth because of acute scarcity of water. This is why most of the regions under this climate are either devoid of any vegetation such as Lybian and Arabian deserts or if there is any vegetation at all, that is very little, sparse and bushy in character. The vegetation of hot desert climate is of xerophytic type which has special characteristics to withstand harsh climate characterized by extreme aridity, high temperature and very high rate of evaporation. They have their own moisture conserving devices such as long roots, thick barks, waxy leaves, thorns and little leaves so that they may avoid evapotranspiration and consequent loss of moisture from them. Most of the vegetation are found in the form of bushes. Cactus, acacia, date palm, a few flowering plants etc. form the composition of natural vegetation of hot desert climate.

14.5 SUBTROPICAL DRY SUMMER CLIMATE OR MEDITERRANEAN CLIMATE (Cs CLIMATE)

Location

The Mediterranean type of climates, climatically known as subtropical dry summer climates, is called Mediterranean type because most of the areas falling under this climate are situated around the Mediterranean Sea. The Mediterranean climate or biome is also called as **sclerophyll ecosystem** or **biome** because of the development of special features and characteristics in the dominant trees and shrubs to adapt to the typical environmental conditions of this climate-dry summer and wet winter. Though the Mediterranean type of climate covers only 1.7 per cent area of the globe but this is most clearly defined climate and is easily differentiated from other climatic regions. The Mediterranean climate has three distinct characteristics : (i) wet winter and dry summer season, (ii) warm and hot summers, and mild winters, and (iii) abundant sunshine throughout the year (90 per cent in summer and 50 to 60 per cent in winter). This climate has developed between 30^0-40^0 (some times upto 45^0) latitudes in both the hemispheres in the western parts of the continents (fig. 14.5). This climatic region includes (A) European, Asiatic and African lands bordering the Mediterranean Sea e.g. (1) European lands —Rhone-Saone Valleys of France, southern Italy, Greece; (2) Asiatic lands-western Turkey, Syria, Lebanon, western Israel; (3) north-coastal Africa—Morocco, northern Algeria and Tunisia and the area north of Bengasi in Lybia, (B) central and southern California in the USA, (C) central Chile in South America, (D) the Capetown area of South Africa, and (E) the coastal zones of southern and south-western Australia. The Mediterranean type of climate owes its origin to the seasonal shifting of wind and pressure belts due to northward (summer solstice) and southward migration (winter solstice) of the sun. Thus, these areas come under the domain of westerlies in winter season. Since the westerlies are moisture laden because they come from over the oceans and are associated with temperate cyclones, they give sufficient rains during winter season. On the other hand, they come under the influence of subtropical high pressure belt and associated anticyclones during summer season and hence there is no rainfall.

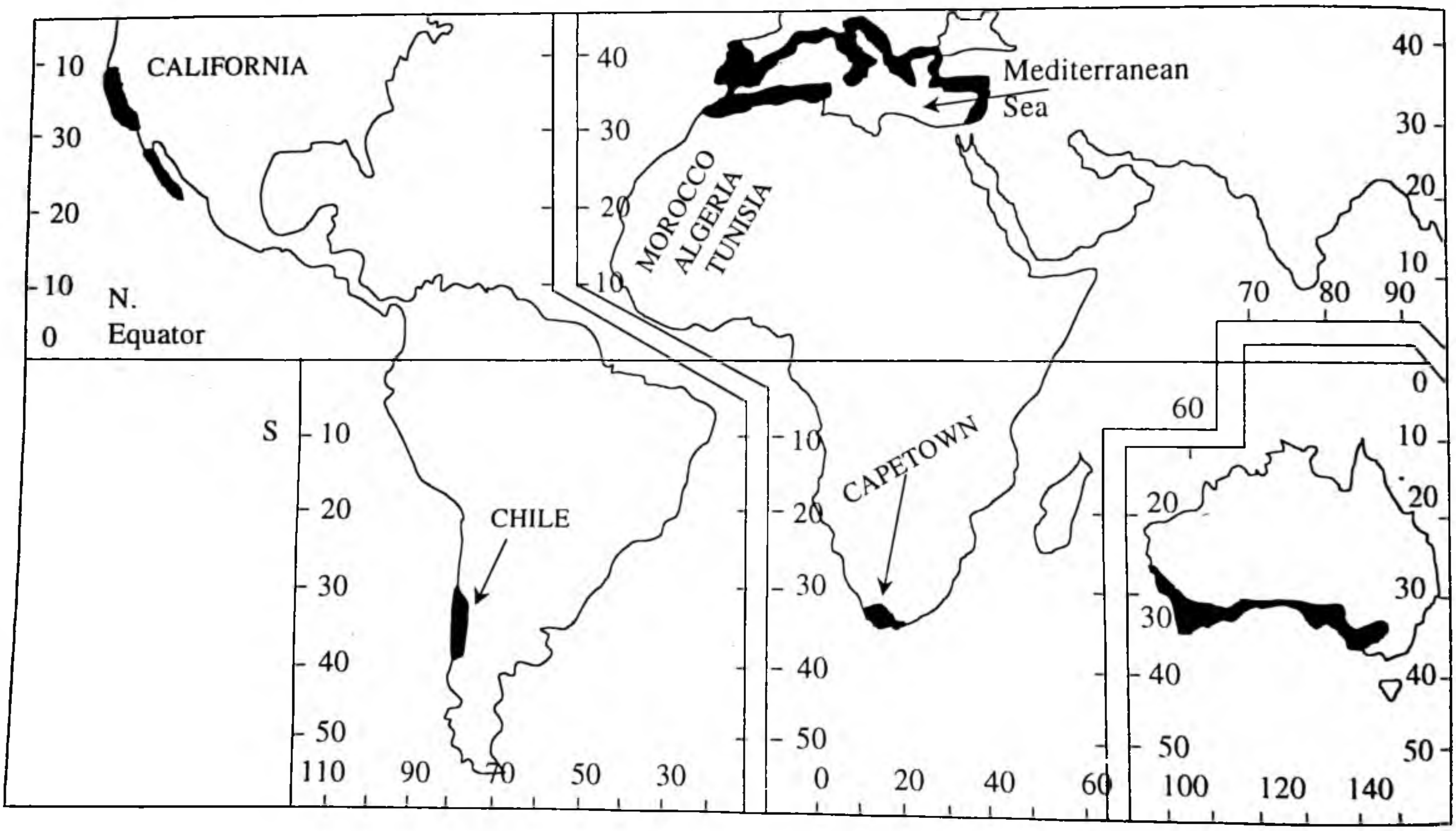


Fig. 14.5 : Spatial Distribution of Mediterranean Climate

Temperature

The average temperature during cool winter season ranges between 5⁰C and 10⁰C whereas mean summer temperature varies from 20⁰C and 27⁰C and thus the mean annual range of temperature becomes 15⁰C to 17⁰C or even more. In fact, the Mediterranean climate is considered as resort **climate** because of its pleasant and comfortable winter season. The Mediterranean climate whether having coastal or inland location generally records temperature above freezing point during winter season as the average temperature of the coldest month ranges between 4.4⁰C and 10⁰C. The mean January temperature is recorded as 7.7⁰C at Sacramento in California (USA), 6.1⁰C at Marseille (France), 12.8⁰C at Perth (Australia) and 6.6⁰C at Rome. Some times, the temperature becomes so low at nights that frost occurs which is very much injurious to field crops. The valleys and depressions have freezing to subfreezing temperatures in winter and hence valleys are avoided for sensitive crops like citrus fruits which are grown on hill slopes. Los Angeles (California, USA), Naples (Italy) and Sacramento (California, USA) have recorded lowest temperatures of -2.2^0C -1.1^0C and -8.3^0C respectively. It may be pointed out that occasional fall of temperature below freezing point is limited to a few minutes to a few hours only. Summer temperature rises above 26^0C *e.g.* Red Bluff of Sacramento valley records 27.5^0C whereas average temperatures during summer season are 26.6^0C in European Mediterranean lands and 24^0C in north-west Africa. It may be mentioned that high summer temperatures are never uncomfortable due to low relative humidity. Daily maximum temperature in summer goes beyond 26^0C. For example, the Great Valley of California records daily maximum summer temperatures ranging between 30^0C and 32^0C. Red Bluff and Sacramento have recorded highest daily maximum temperatures of 45.5^0C and 46^0C respectively so far. The night temperature during summer season falls to 15.5^0C, thus diurnal range of temperature becomes as high as 30^0C. Daily and annual ranges increase from coastal areas to inland areas.

On the basis of temperature variations the Mediterranean climate is divided into 2 subtypes *e.g.* Csa and Csb. Csa climate, characterized by hot summer, has inland location whereas Csb climate of mild summer is located along the coastal margins of the continents. It may be pointed out that temperatures of the Mediterranean climatic regions except those around Mediterranean Sea are largely affected by cool oceanic currents *e.g.* Californian region by cool California current, Chilean region by cool Peru current, Cape Town region by Benguela current etc.

Air Pressure and Winds

In fact, the Mediterranean climate is the outcome of the seasonal shifting of pressure and wind belts. All the pressure belts except polar high pressure belt move northward from their normal positions during northern summer (summer solstice when the sun becomes vertical over the tropic of Cancer on June 21) and thus subtropical high pressure system extends over the regions of Mediterranean climate (30^0N to 40^0N) and anticyclonic conditions dominate the weather conditions causing subsidence of air from above, horizontal divergence of surface winds, stability of air resulting into dry conditions. Sirocco local hot winds blow from Sahara northward picking red sands which are brought to Italy, Spain, southern France and Greece. Summer winds are generally hot and dry. These areas come under the domain of westerlies during winter season when the sun moves southward (northern winter). The westerlies are associated with temperate cyclones originating in the middle latitudes. Since the westerlies are associated with temperate cyclones and come from over sea surfaces and hence being moist give sufficient rainfall in the coastal areas. Some local winds like Bora, Mistral (cold winds) etc. affect the local weather conditions of the European Mediterranean lands during winters.

Precipitation

The mean annual rainfall ranges between 37 cm and 65cm, the most portion of which (more than 75 per cent) is received during winter season mainly between December and March in the northern Hemisphere and between May to September in the southern hemisphere. The winter rainfall is received through cyclonic storms associated with moist westerlies. The summer season is almost dry. Because of moderate to scanty rainfall the Mediterranean climate is called as subhumid climate. The orographic rainfall is common in those coastal areas (*e.g.* California) which are backed by mountain ranges parallel to the coasts. Though winter season is quite wet but the sky is seldom overcoast for longer duration in continuation and thus abundant sunshine is available even during wet winter season. For example, Red Bluff (California, USA) has only 11, 12, 10 and 10 rainy days in December, January, February and March respectively. January is the rainiest month in San Bernardino and Los Angeles but there are only 7 rainy days. January being the coldest month of Red Bluff receives 11.5 cm of rainfall while July being the coldest month of Perth (Australia) receives 16 cm of rainfall. All these indicate the intensity of rainfall during winter months in the Mediterranean climatic regions. Summer season is characterized by scanty rainfall, almost dry weather, clear skies, and bright sunshine. Besides temporal variation, there is also spatial variation of rainfall. Generally, the amount of rainfall increases poleward and thus increases from south (24 cm at San Deigo, 29 cm at Los Angeles) to north (58 cm at Sansfransisco) in California.

The seasonal regime of rainfall causes fluctuations in the soil-water and soil-moisture regimes during winter and summer seasons. The amount of soil-water increases during winter season because of winter and spring rainfall which is responsible for maximum growth in vegetation but dry summer season causes deficiency in the soil-water content because of loss of water and moisture due to increased evaporation and evapotranspiration because of substantial increase in temperature and of course due to general lack of rainfall during summer season.

Natural Vegetation

Though the Mediterranean regions are widely scattered over different continents, there is more or less broad generalization in the overall structure and composition of vegetation community of all the regions of Mediterranean biome. The structure of Mediterranean vegetations is such that they can withstand the aridity of summer season. Consequently, the leaves have developed sclerophyllous characteristics in that they are stiff and hard and the stems have thick barks. The Mediterranean vegetation community consists of a variety of sclerophyll plant formation classes which range from Mediterranean mixed evergreen forests (in the coastal lands immediately bordering the aseas and the oceans) to woodland, dwarf forests and scrubs. The vegetation community is dominated by trees and shrubs. The shrubs are differently named in various parts of the Mediterranean biome on the basis of local names *e.g.* **maquis** or **garigue** in southern Europe, **chaparral** in California, **fymbos** or **fymbosch** in South Africa , and **mallee scrub** in Australia.

The **xeromorphic structure** such as thickened suiticles, grandular hairs, sunken stomata etc. enables the plants to withstand dry conditions. The sclerophyllous structure of plant leaves enables them to regulate the gaseous exchange according to the availability or scarcity of water during different seasons of the year. The plants have also developed special types of root systems in accordance with the regional environmental conditions mainly the availability of moisture. The European Mediterranean regions are characterized by multi-layered structural pattern of veggtation community consisting of (i) topmost layer of evergreen and deciduous oak trees, (ii) middle layer of shrubs locally known as **maquis** or **garigue**, and (iii) the ground layer of numerous herbaceous plants. The Californian Mediterranean lands are characterized by the (i) topmost layer of oak trees, (ii) the middle layer of **chaparrals**, equivalent to European **maquis**, and (iii) the ground layer of herbaceous plants and grasses. The South African Mediterranean Biome is characterized by attractive flowering plants of numerous varieties *e.g.* Erica, Ereesia, Lobellia, Kniphofia species etc. The shrubs are locally called as **fymbos**. The Australian Mediterranean climate is characterized by numerous species of eucalyptus.

Fire, both natural and man-included, is normally an annual occurrence in the Mediterranean climatic regions. Burning, mass clearance of natural vegetation for agricultural and commercial purposes, overgrazing of grasslands etc. have led to accelerated rate of soil erosion, increase in the silt load of major rivers and transformation of original natural vegetation.

14.5.1 MEDITERRANEAN BIOME

The location, distribution of areas of Mediterranean climate and climatic characteristic features have been discussed in the preceding section 14.5.

Vegetation Community

Though the Mediterranean regions are widely scattered over different continents, there is more or less broad generalization in the overall structure and composition of the vegetation community of all the regions of the Mediterranean biome. The structure of the Mediterranean vegetations is such that they can withstand the aridity of the summer season. Consequently, the leaves have developed sclerophyllous characteristics wherein they are stiff and hard and the stems have thick barks. The Mediterranean vegetation community consists of a variety of sclerophyll plant formation classes which range from Mediterranean mixed evergreen forests (in the coastal lands immediately bordering the seas and the oceans) to woodland, dwarf forests and shrubs. The vegetation community is dominated by trees and shrubs. The shrubs are differently named in the various parts of the Mediterranean biome on the basis of local names *e.g.* **maquis** or **garrigue** in southern Europe, **chaparral** in California, **fymbos** or **fymbosch** in south Africa and **mallee scrub** in Australia.

The plants of the Mediterranean biome have developed several morphological characteristics to withstand dry conditions. Such structure is called **xeromorphic structure** such as thickened suticles, grandular hairs, sunken stomata etc. The sclerophyllous structure of the plant leaves enables them to regulate the gaseous exchange according to the availability or scarcity of water during different seasons of the year. A few species of trees such as **mastic trees**, have the mechanism of adjusting themselves to the changing weather conditions during the year. For example, the mastic trees are able to close their stomata during dry summer season or even during winter drought so that they can reduce transpiration from their leaves to minimum and hence can conserve moisture. Some trees have developed smaller leaves (such as **chamise**) so that they allow minimum loss of moisture through transpiration. Some trees have thorny leaves (such as **succulent cactus family**).

The plants of the Mediterranean biome have also developed special types of root systems in accordance with the regional environmental conditions mainly the availability of moisture. For example, some plants have extensive root systems with strong tap root which extends even into the consolidated parent rocks (such as the roots of almond); some plants have such root systems which develop above the ground as well as quite deep inside the ground (such as the root of chamise); some plants have bulbous or tuber roots (such as the geophyte plants, e.g. different types of flowers like dahlia) etc.

There are some regional variations in the species composition and vertical structure of the vegetation community in the various parts of the Mediterranean biomes as given below:

(i) **European Mediterranean Biome** is characterized by multi-layered structural pattern of vegetation community wherein three distinct layers (strata) have developed. The topmost first layer or the canopy layer is dominated by oak tree which is of two types *e.g.* (a) evergreen oak and (ii) deciduous oak. There are several species of oak in the European Mediterranean biome. The sequence of trees changes with the increasing altitude *e.g.* the evergreen oaks are found at the lower height and with the increasing height the sequence of trees is formed by deciduous oaks, beech, fir and pine. The second or the middle layer is formed of shrubs which include the species like Arbutus, Pistacia, Rhammus, Ceratonia etc. These shrubs attain the height of 2m or even more which are clearly differentiated from the topmost layer of the dominant oak trees of 3 to 4 m in height. These shrubs provide valuable forages to the animals and valuable products to human beings like gums, resins, tannins, dyes etc. The continuous grazing, natural and anthropogenic frequent fires and felling of trees have largely transformed the shrub community called as **maquis** into **garrigue.** The garrigue shrubs have also been modified by continued human activities and transformed into **batha** (dwarf shrubs). The third or the ground layer consists of numerous herbaceous plants.

(ii) **North-American** or **Californian Mediterranean Biome** is dominated by different species of oak trees and **chaparral** shrubs. The first or the topmost layer is formed by the canopy of oak trees reaching the height between 6m and 23m. The oak has short but thick stem and flattened crown. The second or middle layer is dominated by various shrubs locally called as **chaparrals.** The ground layer is dominated by herbaceous plants and grasses. Chaparrals generally become gregarious in the areas of less fertile and light soils. The chaparrals of California are the counterpart of the European maquis. The dwarf shrubs (like **batha** of the European Mediterranean biome) locally called as **sage scrub** have developed in many parts of the Californian Mediterranean biome. The Mediterranean biome of Chile of South America has also developed vegetation quite similar to that of the

Californian Mediterranean biome. The Californian chaparrals are called **mattoral** in Chile.

(iii) **South African Mediterranean Biome** is characterized by the dominance of small but attractive flowering plants of numerous varieties. These plants have been extensively migrated by deliberate actions of man to various gardens of numerous countries of the world. These garden flower plants include Erica, Ereesia, Lobellia, Kniphofia species etc. The shrubs belong to sclerophyllous categories as these are characterized by hard, stiff and thick leaves. These sclerophyllous shrubs are locally called as **fymbos.** It may be pointed out that this region was originally covered by temperate forests before the arrival of Europeans in this area. The Europeans largely removed the original forests for the purpose of agriculture and thus there developed the secondary succession of vegetation which now has taken the form of present-day **fymbos.** The large-scale transformation of original habitats through forest clearance and mass hunting of animals by the Europeans resulted into the obliteration of several species of animals from the South African Mediterranean biome. For example, **quagga,** a species of zrbra, has now become totally extinct. Only a few species of antelope like duiker and steembuck are found only in the dense cover of **fymbos.** Hyraxes, baboons, and leopard ane found in small number only in the mountainous areas.

(iv) **Australian Mediterranean Biome** is dominated by the species of eucalyptus. Thus, the topmost layer or the canopy layer is formed by abcut 100 species of evergreen eucalyptus trees with the height of 70m or ever more. The tallest species of eucalyptus is **karri.** It may be pointed out that the forms of vegetations change inland from the coastal areas and thus several zones of vegetations are found from north to south. The southernmost coastal land having maximum amount of annual rainfall is characterized by the dominance of eucalyptus forest which is replaced by **jarrah** forest in the north. Further northward the forest cover becomes thin and is finally replaced by grasslands. **Malle scrubs** have developed to the north and east of grasslands. There are numerous animals in the malle scrubs.

The average **net primary productivity (NPP)** of the Mediterranean biome is about 700 dry grams per square meter per year whereas the total net primary production of all parts of the Mediterranean biome is 6×10^9 tons per year. The NPP of 700 dry grams per square meter per year generates a biomass of 6000 grams per square meter.

Animal Community

Like vegetation, there is also regional variation in the animal communities of the various parts of the Mediterranean biomes of the world. The Mediterranean biomes of California and Chile are characterized by more or less similar animal species. There are numerous animals in these two regions because of abundant supply of food from the good cover of various types of shrubs.

There are about 201 species of vertebrate animals in south California, of which about 75 per cent are bird species. The large mammals of Californian and Chilean regions include mule deer (in California) and Chilean guanaco but the latter is no more a browsing animal rather it has changed its feeding habit and it has been transformed to grazing animals. The mammals are now dominated by ground squirrels, wood rats and mule deers. Many of the predator species like wolf and mountain lion, diversivores like grizzly bear have now become rare species because of increasing pressure of man of the Mediterranean vegetation. The other important animals include several species of rodents such as rabbits, the rabbits predators such as cyote, similar to Chilean fox, other predators such as lizards, snakes, and several types of raptorial birds like kites, falcons, hawks etc.

Most of the original native animals of the South African Mediterranean biome have now become either extinct or rare due to the destruction of their natural habitats through extensive forest clearance by the European settlers. For example, quagga, a type of zebra, which was an important species, now has become totally extinct whereas bontebok, a type of antelope, has now become a rare species and has been pushed to remote areas. Some animal species, which were very important before the arrival of Europeans in this area, have now occupied remote areas to escape from the hunters. These animals include some species of antelopes (which now live in the dense shrubs of high ground) like duiker and steenbuck; rodent like browsing small animals like hyraxes (which have now been pushed to mountainous areas); baboons and leopards (which also live though in very small number, in the remote hilly and mountainous areas).

The Australian Mediterranean biome is characterized by numerous types of birds and animals. The marsupials include kangaroos mainly western grey kangaroo. There are numerous varieties of wallaby and mice. The typical birds of the shrub habitats and grassland are honeyeasters, whistlers, wrens, robins, quail-thrushes etc.

Man and Mediterranean Biomes

Man has directly (through his deliberate action) and indirectly adversely affected the flora and fauna of the Mediterranean biomes. Fire, both natural and man-induced, is a normally annual occurrence in the Mediterranean biome. The natural forest fires occur through lightning whereas man burns the grasses to get luxuriant growth next season. There is a common practice to burn the vegetation each year or after two or three years after heavy grazing and browsing by sheep and goats. Similarly, vegetations are burnt in every part of the Mediterranean biomes. The recurrent burning of vegetation has certain positive ecological results e.g. (i) Most of the plant species of the Mediterranean biomes have become fire-resistant and are now well adapted to fires. In other words, the plants, after burning, bear luxuriant growth of new branches, shoots and leaves. For example, numerous stems come out from the burnt stumps of eucalyptus trees; (ii) Some seeds germinate more quickly and properly after fires; (iii) Burning of vegetation transforms the organic matter into ashes and thus facilitates the mineralisation of organic matter and ultimately makes the mineralised organic mater available to plant roots, (iv) Fire destroys poisonous compounds secreted by plant roots. If undestroyed, these poisonous compounds are very injurious to plant communities because these do not favour decomposition of leaf litters and prevent nitrogen fixation in the soils.

The burning of vegetation has certain negative results as well. For example, soil structure is changed by frequent fires and thus is subjected to accelerated rate of soil erosion during rainstorms. Besides burning of vegetation, mass clearance of natural vegetation for agricultural and commercial purposes, overgrazing of grasslands and large-scale hunting of animals have led to elimination of certain animal species, accelerated rate of soil erosion, increase in the silt load of major rivers and alteration of original natural vegetation, habitats and micro-climates.

14.6 CHINA TYPE OF CLIMATE (Ca) (Subtropical Humid Climate)

Location

China type of climate, climatologically known as subtropical humid climate, is characterized by hot summer, mild to cold winters, spatial variations in temperature, humidity and precipitation and is located between 20^0-40^0 latitudes in both the hemispheres along the eastern parts of the continents (fig. 14.6). This climatic region is flanked by inland dry regions in the west (except in Po and Danube basins), by monsoon climatic areas in the south, by humid continental climate in the north, and by oceans in the east. The subtropical humid climate (Ca) is found in the following regions-south-east and south China (south of Yellow river); Po Basin; Danube Basin; south-eastern USA: south-eastern Brazil, Paraguay, Uruguay and north-eastern Argentina; south-eastern Africa;' and east coast of Australia.

It is apparent that Mediterranean type and China type of climates are found in the same latitudinal locations but are differentiated on the following counts: (i) Mediterranean climate is found in the western parts of the continents while China type of climate is located along the eastern coastal areas of the continents, (ii) Mediterranean climate is characterized by wet winter and dry summer whereas in China type of climate summer season receives maximum rainfall though rainfall is received throughout the year, (iii) Mean annual rainfall is higher in China type of climate than Mediterranean climate. China type of climate is also called as **sub monsoon climate** because of its near similarity with monsoon climate.

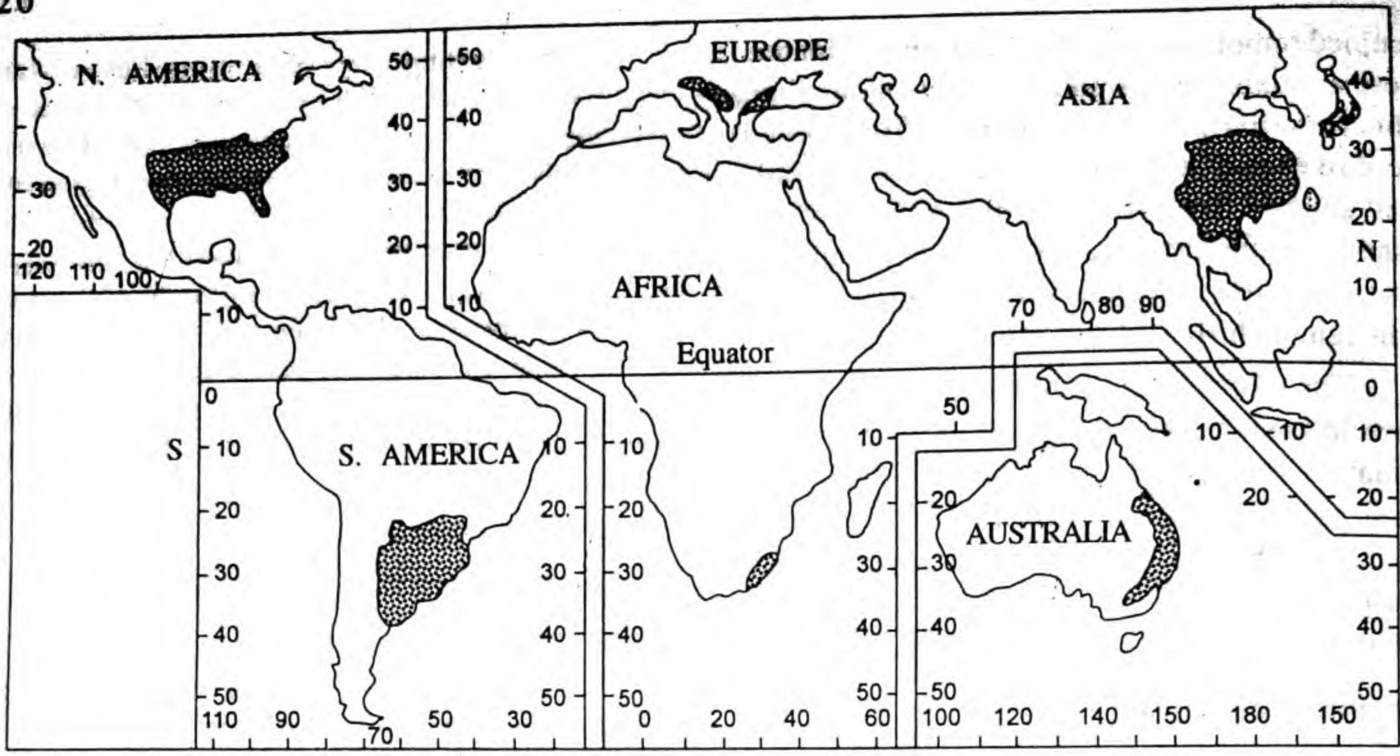


Fig. 14.6 : Distribution of China type of climate.

Temperature

The coastal parts of China type of climate are frequented by warm oceanic currents (e.g. warm Gulf Stream off the east coast of the USA, warm Brazil current along the east coast of South America, warm east Australia current off the east coast of Australia, Kuro Shio current off the coast of China, and Mozambique current along the south-east coast of Africa) and thus these warm currents affect the temperatures of coastal areas. The mean summer temperature ranges between 24°C and 26.6°C. The month of July records mean temperature of 28°C at Charlston (South Carolina, USA) and Montgomery (Alabama, USA), 27.2°C at Shanghai whereas January, the warmest month in the southern hemisphere, records mean temperature of 25°C at Brisbane (Australia) and Durban (Africa), and 23.3°C at Buenos Aires (South America). Daily maximum temperature crosses 37.7°C (100°F). For example, maximum daily temperature at Montgomery is recorded as 41°C in July and 41.6°C in August. Similarly, Savannah of Georgia (USA) has recorded 41°C as maximum daytime temperature in July. It may be pointed out that high summer temperature is also associated with high relative humidity and hence the weather becomes uncomfortable. The loss of heat during nights through outgoing longwave radiation is retarded because of cloudiness and hence temperature does not fall appreciably at nights resulting into low diurnal range of temperature. For example, the mean maximum and mean minimum temperatures of Montgomery (Alabama, USA) are 32.8°C and 22.2°C respectively and thus diurnal range of temperature becomes 11.6°C.

Generally, winters are mild as mean temperature ranges between 6.6°C and 10°C. Mean winter temperature is recorded as 9.4°C at Montgomery (Alabama, USA), 3.3°C at Shanghai, 10°C at Buenos Aires, 11.7°C at New Orleans (USA), 6.1°C at Nagasaki, and 11°C at Sydney. Mean annual range of temperature in China type of climate is not large but is marked by wide range of spatial variations. For example, mean annual range of temperature is 12.8°C at Buenos Aires and Sydney, 10.5°C at Montgomery and 24°C at Shanghai. In fact, annual range of temperature is controlled by the extent of land areas and the strength of winter monsoon winds. The more extensive the land areas and stronger the winter monsoon, the larger is the annual range of temperature. The arrival of cold polar winds during winter season causes temperature to fall below freezing point. For example, in the absence of any mountain barrier from west to east in North America, the extremely cold continental polar airmass invades the whole of the plains of the USA and reaches the Gulf coastal plains of the country and thus the temperature falls below freezing point (about -12°C) in the Gulf coastal state of the southern USA during winter season.

Air Pressure and Winds

The continental and oceanic areas are characterized by low and high pressure systems during summer season, with the result monsoons are developed. Thus, tropical maritime airmass (mT) develops over land areas falling in Ca climate mainly over China and southeastern USA. This air mass is south-easterly in the northern hemisphere while it is north-easterly in the southern hemisphere (during summer season). High pressure systems develop over south-western and northern central Pacific Ocean and near Azores in the Atlantic Ocean. These tropical maritime airmasses are also associated with tropical cyclones which yield sufficient rainfall. These tropical cyclones are called typhoons in China, hurricanes in the USA and southern busters in Australia. The pressure system is reversed during winter season as high pressure develops over continental areas while oceanic areas are characterized by low pressure systems. Thus, the winds become offshore. This is the reason that the coastal areas of the eastern and south-eastern USA are not much benefited from the warm Gulf Stream because the winds are offshore.

Precipitation

Though average annual precipitation in sub-tropical humid climate (Ca) ranges between 75 cm and 150cm and some times it becomes as high as 250 cm in some favoured locations but there is wide range of variation in the seasonal and spatial distribution of annual rainfall. Generally, rainfall decreases from coastal areas to the inland locations. On the basis of seasonal distribution of rainfall this climate is divided into two subtypes e.g. (i) Caf climate having rainfall throughout the year, and (ii) Cw climate having dry season during winter. On an average, the summer rainfall in China type of climate is definitely abundant and exceeds evapotranspiration. The summer rainfall is received through cumulus clouds resulting from convective currents caused by intense local heating of the ground surface. Besides, tropical cyclones (e.g. typhoons in China and hurricanes and tornadoes in the USA) also yield heavy downpour with cloud thunder and lightning. The Gulf coastal states of the USA are generally frequented by large number of thunderstorms. For example, Florida experiences at least 60 thunderstorms each year. These thunderstorms are associated with unstable tropical maritime air mass. The summer rainfall in China and Japan is divided into three types of regime viz. (i) maximum rainfall period of early summer season, (ii) maximum rainfall period of late summer season, and (iii) minimum rainfall period of middle summer season. Some times, the rainfall occurring from hurricanes in the south-east USA and from typhoons in China is so heavy that catastrophic floods are caused.

Hurricanes very often strike the southern and south-eastern coasts of the USA. The Gulf coasts of Louisiana, Texas, Alabama and Florida are worst affected areas. The Galveston, and Texas (USA) disaster of September, 8, 1900 tells the story of devastation caused by hurricanes in Gulf coastal states of the USA. The terrible hurricane generated a strong storm surge (tidal wave) which raced inland and killed 6000 people mostly through drowning caused by inundation under 3 to 4.5m deep water.

Winter rainfall is generally received through winter cyclones which are associated with the westerlies. Though the duration of individual rainstorm during winter season is much longer but total rainfall is comparatively less. It may be pointed out that inspite of less rainfall during winter season there is more cloudiness and larger number of rainy days than during rainier summer season. For example, 5cm of January rainfall of Shanghai is received within 12 days whereas 15 cm of August rainfall is received in only 11 days. Some times, there is occasional frost and snowfall during winter season.

Natural Vegetation

The China type of climate characterized by abundant rainfall, high temperature and long growing season of 7 to 12 months favour luxuriant growth of natural vegetation. Dense forests of evergreen nature are found in more humid areas but areas of moderate rainfall are characterized by deciduous sparse forests and grasslands. Normally, mixed forests of coniferous trees and broad leaf trees are found. The broad-leaved forests are both evergreen and deciduous depending on the spatial variation of distribution of annual rainfall.

14.7 MIDDLE LATITUDE STEPPE CLIMATE (BSK)

Location

The middle latitude steppe climate (BSk) spread over temperate grasslands is located in the interiors of the continents which come in the westerly wind belt but because of their more interior locations they do not get sufficient rainfall and hence the grasslands are practically treeless. The temperate grassland steppes of the southern hemisphere are located along the south-eastern margins of the continents (fig. 14.7) and therefore have more moderate climate than their counterparts of the northern hemisphere because of more marine influences as they are closer to marine environments. The temperate grasslands of Eurasia, known as **steppes**, are most extensive as they extend for a distance of more than 3200 km from the shores of the Black Sea across the Great Russian Plain to the foothills of the Altai Mountains. Their continuity is broken at few places by the highlands. There are also some isolated patches of steppes e.g. in Hungry (known as **Pustaz**) and in the plains of Manchuria (Manchurain Grassland). The temperate grasslands in North America (extending in Canada and USA both) are locally known as **prairies** which extend from the foothills of the **Rockies** in the west to the temperate deciduous forest biome in the east. The temperate grasslands of the southern hemisphere include the **pampas** of Argentina and Uruguay of South America, **bush veld** and **high veld** of South Africa, and **downs** of the Murray-Darling Basins of southeastern Australia and **Canterbury grasslands** of New Zealand (fig. 14.7).

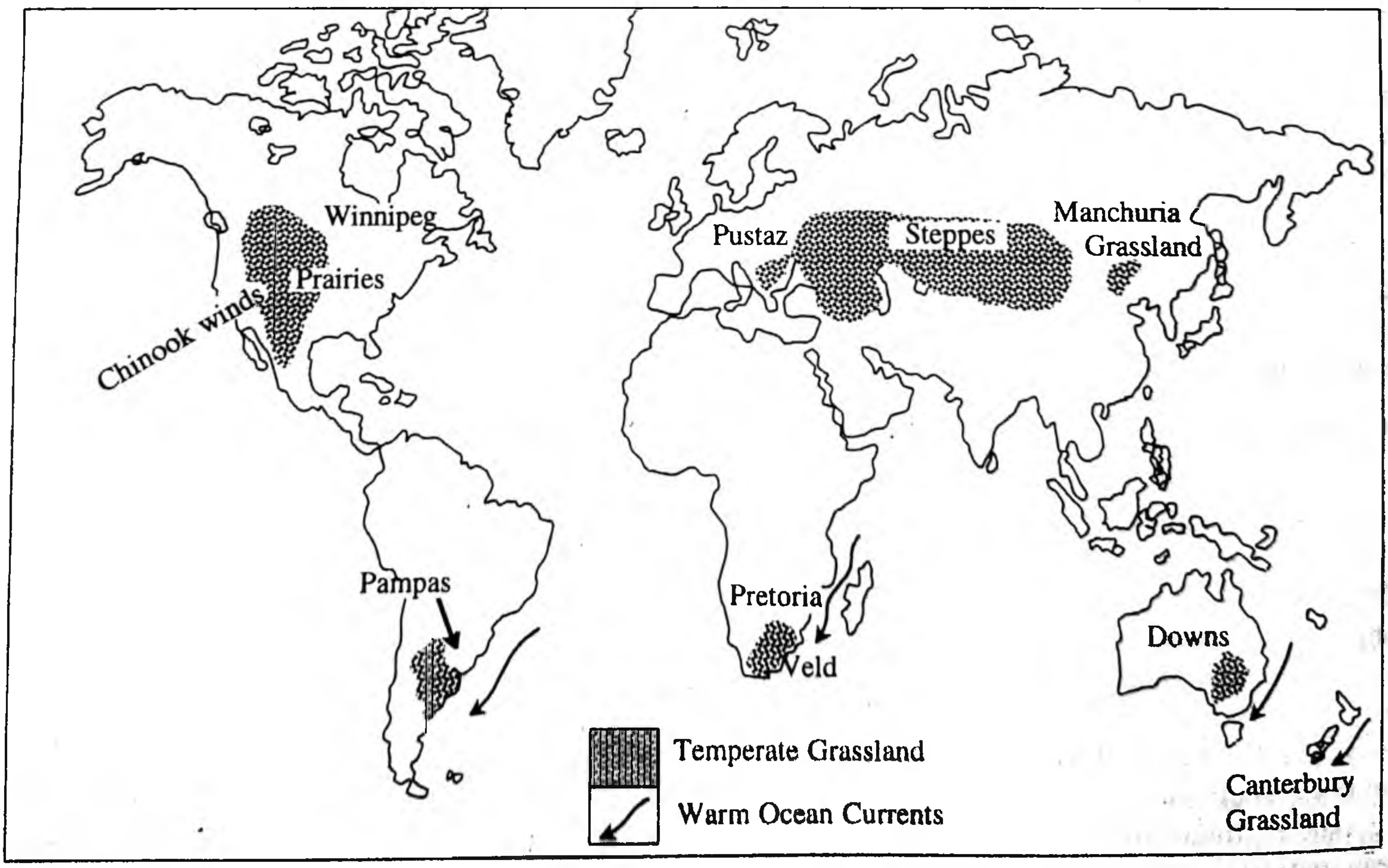


Fig. 14.7 : Spatial distribution of temperate steppe or grassland climate.

Temperature

The temperate steppes are characterized by continental climate wherein extremes of summer and winter temperatures are well marked but the temperate grasslands of the southern hemisphere are marked by more moderate climate. Summers are warm with over 20^{0}C temperature in July (Winnipeg, Canada) and over 22^{0}C in January (Pretoria, South Africa, January is summer month in the southern hemisphere). Winter season becomes very cold in the northern hemisphere because of enormous distances of temperate grasslands from the nearest sea. Winnipeg records –20^{0}C in January. The average temperatures during winter season for Tashkent (Uzbeck Republic) and Semipalatinsk (Kazakh Republic) are O^{0}C and –12^{0}C respectively. The steppe climate of the southern hemisphere is never severe rather it is moderate because of nearness to the sea. The average winter temperature ranges between 1^{0}C and 12^{0}C in the southern hemisphere.

The steppe climate is characterized by high annual range of temperature. For example, Winnipeg (Canada) records mean annual range of 40^{0}C. Laramine (Wyoming state of USA) records annual range of 23.4^{0}C (-6.7^{0}C in January and 16.7^{0}C in July). Due to marine influences the mean annual range of temperature in the southern hemisphere is much lower than the northern hemisphere as it is around 10^{0}C to 12^{0}C Only. Diurnal range of temperature is also very high in the temperate steppe climate.

Precipitation

The mean annual precipitation ranges between 25 cm to 75 cm in different locations of the temperate grassland steppe areas. The winter precipitation in the northern hemisphere is usually received in the form of snowfall and most parts of Eurasian steppes are snow-covered for several months during northern winters. Most of the annual rainfall is received during summer season.

Regional Characteristics

The Eurasian steppe climate covers the largest area in the former Soviet Union (now the Commonwealth of Independent States-CIS and other Republics of former USSR) wherein it extends from eastern Europe to western Siberia and between temperate coniferous forests in the north and arid regions in the south-west. The Eurasian steppes are divided into (i) **forest steppe,** and (ii) **grass steppe** wherein the former receives mean annual precipitation of 50 cm to 60 cm whereas the latter receives 40 cm to 50 cm as mean annual precipitation. The following sequences of vegetation communities are found from north to south: (i) **forest steppe** (consisting of oak, elms, limes mapple, a few arboreal vegetation of Siberian Steppe such as birch with mixture of aspen and willow), (2) **meadow steppe** (consisting of the species of turf grasses such as Stipa and Fescue and numerous herbaceous flowering plants such as Trifolium and several types of daisy, (3) **grass steppe** (consisting of grasses mainly tussock-forming species of Stipa, a few flowering xerophytic shruby species of Artemisia, (4) **semi-arid xeromorphic steppe** dominated by xerophytic grasses such as Fescue and feather grass species, (mean annual precipitation ranging between 30 cm to 35cm).

The North American Prairie has developed in the USA and Canada between the foothills of the Rockies in the west and temperate deciduous forest biome in the east. On the basis of decreasing trend of mean annual precipitation from east (105cm) to west (40cm) the North American Prairies are divided into 3 subregions e.g. (1) **tall grass prairie** (most dominant species of tallest grass are Bluestem and Switch Grass which attain the height of 1.5cm to 2m, few patches of oak and hickory trees are also found), (2) **mixed prairie** (most extensive cover in the Great Plains of the USA, mixture of medium grasses, 0.6 to 1.5m in height, and short grasses such as little bluestem, needle grass-Stipa sparatea, June grass and short and bunch grasses such as buffalo grass and blue gramma, and (3) **short grass prairie** (developed over western part of the Great Plains and dominated by short grasses of 60cm height).

The South American Pampas are developed over 12 per cent area of Argentina and are more humid than Eurasian steppes. The mean annual precipitation decreases from east (coastal land, 90 cm) to west (45cm). Thus, the Pampas are divided into two sub-types e.g. (i) Humid Pampa and (ii) Subhumid Pampa. The humid Pampa, developed in the eastern part of Argentina, is characterized by tall grasses whereas increasing aridity westward results in the growth of short grasses in the western sub-humid Pampa.

The African veld has developed on the high plateau land of varying heights (1500 m to 2000 m) in the south-eastern part of South Africa. The African Velds include the temperate grasslands of southern Transwall and Orange Free State of South Africa and some parts of Lisotho. Plant growth is not possible because of uncertainty of rainfall, increasing aridity, severity of frosts during night and high daily range of temperature during winter season and thus true climax grasslands of African Velds have developed.

The Australian downs have developed in the south-eastern parts of Australia and in the northern part of Tasmania. The region is characterized by (i) relatively warmer winter season than the temperate grasslands of the northern hemisphere, and (ii) mixture of grasses with eucalyptus trees. The grasslands gradually change from south (Australian coast) to north (interior land) in accordance with the decreasing trend of mean annual precipitation from south (152cm) to north (63.5). The region is further divided into distinct 3 subregions e.g. (1) temperate tall grasslands, (2) temperate short grasslands, and (3) xerophytic grasslands.

14.7.1 TEMPERATE (STEPPE) GRASSLAND BIOME

The location, spatial distribution of regions of steppe climate and its characteristic features have been already discussed in the preceding section 14.7.

Vegetation Community

Grasses are most dominant members of the different regions of the temperate grasslands of both the hemispheres. The perennial grasses, mostly belonging to the family of **gramineae** of this biome are considered to be the **climax community**. Besides, some herbaceous plants are also found in this biome but trees and shrubs are conspicuous by their general absence. There are two concepts of the evolution of temperate grasslands biome viz. (i) The temperate grasslands are the result of climatic conditions and pedogenic properties of these areas. The extreme continental climate and limited supply of water to the plants because of low rainfall are the main factors for the dominance of grasses and general absence of trees and bushes, and (ii) The climatic origin of the temperate grasslands is not always acceptable because many scientists believe that these grasslands are the result of human activities mainly burning of vegetation.

This biome exhibits close relationships among vegetation types, soil types and climatic conditions and between plant and animal communities. The temperate grassland biome is unique in the sense that it has single-layered structure of vegetation community where the upper canopy of the grasses is formed by their leaves but for a short period the flowering stalks also join the canopy and add grandeur to the top layer. The flowers do not have petals. The pollination of flowers and the dispersal of seeds are facilitated by wind. It may be pointed out that most of the areas of the temperate grasslands have been now cleared and are used for cereal crops. Thus, the temperate grasslands have become now the grainaries of the world and the heartland of the world dairy industry. Since there are some spatial variations in the general characteristics of the vegetations of the different parts of the temperate grasslands of the northern and the southern hemispheres, a brief separate description of vegetation characteristics of each region is necessary to understand the overall nature of the vegetation community of this biome.

(1) **Eurasian Steppes** :The steppe biome has the largest areal extent in the former Soviet Union wherein it extends from eastern Europe to western Siberia and between temperate coniferous forest in the north and arid regions in the south-west. The Russian Steppes are divided into two sub-types on the basis of vegetations e.g. (i) **forest steppe, and** (ii) **grass steppe.** These two combined together represent 12 per cent of the total geographical area of the former Soviet Union. The forest steppe consists of alternate bands of woodland and open steppe. The European forest steppe is represented by oak, limes, elms and maple while the Siberian part of forest steppe consists of birch, aspen and willow. The intervening bands of open steppes in the forest steppes are called **meadow steppes** which are characterized by the common genera of grasses

of fescues (Festuca) and feather grasses (Stipa). The forest steppes receive mean annual precipitation between 500 mm-600 mm whereas the grass-steppes receive mean annual precipitation of 400 mm-500 mm.

The combinations of climate, vegetation and soil change from north to south in the Russian Steppes. In the extreme northern part of the Russian Steppes are found forest-steppes. The soils of the woodland steppe or the forest steppe are degraded **chernozem** because the chernozem has been extensively leached out and transformed into grey forest soils. The grass-steppes, further south of the forest-steppe, is characterized by true chernozem soil. Further southward, the increasing aridity has been responsible for the transformation of true grass steppe into **semi-arid steppe** which is associated with chestnut soil. Further southward, the climate becomes arid and steppe grasslands cease to exist. The following sequences of vegetation are found from north to south in the Russian Steppe:

(i) **Forest Steppe** consists of trees mainly oak, elms, limes, mapple, a few arboreal vegetation of Siberian steppe such as birch with mixture of aspen and willow. The soils have degraded chernozem. There are alternate bands of open steppes between the woodland bands.

(ii) **Meadow steppes** are open steppes between the woodland zones of the forest steppes as described above. The meadow steppes have developed in the areas of well developed deep chernozem soils. These are characterized by the species of turf grasses (such as the species of Stipa and Fescue) and numerous flowering herbaceous plants (such as Trifolium and several types of daisy).

(iii) **Grass steppes** are found over well developed deep chernozem soils and are dominated by grasses, wherein the tussock forming species of Stipa are the most important members of the vegetation community. Besides, a few flowering xerophytic shrubby species of Artemisia are also found in the southern marginal belt of the main grass steppes.

(iv) **Semi-arid xerophytic steppe** is found in the extreme southern and south-western parts of the Russian Steppes where the xerophytic grasses (such as fescue and feather grass species) are also associated with chestnut soil and semi-arid climatic conditions (mean annual precipitation ranging between 300 mm and 350 mm). A few species of xerophytic herbs (such as Artemisia) and some ephemeral herbs are also found in this semi-arid tract.

(2) **North American Prairie** has developed in the U.S.A. and Canada between the foothills of the Rockies in the west and the temperate deciduous forest biome in the east. On the basis of decreasing trend of mean annual precipitation from east (1050 mm) to west (400 mm) and gradient of falling Net Primary Productivity (NPP) the North American Prairies are divided into 3 sub-regions viz. (i) tall grass prairie, (ii) mixed grass prairie and (iii) short grass prairie. It may be pointed out that there is a complete sequence of taller to shorter grasses from east to west.

(i) **Tall grass prairie** is found in the eastern part of the north American Temperate Grasslands (Prairies) wherein the most dominant species of the tallest grass are bluestem and switch grasses which attain the height of 1.5 to 2.5m. There are a few patches of oak and hickory trees within the vast areas of tall grasses.

(ii) **Mixed prairie** has most extensive cover in the Great Plains of the U.S.A. This belt extends between the U.S.—Canada border in the north and Texas in the south. This prairie is characterized by the mixture of medium (0.6-1.2m in height) and short grasses such as little bluestem, needle grass (Stipa spartea), june grass (Koeleria cristata) and the short and bunch grasses such as buffalo grass (Buchloe dactyloider) and blue gramma (Bouteloua gracilis).

(iii) **Short grass prairie** is developed in the western part of the Great Plains and is dominated by the species of short grasses which seldom exceed the height of 60cm.

(3) **South American Pampas** have their most extensive cover in Argentina where these account for about 15 per cent of the total geographical area. The South American Pampas are comparatively more humid than the Eurasian Steppes and North American Prairies. The mean annual precipitation decreases from the east (coastal land, 900 mm) to

the west (450mm). Thus, the Pampas are divided into two sub-types e.g. (i) **humid pampas**, and (ii) **subhumid pampas.** The humid Pampa, developed in the eastern part of Argentina, is characterized by tall grasses whereas the increasing aridity westward results in the growth of short grasses in the western sub-humid Pampa. The important grasses of the Pampa include Briza, Bromus, Panicum, Paspalum, Lolium etc. It may be pointed out that the grasses of the Pampas have multi-layered structure which is the result of the availability of moisture, soil and effects of grazing by the animals. Man has introduced lucerne plant of legume species which forms good forage for the animals. Major part of the Pampas has been cleared of their original grasses and has been converted into agricultural farms mainly wheat fields.

(4) **African Veld** has developed on the high plateau land of vaying heights (1500 to 2000m) in the south-eastern part of South Africa. The African Velds include the temperate grasslands of southern Transwaal and Orange Free State of South Africa and some parts of Lisotho. It may be pointed out that the South American Pampas are developed on flat lowland terrain whereas the south African Velds have developed over 1500-2000 m high plateau surface where the growth of plants is not possible because of uncertainty of rainfall, increasing aridity, severity of frosts during nights and high daily range of temperature during winter season. Thus, the true **climax grass lands** of African Velds have developed. There are much variations in the composition and structure of grasses because of variations in the topographic characteristics, soils, altitudes and climatic conditions. Based on aforesaid considerations the South African Veld biome is further divided into 3 sub-types viz., (i) Themeda Veld, (ii) Alpine Veld and (iii) Sour Veld.

(i) **Themeda veld** has developed at the altitude ranging between 1500 m and 1700 m where mean annual precipitation of 650 mm to 750 mm is recorded. The most dominant grass species is red grass (Themeda triandra) which has developed on black turf soils. It may be pointed out that the original dominant red grasses of this biome have been transformed to less useful xerophytic forms because of continued pressure of overgrazing by man.

(ii) **Sour Veld** represents those areas of Themeda Veld which are dominated by relatively less important grasses such as Aristida, Eragrostis and Hyparrhenia.

(iii) **Alpine Veld** is found over relatively higher altitudes (2000-2500 m) of the Darkensberg Mountain where Themeda grasses are found mixed with Festuca and Bromus which are developed on black soils.

(5) **Australian Downs** have developed in the south-eastern parts of Australia and northern part of Tasmania. This region is characterized by (i) relatively warmer winter season than the temperate grasslands of the northern hemisphere (Eurasian Steppes and North American Prairies) and (ii) mixture of grasses with eucalyptus trees. The grasslands gradually change from south (Australian coast) to north (interior land) in accordance with the decreasing trend of mean annual precipitation from south (1524 mm) to north (635mm) Thus, 3 distinct and different grasslands are found in the Australian Downs (temperate grasslands) e.g. (i) temperate tall grasslands, (ii) temperate short grasslands and (iii) xerophytic grasslands.

(i) **Temperate tall grasslands** have developed in a region which extends from the eastern coastal lands of New South Wales to Victoria and eastern Tasmania. The dominant grasses are Poa tussock and Themeda Australia. The Themeda Australia is also called as kangaroo grass because it is very much palatable to kangaroos. Danthonia pallida dominates the areas with drier environmental condition.

(ii) **Temperate short grasslands** have developed parallel to but north of the Temperate Tall Grasslands as discussed above. The important grasses developed in this biome include short species of grasses such as Danthonia and Stipa gegera of grasses.

(iii) **Xerophytic grasslands** are developed further northward such as the interior lands of New South Wales and Queensland which are characterized by semi-arid climatic conditions and the grasses, which have developed in this biome, are adapted to dry conditions. The important species of this biome are Aristida and Mulga (a shrub species).

(6) **Canterbury Grasslands of New Zealand** The original temperate grasslands were developed in the eastern part of the southern island and the central part of the northern island of New Zealand wherein the tussock or bunch grasses were the dominant species but man has changed and transformed the original structure of the temperate grasslands within the last 100 years or so through his economic activities. At present there are two main types of grasses in the temperate grassland biome of New Zealand e.g. (i) short tussock grasses having the main species of Festuca and Poa, are 50 cm tall and yellow-brown in colour, and (ii) tall tussock grasses (main species being Chinomechloa) are found relatively over higher grounds.

The average Net Primary Productivity of the Temperate Grassland Biome is 600 dry grams per square meter per year whereas the total Net Primary Production of all the regions of this biome spread in the northern and the southern hemispheres is 5.4×10^9 tons per year. The average biomass of these grasslands is about 1600 grams per spuare meter. It may be pointed out that the temperate grasses have well developed network of root systems. The roots may penetrate upto 2m in the ground whereas the shoots of the grasses are only 0.6 to 1.2m above the ground. It is thus obvious that the root systems of the temperate grasslands have more biomass (2000 grams per square meter) than the biomass of grass standing above the ground (1600 grams per square meter). The long and dense mesh of root systems of short and bunch grasses such as blue grama and buffalo grasses account for 50-55 per cent of their total biomass.

Animal Community

The animal community of the temperate grassland biome is characterized by unique property in that every grassland region of the southern and the northern hemispheres is dominated by a few species of large mammals for example, buffalo and pronghorn antelope in the North American Prairies; wild horse and saiga antelope in the Eurasian Steppes; antelopes in the South African Velds and guanaco in the South American Pampas. Secondly, the large herbivorous animals of the temperate grasslands are endowed with sturdy bodies so that they are able to protect themselves to some extent from their predator enemies like wolf and coyote. Thirdly, the grazing mammals have developed migratory habits so that they may avoid overuse of their forage and thus can conserve their food resources. Inspite of the aforesaid and even more similarities in the animal communities of different regions of the temperate grassland biome there are some regional variations as well.

(1) The most important animals of the Eurasian steppes are saiga antelopes of the western steppes and Mongolian gazelles of the eastern steppes and the rare species of wild horses of the ungulate category (animals having hoofs). Among the burrowing animals rodents are important species. These rodents and mole rats dig out long and circuitous tunnels in the soft-dry soils to store food and to protect them from the severe cold. They remain indoor throughout the day (in side their tunnels) but come out of their tunnels during nights to get food. Predator animals include wolves, eagles, large hawks etc. which depend on rodents for their food. Polecat is also an important species of smaller predator animals.

(2) The bisons and pronghorns dominated the animals community of the North American Prairies before the arrival of the European settlers, explorers and fur traders in this continent but now these animals are on the verge of extinction because of their indiscriminate mass hunting by the European immigrants. Similarly, there were numerous species of rodents in the American Prairies such as gophers and prairie dogs which used to live in long and narrow tunnels dug-out in the loose and dry soils to protect them from the predators during day-time but most of these rodents have been either eliminated or markedly reduced in number because of removal of grasses on a large-scale for agricultural development. A large number of predator species depending primarily on rodents such as hawks, eagles, rattle-snakes, foxes, wolves etc. have also been adversely affected by ever-expanding agriculture in the prairies. Thus, the agricultural development of the North American Prairies has provided food to large number of human population on the one hand but this practice has disturbed the original natural ecosystem of the

Prairie grassland and has created ecological imbalance on the other hand.

(3) The South American Pampas have now become major wheat fields and the remaining grasslands are so open that herbivorous animals are provided little natural refuge and protection from predator animals. The Pampa deer is important among many species of herbivorous grazing animals whereas rodents mainly viscacha and mara are important burrowing species of mammals which like the rodents of the North American Prairies live in long and circuitous tunnels in the loose and dry soils. Rhea is very important flightless species of birds which resembles emu of the Australian Downs and ostrich of African Savanna. Inspite of its giant body size the Rhea becomes successful to some extent in protecting him from his predators because his colour helps him to become invisible in the surroundings of the local vegetation and his height enables him to see and detect the enemies (predators). The predator animals include manned wolf which depends on rodents, birds and even small reptiles. The Pampas are enriched by many migratory seasonal birds such as herons, geese, ducks, etc.

(4) The animal life of the South African **Velds** has been largely affected and modified by human activities. The region was earlier enriched by large herds of game, antelopes, hyaenas, jackals, lions, leoparads etc. (all belonging to carnivorous category) and zebra but now these animals are not seen in the Veldean grassland because large-scale hunting has either eliminated them or has forced them to seek refuge in other areas. Since most of the natural habitats of these animals have been converted into farmlands, the original animals have also been replaced by domesticated animals such as farm animals, cattle (for dairy purposes), sheep and goats. Some of the birds and most of rodents are still found in this biome because the birds having high degree of mobility easily escape from their most dangerous enemy (man) while the rodents hide them in the long and circuitous earthen tunnels. The important species of rodents are springhare and gerbil whereas important species of carnivorous group of burrowing animals include yellow mongoose.

(5) The Australian Downs are dominated by kangaroos which are of three types e.g. (i) red kangaroos, (ii) grey kangaroos, and (iii) wallaroos. The European rabbits introduced in this biome have so greatly multiplied within the last 100 years or so that they have now outnumbered other animals and have become dominant animal species of the Australian temperate grasslands. The introduction of sheep for commercial purposes has also altered the composition of animal community in this grassland biome. Emu is the typical flightless bird species of this region.

(6) The New Zealandean Grassland Biome is characterized by almost general absence of herbaceous mammals because of the fact that this island probably has always been isolated from the other landmases and therefore no migration of animals from other areas into New Zeland could be possible. Previously this biome was inhabited by giant flightless birds, the moas, but now these have disappeared because of their large-scale hunting by man.

Man and Temperate Grassland Biome

The climatic conditions, resultant soils, native and transformed regional vegetations, animal communities and of course man produced a unique interactive temperate grassland biome ecosystem but the dominant activities of man and their widespread impacts on the total transformation of this biome/ecosystem have altogether changed the very nature of this biome/ecosystem. 'So virgin grasslands are rare since most of them have been altered by pastoralism of domesticated animals, replaced by agricultural ecosystems, or converted into a different species composition through the use of biocides (weed and/or pest killers) or mechanical processes such as brush removal, seeding with leguminous species or simply through the invasion of new (including exotic) species following utilization by man' (I.G. Simmons, 1982)

No other natural ecosystem or biome tells the story of the impact of human activities better than the temperate grassland biomes of the world. Majority of the original grasslands have now been converted into agricultural farmlands which have now become famous 'grainaries of the world'.

Wheat, corn and dairy farming now occupy most of the areas of the North American Prairies (of the U.S.A. and Canada); wheat fields have replaced most of the Steppes of Kazakhastan and of northern China; South American Pampas are now extensively farmed for wheat and the semi-arid temperate grasslands have been converted into great sheep and cattle ranches of the world.

The wide-spread agricultural development in the temperate grassland biomes at the cost of natural and original stands of rich grasses of numerous varieties have led to the emergence of several ecological and environmental problems.

(i) The conversion of natural grasslands of this biome resulted into the obliteration of natural habitats of the animals of numerous speceies. Thus, the disappearance of natural habitats or their overall transformation has caused disappearance and extinction of several animal species. For example, bisons and pronghorns, once the dominant animal species of the North American Prairies, are now facing imminent extinction; many rodents of the temperate grasslands have now become endangered species because of the destruction of their natural hideouts of tunnels dug-out in the loose and dry soils through large-scale ploughing by tractors; many of the animal species such as game, antelopes, zebras, lions, leopards and hyaenas have disappeared from several temperate grasslands etc.

(ii) Large-scale hunting of animals has resulted into phenomenal decrease of the populations of some animals, migration of some animals to other areas and disappearance and extinction of some animals. For example, many species of animals such as game, antelope, zebra, lions, leopards, hyaenas etc. have disappeared from the African Velds because of mass hunting of animals by the European immingrants.

(iii) The introduction of new species of exotic animals has altogether changed the compositions of native vegetation. For example, the introduction of sheep by the European settlers in Australia has changed the composition of vegetation community which was originally suited to the native marsupial animals. The introduction of European rabbits into Australia by the European immigrants has resulted into such a phenomenal growth in their populations that they have become menace to both the natural vegetation community and man. Predator foxes have been introduced in this region to control the ever-increasing population of rabbits but this has not produced any fruitful result.

(iv) The introduction of new species of exotic plants into many parts of the temperate grasslands has either suppressed the native natural vegetation or has eliminated many plant species. For example, the introduction of a new species of leguminous plants such as clover and grasses such as Bromus hardeum and perennial ryegrass by European immigrants into Australian temperate grasslands has suppressed several species of native perennial grasses.

(v) Extensive cultivation of the semi-arid prairie regions of the Great Plains of the U.S.A. has resulted into enormous deflation of dry, loose and friable soils by wind which (deflation of soil particles) generates dust storms during the periods of drought which cause great damage to crops and human property in the Mississippi plains. Due to greater frequency of intense dust storms the areas of the semi-arid parts of the western Kanasas, Texas and Oklahoma are called **Dust Bowl.**

(vi) The large-scale removal of vegetation for agricultural purposes has resulted in the loosening of the soil cover because of the destruction of dense network of root systems of grasses. This change in the soil cover has resulted into accelerated rate of soil erosion and therefore loss of otherwise rich and fertile soils.

14.8 WEST EUROPEAN TYPE OF CLIMATE (Cb)

Location

West European type of climate (Cb) also known as **marine west coast climate** is located between 40^0 and 65^0 latitudes in both the hemispheres along the western coasts of the continents. This climatic region is surrounded by Mediterranean climate in the south, continental dry climate in the east and semi-arctic climate in the north. The inland extension of this climate is controlled by topographic features. For example, wherever the coast is paralleled by mountain ranges, this climate is found in a very narrow coastal belt e.g. marine west coast climate is confined to the coastal strips along the western coasts of North and South Americas because of Rockies and Andes. On the other hand, wherever relief barrier does not exist, marine influences reach far inland e.g. north-western Europe. Thus the west European type of climate has developed over north-western Europe (including Great Britain, western Norway, Denmark, northwest Germany, Netherlands, Belgium, Luxemberg, and north-western France), British Columbia of Canada, Washington and Oregon states of the USA, south-west coast of Chile (S. America), south-east coast of Australia, and Tasmania and New Zealand.

Temperature

The temperatures, in the west European climate, are affected by marine influences, warm ocean currents and prevailing winds and air masses. In fact, the moderating effects of sea bring down the difference between summer and winter seasons considerably. This climate is characterized by cool summer and mild winters. Average temperature during summer season ranges between 15°C and 21°C. Thus, the summer months are characterized by **negative thermal anomaly** i.e. the coastal regions in the marine west coast climate record relatively lower temperature during summer season than the average temperature for their latitudes. There is very negligible variation in the spatial distribution of temperature during summer season as it is indicated by mean July temperature of the following stations = 17°C at Seattle (USA), 14.4°C at Bergen (Norway), 15.6°C at Dublin (Ireland), and 19°C at Paris (France). The daily minimum temperatures in July at Seattle and Bellingham (Wales) are 12.8°C and 10.6°C respectively while daily maxima at these stations are 22.8°C and 21.7°C respectively. Thus, diurnal range of temperature in July for Seattle and Bellingham becomes 10.0°C and 11.1°C. Some times, daytime summer temperature exceptionally rises to 32°C –38°C.

Winters are exceptionally milder for their latitudes due to proximity of warm ocean currents and thus the coastal locations of western Europe are characterized by **positive thermal anomaly** i.e. they record higher temperature than the average temperature of their respective latitudes due to the influence of warm North Atlantic Drift (extension of warm Gulf Stream). The positive thermal anomaly of 11.°C to 17°C is a common feature. The winter temperature decreases rapidly from the coasts towards the interior parts in Europe due to decreasing marine influence inland. This is why the January isotherms instead of following latitudes become parallel to the coasts. The mean January temperature in coastal areas of N.W. Europe ranges between 4°C and 10°C but it becomes -18°C to -40°C in the interior continental locations of Eurasia. The night temperature generally falls below freezing point and hence ground frost is of very common occurrence. Cold waves are generated due to arrival of cold continental polar air masses.

The marine west coast climate comes under the domain of westerlies which are regular features throughout the year. Since these winds come from over the oceans and hence they are moist and give precipitation. These westerlies are also associated with temperate cyclones which are the main sources of precipitation. The poleward margins are dominated by subpolar low pressure belt of dynamic origin where unstable polar front is formed due to convergence of two contrasting air masses e.g. warm and moist westerlies and cold polar air mass. This polar front thus causes the development of temperate cyclones which move in easterly direction under the influence of westerlies.

Precipitation

Marine coast climate or West European type of climate is basically humid climate and is characterized by abundant and uniformly distributed precipitation throughout the year but winter maximum is the characteristic feature of coastal locations while interior locations record summer maximum. Inspite of abundant precipitation all the year round there is much spatial variation in its amount. Generally, precipitation decreases from the coasts towards interior locations and from north to south along the coast. The regional distribution of precipitation is highly controlled by topographic factor. The areas of low reliefs receive relatively low precipitation. For example, the north-western

European lowland in the absence of any effective relief barrier receives mean annual precipitation ranging between 50 cm and 75 cm. On the other hand, the western coastal areas of North America and of Chile in South America falling under marine west coast climate receive high mean annual precipitation ranging between 250 cm and 375 cm because of the presence of the Coast Range mountains in North America (parallel to the coast) and the Andes in South America (parallel to the coast). The leeward slopes of these mountains become dry because of very low precipitation as they fall in **rainshadow region.**

Though the precipitation is uniformly distributed throughout the year but winter season receives more than the summer season, but there is no dry month. These conditions are confined only to the coastal location because interior locations receive more precipitation in summers than in winters. The precipitation in lowland areas (plains) is cyclonic in nature and is usually received in the form of drizzles and continues for fairly long time. Sky remains overcast for several days in continuation. The winter cyclonic precipitation is very widespread. The summer precipitation is of short duration but is stormy and heavy. The 6 cm July precipitation of London is received in 13 days while 5.3cm January precipitation comes in 15 days. The thunderstorms are very few in number. It is interesting to note that though the mean annual rainfall is moderate but it is received in large number of rainy days. For example, the mean annual precipitation of 56.5 cm of Paris is received in 188 rainy days while London gets mean annual precipitation of 71.3 cm in 164 days. The percentage of cloudiness is also much higher in this climate e.g. the Pacific coastal areas of N. America record average annual cloudiness between 60-70 per cent while it is 70 per cent in the western Europe. Winter months are also characterized by snowfall but the number of days receiving snowfall is less than in other climates located within the same latitudes. The snow days in London, Paris and Seattle (representing low land loation) are 13, 14 and 10 respectively. The frequency of snow-days and intensity of snowfall both increases poleward and towards interior locations.

Natural Vegetation

The abundant precipitation throughout the year has given birth to dense forests of three types e.g. (i) broad-leaf deciduous forest (oak, birch, walnut, maple, elm, chestnut etc.), (ii) needle-leaf (coniferous) forest (pine, fir, spruce etc.), and (iii) mixed forest but cleared in British Isles and European countries due to urban and agricultural development. Dense forests are now found only on mountains and highlands. Douglas fir, redwood, hemlock, spruce, cedar etc. soft wood forests of much commercial use are found in the states of Washington, and Oregon of the USA and British Columbia of Canada.

14.9 BOREAL OR SUBARCTIC OR TAIGA TYPE OF CLIMATE (E CLIMATE)

Location

The boreal or sub-arctic climate representing the boreal forest biome or temperate coniferous forest biome and the most extreme type of microthermal climate is called **taiga type** or Siberian type of climate and includes the areas of subarctic regions of North America (extending from Alaska of the USA across Canada to Hudson Bay in the east) and Eurasia (from the Scandinavian Peninsula across the Russian Siberia to the Bering Sea) (fig. 14.8). Besides, there are small patches of this climate at higher altitudes in Germany, Poland, Switzerland, Austria and other parts of Europe and on the high Rocky Mountains of North America. In fact, the taiga climate is located between the tundra climate in the north and the temperate grassland biome (climate) (Eurasian steppes and North American Prairies) in the south. The taiga climate is conspicuous by its total absence in the southern hemisphere because of narrowing trend of continents towards the south pole. The vicinal location of taiga climate extends from 50^0- 55^0N to 65^0-70^0N latitudes.

Temperature

The taiga type of climate is characterized by extreme continental climate marked by bitterly cold winter of long duration and cool short summer season of brief period extending over one to three months. Spring and autumn are merely brief transitional periods between summer and cold seasons. The 10°C isotherm of the warmest month forms the northern boundary of this climatic region. The winter season extending over 8 months always records temperatures below freezing point as is apparent from the average January temperatures of the following inland locations = –26°C at Eagle (Canada), –30.6°C at Dawson (Canada), -24°C at Okhotsk (Russia), –43.3°C at Yakutsk (Russia), –50.6°C at Verkhoyansk (Russia) etc. The Siberian taiga climate records the lowest minimum temperature e.g. Verkhoyansk –68°C and Oimekon -66.8°C (Russia, lowest temperature everrecorded) while the lowest minimum temperature recorded so far in North American sub-arctic climate at Snag (Yukon, Alaska, USA) is -62.8°C.

In comparison to severe cold winter months, temperature during brief summer season increases rapidly. July being the warmest month has an average temperature of 16°C. It may be pointed out that several interior locations record temperature below freezing point even in the month of July. The growing season is between 50 to 70 days only because soil water is frozen for 5 to 7 months of winter season in continuation. The annual ranges of temperature are very large and greatly vary from place to place. For example, the temperature of the coldest and warmest months of Moscow are -12°C and 20°C respectively and thus the annual range of temperature becomes 32°C. Verkhoyansk records the annual range of temperature of more than 64°C.

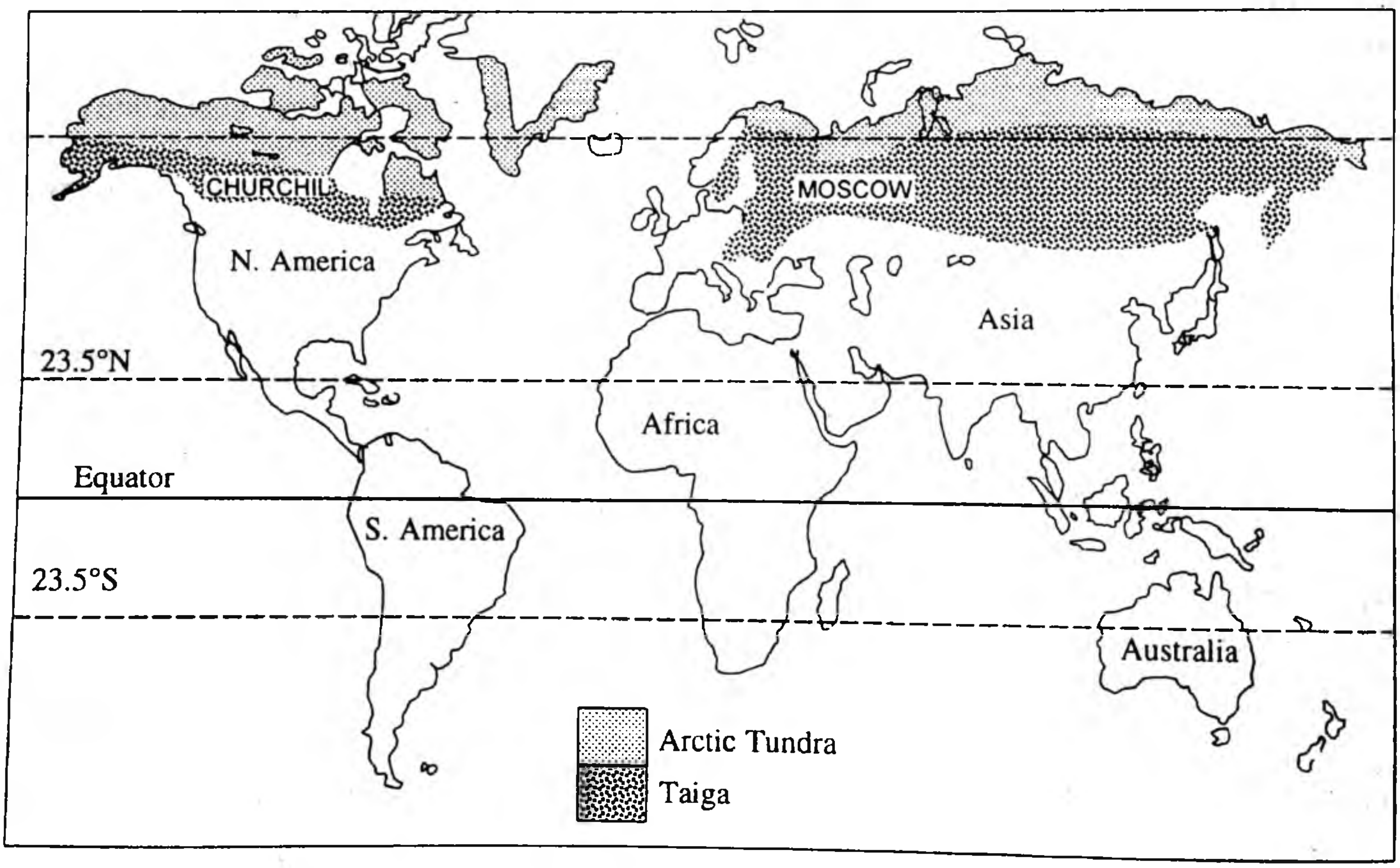


Fig. 14.8 : Location of taiga and tundra types of climate.

Precipitation

The subarctic or taiga type of climate is characterized by low mean annual precipitation because (i) extremely low temperature for longer period of the year does not favour evaporation and thus there is very low amount of absolute humidity in the air, (ii) the regions falling in taiga type of climate are located in the leeward sides of the continents and in the interior regions and thus they are away from the marine influences, and (iii) the regions are characterized by polar high pressure, anticylonic conditions are evidenced by subsidence of air from above and divergence of surface winds. The mean annual precipitation ranging between 37 cm and 60 cm is received mostly in the form of fine, dry snow which accumulates throughout the winter and is released as surface water due to thawing because of increase in temperature during brief summer season. It may be pointed out that the precipitation is more or less uniformly distributed throughout the year whether in liquid form as rainfall (during summer) or snowfall during winters.

The following are the main characteristic features of subaractic taiga type of climate:

(i) Bitterly cold long winter season (temperature below zero degree centigrade at least for 6 months).

(ii) Heavy snowfall during winter season.

(iii) Formation of permafrost ground (permanently frozen ground) because of freezing of ground moisture due to subfreezing temperature.

(iv) Cool summer of short duration having precipitation in liquid form (rainfall and melting of snow cover).

(v) Growing period of vegetation ranging from 50 days a year along the northern boundary to 100 days along the southern boundary.

(vi) High range of variability in the spatial distribution of annual precipitation.

(vii) Extreme annual range of temperature (ranging between 25^{0}C during summer months and 40^{0}C during winter months).

Natural Vegetation

The coniferous trees are the most dominant member of taiga climate or the Boreal Forest Biome. These trees form dense cover of forests which are the richest sources of softwood in the world. There are four major genera of evergreen coniferous trees e.g. (i) Pine (white pine, red pine, Scots pine, jack pine, lodgepole pine etc.), (ii) Fir (doughlas fir, balsam fir etc.), (iii) Spruce (Picea), and (iv) Larch (Larix). Besides, a few species of temperate deciduous hard-wood trees have also developed in this climate mainly in those areas which have been cleared by man through felling of original temperate coniferous trees. Thus, the temperate deciduous trees represent the 'secondary succession of vegetation' which includes alder, birch and poplar.

14.10 TUNDRA CLIMATE (Ft)

Location

Tundra is a Finnish word which means barren land. Thus, the tundra region having least vegetation and polar or arctic climate is found in North America and Eurasia between the southern limit of the permanent ice caps in the north and the northern limit of taiga or subarcitc climate in the south. Thus, tundra climate has developed over parts of Alaska (USA), extreme northern parts of Canada, the coastal strips of Greenland and the arctic seasboard regions of European Russia and northern Siberia. Besides, tundra climate has also developed over arctic islands (fig. 14.8). Vegetations rapidly change to the north of treeline because of increasing severity of climate.

Tundra climate is further divided into two subtypes e.g. (i) **arctic tundra climate,** and (ii) **alpine tundra climate** (which is found over high mountains of tropical to temperate areas). Based on variations in general vegetation characteristics arctic tundra is divided in 3 zones from south to north viz. (i) low arctic tundra, (ii) middle arctic tundra, and (iii) high arctic tundra. It may be pointed out that high, middle, and low are not indicative of altitudes rather these indicate latitudes.

The poleward boundary of tundra climate is demarcated by 0^{0}C isotherm of the warmest month of the year while 10^{0}C isotherm of the warmest month makes the equatorward boundary.

Temperature

The tundra climate is characterized by general absence of insolation and sunlight and very low temperature throughout the year. The average annual temperature is 12^{0}C. Winters are long, bitterly cold and very severe while summers are very short but cool. The warmest month of the year records average temperature between 0°C and 10°C. It is interesting to note that diurnal range of temperature is very low because of very little difference in day and night temperatures but the annual range is quite large. The severe climate does not favour much vegetation growth and hence most of the areas under tundra climate remain barren land. The ground surface is covered with snow at least for 7 to 8 months each year. The region is swept by speedy cold powdery storms known as blizzards. Growing season is less than 50 days in a year. The ground is permanently frozen (permafrost). Even soil is also perennially frozen.

Precipitation

Mean annual precipitation, mostly in the form of snowfall, is below 40 cm. The absolute humidity is very low because of very low rate of evaporation due to very low temperature throughout the year. The divergent system of air circulation and anticyclonic conditions do not favour much precipitation. Most of the annual precipitation is received during summer and autumn because of relatively higher temperature.

Natural Vegetation

There is prefect relationship between vegetation and the condition of moisture in the soils. The characteristic lithosols of tundra biome support only lichens and mosses. Only 3 per cent species of the total world species of plant could develope in tundra climate because of the severity of cold and the absence of minimum amount of insolation and sunlight. The vegetations of tundra climate are cryophytes i.e. such vegetations are well adapted to severe cold conditions as they have developed such unique features which enable them to withstand extreme cold conditions. Most of the plants are tufted in form and range in height between 5 cm and 8 cm. These plants have the tendency of sticking to the ground surface because the temperature of the ground surface is relatively higher than the temperature of the overlying air. The herbs have developed only in those areas where heaps of icy and snow protect the plants from gusty ice winds. Such herbaceous plants include willow the stems of which are very close to the ground surface (hardly a few centimetres above the ground). Though the growth rate of these herbaceous plants is exceedingly slow but their survival period is unbelievably very long (between 150 to 300 years). The evergreen flowering plants develop on the ground like cushions mostly during short cool summers.

14.10.1 TUNDRA BIOME

The location, spatial distribution of tundra climatic region and climatic characteristic features have been discussed in the preceding section 14.10.

Vegetation Community

There is perfect relationship between vegetation and the condition of moisture in the soils. The characteristic lithosols of the tundra biome (a well drained soil) support only lichens and mosses. Arctic gray soils favour the growth of dwarf herbaceous plants and bog soils maintain sedges and mosses. Only 3 per cent species of the total world species of plants could develop in the tundra biome because of the severity of cold and absence of minimum amount of insolation and sunlight. The vegetations of the tundra biome are cryophytes i.e. such vegetations are well adapted to severe cold conditions as they have developed such unique features which enable them to withstand extreme cold conditions.

According to N. Pollumin (1959) there are 66 families of cryophytes in Arctic Tundra Biome. The number of plant species and plant population decreases northward with increasing severity of cold. Most of the plants are tufted in form and range in height between 5 cm and 8 cm. These plants have the tendency of sticking to the ground surface because the temperature of the ground surface is relatively higher than the temperature of the overlying air. The herbs are developed mainly in those areas where heaps of ice and snow protect the plants from gusty icy winds. Such herbaceous plants include willow (Salix herbacea and Salix arctica). The stems and leaves of these herbaceous plants are very close to the ground surface (hardly a few centimetres above the ground surface). Though the growth rate of these herbaceous plants is exceedingly slow but their survival period is unbelievably very long (between 150 to 300 years).

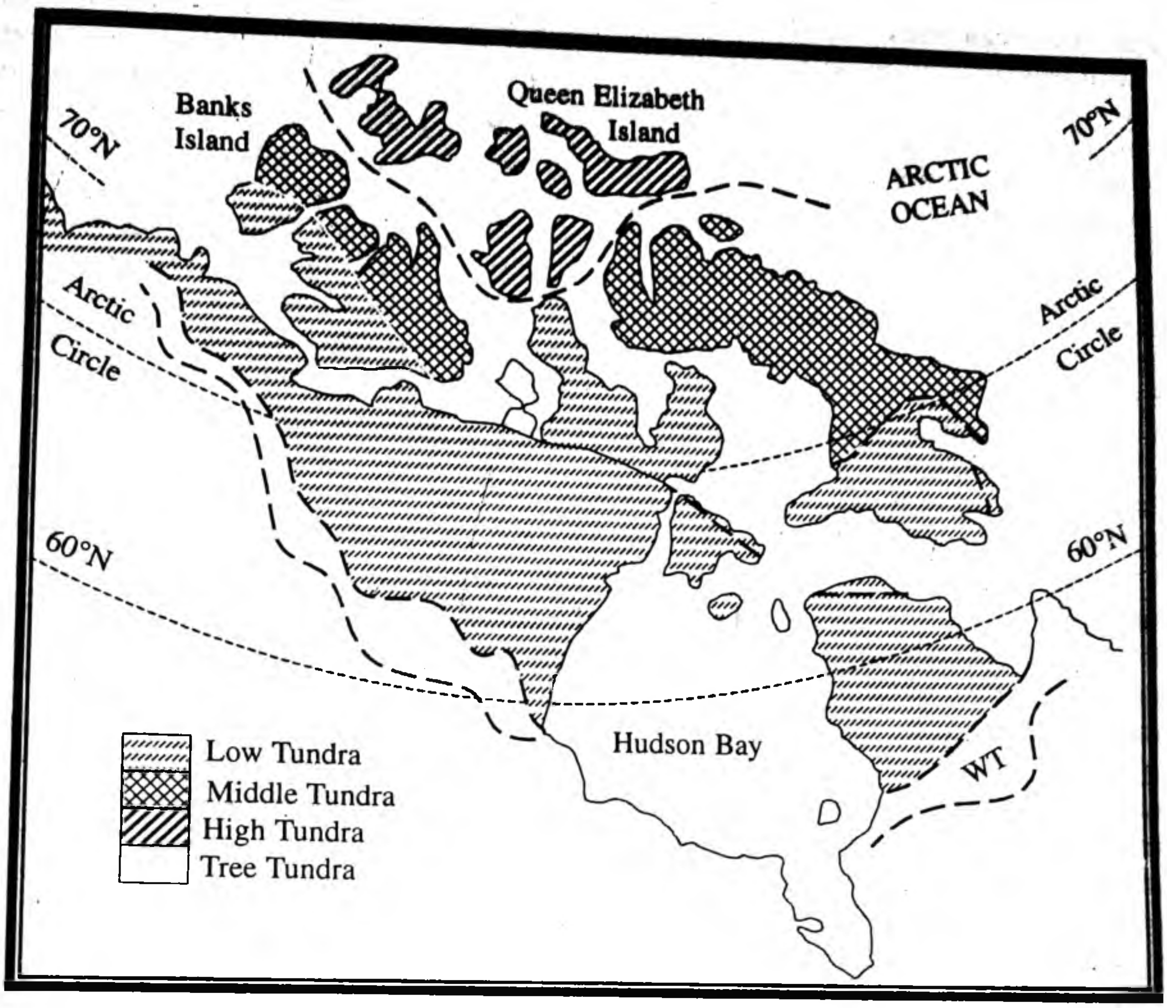


Fig. 14.9 : Divisions of Arctic Tundra of Canada.

The evergreen flowering plants develop on the ground like cushions mostly during short cool summers. These flowering herbaceous plants include moss campion (Silence acaulis). Some plants assume the shape of rosette wherein the leaves radiate from a point and leafless stalk bearing flower grows upward. Saxifragus nivalis is the typical species of rosette plants. Some plants are endowed with the typical features of fleshy leaves, thick cuticle and external covers of hairs (epidermal hairs) around their stems and branches. Some plants grow on the ground like tussocks while other groups of plants grow horizontally on the ground surface like mats or compact turf (such as Dryas octopetala). It may be pointed out that the period available for the growth of tundra plants is of only 50 days during cool summer season, during which all the stages of the life-cycle of a plant are completed e.g. growth of plant tissues, flowering, pollination, ripening of seeds, dispersal of seeds and establishment of seedlings etc.

Animal Community

The animals of Arctic Tundra Biome are grouped into two categories viz. (i) **resident animals**, and (ii) **migrant animals.** Most of the animals leave Arctic Tundra and migrate southward during winter season to escape severe cold because only those animals stay at home during severe winter season which have such typical body structures which enable them to withstand the severity of cold. Thus, the resident animals of relatively larger size have thick and dense insulating coat of fur or feathers around their bodies. Such epidermic insulating cover of fur or features works as blanket and keep the animals warm during severe winters. The American musk ox is a typical example of such animals. This bulky herbivourous animal living in the Arctic Tundra of Alaska, northern Canada and Greenland is endowed with epidermic coat of dense and soft wool around his body and an outer cover of thick and long hairs which are so long that they touch the ground. This thick coat protects the musk ox from cold and moisture because this thick coat works as insulator and is impervious for both, cold and moisture. Musk ox gets rid off this heavy coat during summer season to adjust with relatively warmer environment. Thus, after shedding thick hairy and wooly coat the musk ox presents a ragged appearance. The animals are again endowed with this coat during next winter. The arctic fox has double coats of fur around its body and thus is able to withstand very severe cold. It may be pointed out that the fur coat of the arctic fox enables to bear as much low temperature as -50^{0}C and hence the animal is active even during severe winter season and is able to catch its prey such as lemmings and hares. The resident birds have feathers (such as ptarmigan) which protect them from severe cold. In fact, these feathers work as insulators. The smaller birds protect them from severe cold by shivering or by fluffing their feathers.

Some resident animals of the Arctic Tundra Biome change their colour during different seasons of the year. For example, ptarmigan (a kind of bird) changes the colour of its feathers thrice a year. The arctic foxes and stoat, prominent predator animals having fur coat, are brown in colour during summer season but become white in colour during winter season. Some animals such as wolves and caribou have such hairless feet which act as insulator and do not allow the heat of their bodies to escape. Some smaller animals such as rodents, lemmings, shrews, voles etc. live in burrows and tunnels during winter season to protect them from severe cold and hungry predator animals.

The second category of animals of the Arctic Tundra Biome consists of **migratary animals** which start migrating with the beginning of winter season to warmer areas in the south and return back to their native places during coming spring season. The animals move away from their native places during every winter season because they are not equiped with suitable devices which may enable them to protect themselves from the severity of cold as is the case with the **resident animals** as referred to above. The birds, such as waterfowl, ducks, swans, geese etc., are the first to leave their native places with the arrival of autumn and are also first to come back to their original places in the spring or early summer. Some birds establish sexual contact before they return to their native places during summer season. Some birds return to the same nests which they left at the time of their migration during winter season. Since the summer season is of very short duration and many functions and duties like nesting, pairing or courtship (sexual contact between the pair of male and female birds), laying of eggs, hatching and rearing of offsprings are to be completed within this short period, the most of the birds are not used to have sexual contacts for long duration.

Some birds cover very long distances during the period of their migration. For example, the arctic tern is the most important migratory bird, as it breeds during summer season in the Arctic Tundra and leaves its native place with the beginning of winter season and reaches as far south as Antarctica in the southern hemisphere which is characterized by summer season. It is obvious that the arctic tern is benefited from two summer seasons in a single year. Mosquitoes, midges and blacky are important species of insects which emerge in huge and dense swarms in pools, ponds, lakes, bogs and swamps during summer season. Tundra birds feed and rear their offsprings on huge populations of insects, moluscs and worms which also emerge in huge swarms during summer season in pools, ponds, rivers, lakes, swamps and soils.

Raindeer and caribou are important animals of the category of large migratory animals. These mammals spend winter season in temperate coniferous forest biome or taiga biome located to the south of their native tundra biome and establish sexual contact. It may be pointed out that the female raindeer and caribou conceive through winter mating (sexual intercourse between male and female animals) during their winter migration to temperate coniferous forest but they deliver their offsprings in (calves) tundra regions during summer season when they migrate from temperate coniferous forests to tundra biome. Thus, raindeers and caribous cover distances of hundreds of kilometres each year between summer and winter seasons of the same year. Some times mother raindeer and caribou deliver youngones in the transit and such newly born youngones perish in the way because they are unable to undertake arduous long journey. These animals again move southward in herds as the arrival of winter season is heralded.

This annual rhythm of migration of animals from tundras to southerly temperate coniferous forest regions during winter season and from the latter to the former during summer season continues without any interruption. It is significant to note that this seasonal migration of tundra animals is motivated by the availability and non-availability of food which itself is created by varying weather conditions of the region. The migrating herds of raindeer and caribou are attacked by wolves and several weak, lame and ill animals and many youngones are killed and eaten away by predators. These animals are also attacked by great swarms of numerous mosquitoes and many bloodsucking insects during their summer stay in tundra region. These animals have no better alternative to escape from the attack of aforesaid insects than to take temporary refuge in ponds, lakes or streams which even is nearer to their localities.

Primary productivity in tundra biome is exceedingly low because of (i) minimum sunlight and insolation, (ii) absence or scarcity of nutrients (such as nitrogen and phosphorous) in the soils, (iii) poorly developed soils, (iv) scarcity of moisture in the soils, (v) permanently frozen ground (permafrost), (vi) very short growing period (about 50 days) etc. According to V.D. Alexandrova (1970) the mean regional primary productivity decreases from low Arctic tundra (228 dry grams/m^2/year) to high Arctic Tundra (142 dry grams per square meter per year) whereas the lowest primary productivity of 12 dry grams per square meter per year is found in the polar desert areas. The net primary productivity (NPP) of the Tundra Biome is 140 dry grams per square meter per year whereas the total net primary production of all parts of the tundra biome is 1.1×10^9 tons per year. It may be pointed out that because of severity of climate and resultant poor vegetation, dry areas produce little litter but wet litter accumulates to form peat, and there is very slow and thus low nutrient release to vegetation. It is thus clear that the scarcity of food makes the tundra animals migratory.

Man and Tundra Biome

Man is closely associated with the biota of the Tundra Biome because even his very existence depends upon animals of both terrestrial and aquatic habitats. Previously the Eskimos of Greenland, northern Canada and Alaska; Lapps of northern Finland and Scandinavia; Samoyeds of Siberia; Yakuts of Leena basin and Koryak and Chuckchi of north-eastern Asia spent complete nomadic life depending on their food derived from fish seals, walruses, polar bears and other animals and on other commodities derived from caribou (the relative of Eurasian raindeer is called caribou in North American Tundra), raindeer and various fur animals. Thus the earlier nomadic tundra man inflicted a great damage to tundra animals through his hunting activities. But now the situation has changed as many of the people of the Tundra Biome are leading a permanent or semi-nomadic life. The Eskimos have established permanent settlements and have formed villages in the coastal areas of tundra region and have domesticated caribou and fur animals. Many of Eskimo children have got modern education in the schools. They have adapted to new technologies. For example, deadly rifles have replaced the traditional and out-dated harpoons. Thus, the modern Eskimos equiped with modern technologies are now in a position to damage the tundra ecosystem in the same way as is done by already technologically advanced man in other biomes. The Samoyeds and other tribes of the Eurasian Tundra have also adapted new way of life. Some of them are leading permanently settled life. They rear raindeers and fur animals and even grow food crops mainly wheat in the Siberian Tundra while some tribes still wander with their herds of raindeer across the Eurasian Tundra in search of pastures.

14.11 IMPORTANT DEFINITIONS

Batha : Batha is dwarf shrub of European Mediterranean biome. It is locally called **sage scrub** in California.

Biome : Biome is a large natural ecosystem having physical (abiotic) and biotic components. It comprises total assemblage of plant and animal communities and their mutual interactions.

Dust bowls : The areas of western Kansas, Texas and Oklahoma are called dust bowls due to greater frequency and intensity of dust storms.

Epiphytes : Epiphytes are tropical climbers having no roots on the ground surface but are evolved on the trunks, branches and leaves of trees, shrubs, climbers etc.

Fymbos : The sclerophyllous shrubs are locally called fymbus in South African Mediterranean biome.

Lianas : The tropical long woody climbers (creepers) in equatorial rainforests are called lianas. These are found in all the vertical strata of the forests.

Pampas : The temperate grasslands of Argentina and Uruguay are called 'pampas'.

Pustaz : The isolated patches of steppes in Hungry are locally called 'pustaz'.

Sclerophyll ecosystem : The Mediterranean biome is called sclerophyll ecosystem because of the development of special type of features and characteristics in the dominant trees and shrubs to adapt to the typcail environmental conditions of dry summers and wet winter.

Southern busters :tropical cyclones in Australia are called southern busters.

Winters of tropics : Nights in the equatorial rain forest climate are called winters of the tropics as the relatively low nocturnal temperature becomes uncomfortable to local people.

15

CLIMATIC CHANGE

15.1 MEANING AND CONCEPT

Variability, in both time and space, is an inherent feature of climate, as the atmosphere is always in the state of turmoil and instability leading to variations in weather and climatic conditions. The climatic change, thus, is defined as variations and shifts in weather conditions over space and time of different scales and magnitude resulting into change of climatic type for example, from warm and moist climate to warm and dry climate, from warm and moist climate to cool and moist climate (as happened during Carboniferous period in India) etc. Infact, climatic change refers to drastic or secular changes in heat balance of the earth-atmosphere system, moisture, cloudiness and precipitation caused by either external factors such as variations in orbital characteristics of the earth, solar variability (fluctuations in radiation from the photosphere of the sun), tectonic processes (mainly plate tectonics and displacement of continents and ocean basins), vulcanicity, changes in atmospheric composition in terms of concentration of atmospheric aerosols and carbon dioxide contents etc. or by internal factors such as exchanges of energy between the atmosphere, hydrosphere, lithosphere and cryosphere (ice covered surfaces of both lithosphere and hydrosphere) or by both, at local, regional and global levels. The **climochronology** (history of palaeoclimates) reveals the fact that climates have changed in the geological past and hence it is opined that 'the world's climates have changed in the past, are changing now, and there is every reason to expect that they will change in future' (*J.E. Hobbs*, 1980). If the change is law of nature, the change in climates is a reality because the climate of a region is not fixed and static rather it goes on changing. Some times, the changes are cyclic and rhythmic, such change is called **climatic cycle**. It may be mentioned that James Hutton (a Scottish geologist) while propounding the **concept of uniformitarianism**, postulated the concept of **cyclic nature of earth's history**. The example of occurrences of ice ages during (1) pre-Cambrian period (850-600 million years before present, mbp = million years before present), (2) Ordovician period (450-430 mbp), (3) Carboniferous—Permian periods (300 mbp), and (4) Pleistocene period (2-3 mbp) validates the concept of **cyclic nature of climatic changes.**

The climatic changes are supposed to be quick and rapid rather than slow and gradual but this may not be always true as climate changes both gradually and rapidly, partly and drastically. For example, the climatic change, which occurred during Jurassic period leading to mass extinction of dinasaurs due to sudden onset of cold climate, was rapid and instantaneous. In fact, the rate of climatic changes depends on the nature of causal factors. The rapid Jurassic climatic change is related to sudden collision of the earth and a giant meteors and consequent release of enormous amount of dusts in the atmosphere. One cannot infer the nature of long-period climate on the basis of present-day climatic conditions. It is also an observed fact that the 'cool periods of earth history are periods of greater than normal climatic instability' (*J. E. Hobbs*, 1980).

The human society with present-day weather conditions is seized with the problems of possible climatic changes in near future. The most significant global environmental problem faced by the world community is **global environmental changes** (GEC) leading to probable climatic changes consequent upon global warming resulting from a host of causal factors, namely ozone depletion, increase in the emission of green house gases at alarming rate, deforestation etc. The probable net result of global warming would be climatic changes at local, regional, and global levels. The international communities are scared of catastrophic adverse effects of future climatic changes on different spheres of man and nature, e.g. deglaciation and sea level changes, submergence of island nations and major coastal lowlands, atmospheric dynamics including evaporation and precipitation, global radiation balance, photosynthesis and ecological productivity, plant and animal communities, human health and many more. It may be summarized that climatic change is a reality, it has changed in the past, it is changing at the present, and it will change in future. The change of climate may be slow and gradual, rapid and catastrophic, periodic, semi-periodic or non-periodic, short-term or long-term, may be at local, regional and global scales, it may be due to natural factors or anthropogenic factors. It is, thus, necessary to discuss various aspects of climatic changes, namely scales of climatic changes (both spatial and temporal scales), indicators of climatic changes (i.e. evidences of climatic changes), reconstruction of palaecolimates (climochronology), causes of climatic changes, theories of climatic changes, and effects of climatic changes on both nature and biological communities including human beings.

15.2 SCALE DIMENSION

The climatic variations and changes are viewed in terms of temporal and spatial scales depending on the purpose of studies. The temporal scales of climatic changes range from a very micro-scale involving 10-day period to macro-temporal scale involving thousands to millions of years. 'The variability may be periodic (A), quasi-periodic (B), or non-periodic (C), or alternatively it may show a progressive trend' (*Barry* and *Chorley*, 2002). It may be mentioned that spatial and temporal scales of climatic changes are correlated e.g. as the temporal scale of change becomes shorter, the area also becomes smaller. In other words, the changes may be more perceptible and pronounced in localized area during short period of recorded climatic data, but if we consider climatic data at regional level involving large countries or continents, and at global level, the local level changes are overshadowed. Thus, the climatic changes may be viewed in terms of three temporal scales, namely (i) macro-temporal scale (millions of years), (ii) meso-temporal scale (thousands of years), and (iii) micro-temporal scale (hundreds of years). These three temporal scales correspond to global, regional, and local spatial scales. At regional and local spatial scales the climatic variability can be looked upon at even shorter temporal scales which may range from very micro-temporal scale to increasing time span e.g. (1) 10 days time scale, (e) 10-100 days time scale, (3) 100-1000 days time scale, (4) 1000-10000 days time scale etc. It may be remembered that such changes may be detected only if the instrumented data are very accurate and regular. The climate changes which occurred in the past, say before the industrial revolution, cannot be viewed in such a micro-temporal scales.

Generally, climatic changes are considered at two levels e.g. (1) **short-term changes**, and (2) **long-term changes.** Short-term climatic changes involve the consideration of changes in the energy balance of the earth-atmosphere system leading to periodic changes in weather and climate. This temporal scale involves time span ranging from few years to thousands of years. Short-term climatic changes are either inter-annual or they may persist for many years and are generally caused by anthropogenic factors. On the other hand, long-term climatic changes persist for thousands to millions of years and are exceedingly slow. These are always caused by natural factors.

15.3 INDICATORS OF CLIMATIC CHANGES

The evidences of climatic changes in the past, which are utilized in the reconstruction of **climochronology** (history of palaeoclimates) are called indicators of past climatic changes. The riddle of reconstruction of palaeoclimates is a fascinating puzzle, the solution of which basically depends on **proxy data** (which include alternative sources of data as substitutes for real data) and logical deductions by the investigators. It may be mentioned that recorded data of weather and climate are available only since industrial revolution, more precisely for the last 100 years or so, and hence proxy data for recorded data are the only indicators to decipher the pages of past climatic history and changes on the basis of Huttonian theory of **uniformitiarianism** (postulated by Scottish geologist, James Hutton in the year 1785). This theory was based on two concepts of Hutton, namely (i) **'present is key to the past'**, and (ii) **'no vestige of a beginning, no prospect of an end.'** The principle of uniformitarianism states that *'the same physical processes and laws that operate today, operated throughout geological time, although not necessarily always with the same intensity as now'* (Hutton postulated same intensity of processes throughout geological time).

The indicators (clues) of palaeoclimates may be classified on the basis of basic sources as follows :

(1) **Biological Indicators**

- (A) **Floral indicators**
  - (i) fossil remains of plants
  - (ii) fossilized pollens
  - (iii) oxygen isotopes
  - (iv) tree ring growth (dendrochronology))
- (B) **Faunal indicators (evidences)**
  - (i) fossilized animal remains
  - (ii) distribution and dispersals of animals

(2) **Geological Indicators**

- (A) **Terrigeneous ancient deposits**
  - (i) lacustrine deposits (varves)
  - (ii) evaporite deposits
  - (iii) sedimentary deposits (coals)
- (B) **Marine deposits**
  - (i) sea floor deposits
- (C) **Pedogenic indicators**

(3) **Cryogenic Indicators**

- (A) **Glaciation**
  - (i) ice ages
  - (ii) glaciers and glaciation
  - (iii) ice sheets and ice cores
- (B) **Periglacial evidences**

(4) **Tectonic Indicators**

- (A) **Plate tectonics**
  - (i) pole wandering and continental drift
  - (ii) palaeomagnetism and sea floor spreading
- (B) **Sea level changes**

(5) **Geomorphological Indicators**

- (A) **Morphological features**
  - (i) erratics
  - (ii) sand dunes
  - (iii) river terraces

(iv) duricrusts
(v) pediments
(iv) tors

(B) **Geomorphological processes**

(6) **Historical Records**

(i) flood records
(ii) drought records
(iii) migration of man and animals

1. Biological Indicators

The fossilized organic remains of plants and animals (i.e. organic residues) provide significant evidences and proxy data for contemporary climatic conditions mainly temperatures and moisture. It may be mentioned that the nature and types of organisms and their habitats are determined by a climatic type. After their deaths the plants and animals are preserved in the forms of fossilized organic remains in the contemporary and subsequent geological formations. The analysis of such organic fossils through the application of proper techniques (e.g. carbon dating, oxygen isotope analysis, pollen analysis, dendrochronology etc.) reveals important clues to decipher contemporary past climates. The biological indicators fall under two broad categories e.g. (1) plant (floral) indicators, and (2) animal indicators (faunal indicators).

(1) Plant (floral) Indicators

Presently, there is very close correspondence between the distribution of climate types and vegetation types. Based on the principle of **uniformitarianism,** as stated above, and the concept of '**present is key to the past**' it may be opined that similar relationships and conditions might have prevailed throughout geological history of the earth. Thus, on the basis of fossilized plant remains, the vegetation type is inferred and such inferred information (proxy data) provide clue to determine the nature of climate. For example, the existence of coals having remains of tropical forests, in the north-west Europe and Great Britain remind us hot and humid climate of these areas during Jurassic period. The **plant physiology** gives sufficient information about climatic conditions. For example, the fossil remains of plants having long roots, thick barks, waxy leaves, thorns, little leaves etc. indicate warm and dry climate (warm desert climate), while plants having drip leaves are indicators of warm and very moist conditions (tropical rainforest climate). Now question arises, why plant physiology indicates a particular climate? The answer is simple, the physiological characteristics of plants are indicative of their adaptation to particular type of climatic conditions. A few more examples may be cited. The vegetation community having sclerophyllous characteristics (stiff and hard leaves and stems with thick barks) can withstand extreme aridity of summer season. The plant remains of such sclerophyllous vegetation indicate dry summer and wet winter climate (Mediterranean type of climate). The cryophyte vegetations are well adapted to severe cold conditions as they develop such unique features which enable them to withstand extreme cold conditions. Thus, the fossil remains of cryophyte plants indicate cold climatic conditions (tundra climate).

The remains of vegetation in the thick coal seams of Carboniferous period worldover are related to horsetails and club mosses which develop in marsh and swamp environment. The fossil remains of trees in Carboniferous coal seams do not indicate annual ring growth which reveal the fact that such trees thrived in warm and moist climate with no appreciable seasonal contrasts.

Pollen Analysis

The pollen analysis involves the inference of climatic conditions on the basis of dating of fossilized pollen grains preserved in the inorganic sediments layers. It may be mentioned that pollen grains of flowering plants are very durable organic substances which are duly preserved by the nature. The pollen grains are distributed by wind in wide areas having similar type of vegetation. The science of **palynology,** which is the study of pollen grains and spores of plants, helps in identifying the types of vegetation on the basis of pollen grains, and the vegetation types give clues for deciphering the climate in which that vegetation type might have developed. The pollen analysis involves the identification of layered sequence of pollen grains in the terrigenous sediments, the dating of pollen grains of each layer, determination of vegetation type of each layer and finally the determination of climatic condition of each vegetation type (fig. 15.1). Fig. 15.1 depicts the pollen analysis technique wherein the fossilized pollen grains preserved in lacustrine deposits of lower, middle and upper layers denote dominance of pine in the lower layer, prevalence of pine and spruce in the middle layer, and oak, beech and spruce species of trees in the upper layer under the modern plant covers. On the basis of the principle of uniformitarianism, the lower and middle layers having pollen grains of pine and spruce indicate cool climate while the upper layer containing pollen grains of oak, beech and spruce trees reveals the prevalence of warm and moist climate.

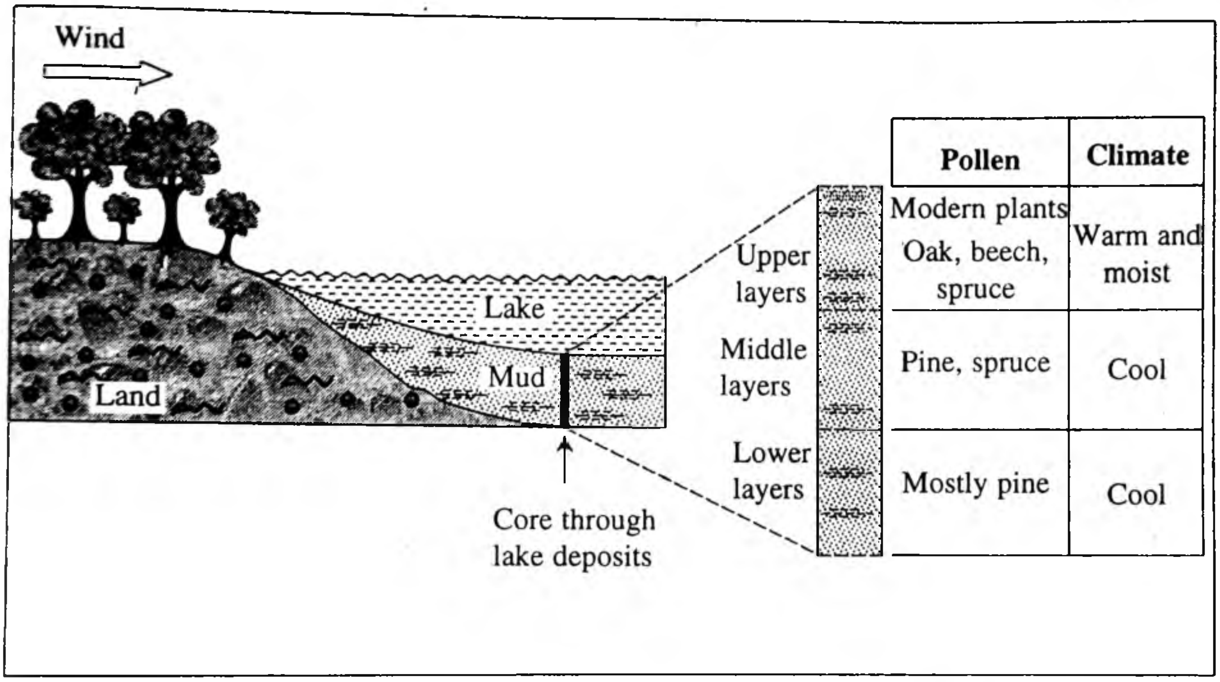


Fig. 15.1 : Presentation of simplified method of pollen analysis for the reconstruction of palacoelimates. After J.E. Oliver and J.J. Hindore, 2003.

It may be remembered that pollens of flowers of plants are blown away by winds, they settle down on land surface as well as water surfaces of lakes, ponds etc. The pollens deposited on land surfaces may decay after lapse of time but pollen grains falling on water surfaces sink down and are deposited in the layers of sediments. The pollens so fossilized in different sedimentary layers are identified and their plant species are determined. The identification of plant species on the basis of their pollen grains then helps in determining the climatic conditions on the basis of present relationship between plant types and associated climatic conditions.

Inspite of wide use of pollen analysis technique in determining vegetation types and associated climatic conditions this method suffers from the following shortcomings.

(i) In the case of mixed vegetation area having several plant species, the pollen grains are mixed and in such circumstances it becomes difficult to separate pollen grains of dominant and co-dominant plant species and hence this technique fails to give desirable result.

(ii) The winds can carry the pollen grains and deposit them in distant places away from the area of the vegetation of which the pollens have been blown away.

(iii) Not all the pollens of vegetation of a region are deposited, rather they are deposited selectively and randomly, and hence they may not be taken as representatives of particular vegetation type.

(iv) The distribution of vegetation has been tempered and modified by human actions, both advertent and inadvertent and hence pollen analysis would not be useful for the reconstruction of climates of recent past mainly since the neolithic times.

(v) 'A vegetation cover only attains maturity after fairly a lengthy period of time, and it is quite feasible that the vegetation established through pollen analysis represents successional stage that is not totally representative of the prevailing climate' (Oliver and Hidore, 2003).

Dendrochronology

Dendrochronology is the science that deals with 'the study of the annual rings of trees in determining the dates and chronological orders of past climatic events'. The ring growth of the trunk and stem of a tree provides significant clues for detecting seasonal rhythms of climate during the life time of the concerned tree. The thickness and spacing, and colour of growth rings indicate the climatic conditions and rate of annual growth of trees. The widely spaced thick growth rings denote warm and moist climate with sufficient rainfall to support luxurious and quick growth of trees, while narrow and closely spaced tree growth rings denote arid climate and poor growth of trees. The colours of growth rings also denote seasonal weather conditions. 'The abrupt change from light to dark-coloured rings (growth rings) delineates the annual increments of growth' (*Oliver* and *Hidore*, 2003). It may be mentioned that the study and interpretation of different aspects of tree rings such as, the size (thick or narrow), number, colour shades, symmetry or asymmetry etc. provide information about climatic and environmental variations sustained by the concerned tree during its life time and hence the climatic events which happened in the recent past, say 3000-4000 years before present may be reconstructed on the basis of dendrochronological characteristics.

The study of tree ring growth, known as dendrochronology, was initiated by A. E. Douglas and his team at the University of Arizona, USA. After the analysis of growth rings of trees in the southwestern USA he found close relationship between annual amount of rainfall and growth rings in the adverse climatic conditions of the S. W. United States. The scientists have become successful in reconstructing the climatic conditions and environmental changes for the last 3000 years on the basis of analysis of growth rings of living trees, and for the last 5000 years on the basis of fossils of dead trees. The scientists at Laboratory of Tree Ring Research, University of Arizona, USA, have also derived logical and fruitful inferences about the relationship between weather elements (e.g. temperature, air pressure, and atmospheric circulation patterns) and widths and spacing of tree rings. Such relationships have also been used to demonstrate climatic fluctuations which took place during the life time of trees.

Dendrochronology also helps in reconstructing the advances and retreats of glaciers in the recent past on the basis of shapes of tree growth rings like concentric (symmetrical) growth rings or asymmetrical rings. It may be remembered that growth rings become concentric and symmetrical as long as the trees remain perfectly erect (perpendicular to the ground surface) but become asymmetrical when the trees are tilted. It is argued that trees are erect when the glacial ice is away from the position of trees but they are tilted when ice comes close to the trees. Thus, erect trees and resultant concentric and symmetrical growth rings are indicative of withdrawal or retreat of glaciers while asymmetrical rings reveal advancing glaciers. It may be mentioned that tilting of trees and resultant asymmetrical growth rings may not be always due to glacial advancement, rather it may also be due to landslides, gusty winds, strong storms etc.

(2) Faunal Indicators

Identification and analysis of fossilized invertebrate animal remains embedded in the sedimentary formations provides significant clues about the climatic conditions that existed during the period of their survivals. In this respect the physiological characteristics of fossils of invertebrate animals (without backbones) and their chemistry are of vital significance wherein two techniques are used to determine their age, namely (1) **radiocarbon dating (C-14 analysis)**, and (2) **isotope analysis.**

The analysis of fossils of bones of invertebrate animals helps in determining the lithological successions of sedimentary formations containing animal fossils and thereafter the sequences of palaeoclimates are reconstructed on the basis of dating of animal fossils and sedimentary layers. It may be remembered that animal fossils are mostly preserved in the bottoms of oceans, lakes and rivers which provided them suitable habitats for their development and survival. Each species of tiny creature (e.g. foraminifera) survives in certain temperature and moisture condition. After death such creatures are embedded in the mud layers of water bodies. The mass deaths of certain species of micro-organisms take place when the temperature and moisture conditions change and become unfavourable to them. New species of organisms develop in accordance with new temperature and moisture regime. This process continues and fossils of animals are deposited in the successive layers of bottom sedimentary layers of seas, lakes and rivers. After determining the lithological successions, the animal fossils in each layer are identified and their dates are determined on the basis of carbon-14 analysis. On the basis of the principle of '**uniformitarianism**' (the comparison of animals of a particular geological period as determined on the basis of C-14 analysis, with identical animals at present provides the climatic conditions in which they lived on the ground that same physical processes and laws which operate today operated throughout geological periods) the climatic conditions of that particular period is inferred.

The **radiocarbon dating method** or **carbon-14 analysis** requires obtaining of cores of mud layers containing animal and plant fossils from the floors of oceans, lakes, and river valleys and the dating of the fossils is accomplished through the analysis of carbon-14 and carbon-12 contained in the skeletons of the fossilized animals. It may be mentioned that skeletons of dead animals 'contain both ordinary carbon and minute trace of isotope carbon-14. The proportion of carbon-14 to carbon-12 remains fixed while the organism is alive. After it dies the carbon-14 begins to decay; by knowing the ratio of carbon-12 to carbon-14, one can determine the age of the shell' (Oliver and Hidore, 2003).

The **isotope analysis of the chemistry** of skeletons of fossilized animals also helps in determining palaeoclimates on the basis of temperature and moisture conditions which are inferred from the body chemistry of dead animals. Oxygen has three non-radioactive isotopes e.g. O^{17}, O^{18} and O^{16} out of which the first two isotopes are not very common but the last one is common and normal isotope. After the evaporation of water, these isotopes crystallize at different rates in the shells i.e. O^{18} isotope settles down more rapidly than the O^{16} isotope because the latter is lighter than the former isotope (O^{18}). It may be mentioned that the rate of crystallization of oxygen isotope is controlled by temperature. The number of settling O^{18} isotope decreases with increase in the temperature of ocean water. Thus, on the basis of number of oxygen isotopes contained in the shells of dead animals the prevailing temperature at the time of the existence of particular animal is determined. For this purpose again the cores of mud layers from the floors of oceans, lakes and river valleys are taken out, oxygen isotopes of shells of each mud layer are determined, temperature condition for each mud layer is inferred and finally temperatures prevailing at the time of deposition of animal skeletons and mud layers are used to ascertain climatic changes.

Two important research projects, namely **CLIMAP** (Climate, Longrange Investigation, Mapping and Prediction) and **COHMAP** (Cooperative Holocene Mapping Project), were concerned with the study of climatic changes which might have occurred in the recent past on the basis of **carbon-14 analysis** and **isotope analysis** of skeletons of organisms embedded in the mud layers at the floors of the oceans. The CLIMAP studies concentrated on the reconstruction of palaeoclimates of about 1,000,000 years before present, while COHMAP project studied the palaeoclimates of the past 10,000 years only.

The occurrence of large numbers of animal fossils in close proximity of a region denotes the fact that they might have been killed during a catastrophic disasters e.g. advancing ice sheets and freezing, severe droughts, meteoric collision with the earth (as is supposed to have happened during Cretaceous period killing dinasaurs enmass) etc. On the basis of such evidences one can infer the climatic and environmental conditions at the time of concerned catastrophic disaster.

2. Geological Indicators

Geological indicators (evidences) of palaeoclimates include lithological characteristics of mainly sedimentary deposits such as lacustrine deposits (varves), evaporites, limestones and coal seams, marine deposits (sea floor deposits), soil profiles etc. Varves are the alternate sequences of layers of fine silts and clays deposited at the floors of lakes and large ponds in such an area which is characterized by alternate freezing and thawing during winter and summer seasons respectively. Thus, the lithological sequences of lacustrine deposits in the aforesaid condition denote periglacial climate. The analysis of annual layers of silt and clay provides an idea of seasonal changes in climate. It may be mentioned that when the surface freezes during winter season, very fine suspended clay particles are deposited in the lakes and ponds but during summer season, when frozen surface thaws (melts), silts with melt water are deposited in the lakes and ponds. Such type of annual banded alternate layers of clay and silt denote periglacial climate.

Evaporite deposits, represented by salt deposits, occur when climate is characterized by high temperature and aridity wherein evaporation exceeds precipitation. In such circumstances water is evaporated and salt contents are left behind. It may be mentioned that this happens only when water on land is saline and thus salt is in solution form. So, the massive salt rocks deposited on land surfaces, such as in South-West USA, Germany, Central Asia, North-West India (mainly Rajasthan and Gujarat), denote hot and arid climatic environment.

Limestones ($CaCO_3$) containing calcium carbonates are deposited in tropical warm oceanic water and hence the occurrence of limestones in the regions having cold climates denotes the fact that the concerned region was under tropical warm climate at the time of limestone deposition.

Duricrusts are indurated hardened surfaces of different kinds such as **laterites, silcretes, calcretes, alcretes, ferricretes** etc. depending on the dominance of constituent minerals. Normally, lateritic crusts are supposed to have been formed in hot and humid climate of tropical and subtropical areas and therefore these are indicative of hot and humid climate. Lateritic crusts are predominantly found in Chotanagpur high lands (Patlands of Ranchi and Palamau plateaus of Jharkhand), and over many areas of Deccan plateau (e.g. Mahabaleshwar and Panchgani plateaus of Maharashtra). The presence of lateritic crusts in certain parts of Europe (e.g. U.K. and Germany) clearly demonstrates the fact that these are not the result of the present temperate climate. 'Such crusts are often interpreted as of Tertiary age, or as having been under continuous formation since the end of the Mesozoic. Exposures of silcretes and calcretes similarly are often related to past rather than present climatic conditions' (**D. R. Stoddart, 1969**).

Pedogenic criteria used to decipher past climates, include the analysis of palaeosols and fossils of plants and animals therein. The alluvial soils buried in older flood plains give indication of moist climate and the dominance of fluvial processes. The older loessic soils indicate dry climate and the dominance of aeolian process. Even the materials involved in the deposition of loess also give clues for climatic conditions. The extensive loess deposits of China having areal coverage of 774,000 km^2 and thickness of 90 m to 300 m consist of materials blown from the deserts of central Asia while the European loess is example of glacial loess. The American loess, extensively found in Illinois, Iowa, Nebraska etc. is partly glacial and partly desert loess. The datermination of palaeoclimates on the basis of fossil remains in the soils is accomplished through radiocarbon dating and isotope analysis, which have already been explained in the previous subsection on floral and faunal indicators.

3. Cryogenic Indicators

Cryogenic indicators are related to the proxy data from the evidences of glaciation, glaciers and icesheets. The science dealing with glaciation and glaciers is known as **glaciology.** The processes of glaciation and deglaciation provide significant proxy data for climatic changes and **fluctuation.** The period of widespread glaciation of larger areas of the globe is called **great ice age** which comprises several glacial and interglacial periods. The glacial period denotes onset of cold climate and advance of ice sheets while interglacial periods indicate relatively warmer periods when ice sheets retreat. The geologists, glaciologists and climatologists have identified a few great ice ages (e.g. pre-Cambrian ice age, Carboniferous ice age, and Pleistocene ice age) when major portions of the globe were glaciated and covered with thick ice sheets which are definite indicators of major climatic changes.

Credit goes to European school of geomorphologists and glaciologists for identification and recognition of ice ages. *Louis Agassiz* (1807-1873 A.D.) is given credit for an early start in this precarious field and for the recognition and identification of the presence of ice age during Pleistocene period as he presented his ideas in the year 1840. A host of geoscientists, namely Jean de Charpentier, John Playfair (1815), Venetz of Switzerland (1821, 1829), Esmark of Norway (1824), Bernhardi of Germany (1832) etc., studied different aspects of Pleistocene ice age. The Scottish geologist James Geikie postulated the concept of 'great ice age' in 1894 which is comprised of several glacial periods which are separated by warm interglacial periods. A. Penck and Bruckner identified four glacial periods during Pleistocene ice age e.g. Gunz, Mindel, Riss, and Wurm which were separated by three warm interglacial periods. Similarly, four glacial periods (e.g. *Nebraskan*, *Kansan*, *Illinoin*, and *Wisconsin*) and three interglacial periods (e.g. *Aftonian*, *Yarmouth*, and *Sangman*) were identified during Pleistocene glaciation of North America. Most of Gondwanaland was glaciated during Carboniferous ice age.

The shapes of glaciated valleys, glacial drifts, erratics (glacial boulders), striations etc. provide important clues for climatic changes.

The glaciers and ice layers provide evidences for temperature and precipitation conditions during different phases of ice ages. Advancing glaciers and ice sheets indicate cold phase and lowering of temperature much below freezing point, while retreat of ice sheets heralds increase in temperature and subsequent ablation of glaciers demonstrates onset of warmer climate. The glaciologists have demonstrated the retreat of Alpine glaciers and resultant shrinking in their length and width about 3000 B.C. (i.e. about 5000 ybp, years before present), followed by re-advance of glaciers about 500 B.C. (i.e. 2500 ybp) and again retreat of glaciers. The Alpine and Scandinavian glaciers registered resurgence in the 17th and 19th centuries while they again started to retreat in the 20th century. All these indicate climatic fluctuations characterized by cooling (advance of glaciers) and warming (retreat of glaciers) periods during the past 5000 years in European continent.

Ice sheets and **ice cores** are most significant cryogenic indicators of palaeoclimates. It may be remembered that the ice sheets are formed by the deposition of several layers of ice. The accumulated snow from the annual snowfall is compressed and is changed to ice wherein the air bubbles and atmospheric dusts are trapped. Thus, every year a layer of ice is deposited upon underlying ice layer. It is evident that the great ice caps of Greenland and Antarctica are comprised of numerous ice layers wherein the then climatic conditions have been preserved. Thus, the study of each ice layer provides ample evidence of the weather and climatic conditions at the time of its formation. The drilling into ice caps is undertaken to obtain ice cores for analysis. The following properties of ice layers derived from the ice cores provide proxy data for temperature, precipitation, composition of atmosphere, storminess, volcanic events, atmospheric pollution etc.

(i) thickness of annual ice layers → precipitation

(ii) chemical analysis of annual ice layers → temperature

(iii) air bubbles trapped in the annual ice layers → atmospheric composition

(iv) dust contents trapped in the annual ice layer → atmospheric circulation and storminess

(v) acid content in the annual ice layer → volcanic events

A few studies of ice cores from Greenland ice sheets (namely, Greenland Ice Sheet Project 1 and 2, GISP-1 and 2) and Antarctica ice sheets have revealed sequences of climatic variations for the last 110,000 years and 160,000 years respectively. The analysis of ice cores to obtain climatic records is based on **isotopes** of oxygen (two very common isotopes are ^{16}O and ^{18}O) wherein the ratio of ^{16}O to ^{18}O provides information about the existing environmental temperatures at the time of the formation of annual ice layers. The isotope analysis of ice cores also reveals relationship between global warming and concentration of greenhouse gases (e.g. carbon dioxide, methane etc.), and level of atmospheric pollution caused by anthropogenic sources since the period of industrial revolution. Besides, the concentration of radioactive elements in the atmosphere and their fallout emitted during nuclear plant disasters (for example, Chernobyl nuclear disaster) and testings of atomic devices, can be measured through the analysis of annual ice layers. The ice core analysis also reveals information about the levels of sulphate content in the air emitted from the volcanic eruption. With the improvements in the technologies of obtaining ice cores, studies are carried out to reconstruct the atmospheric conditions mainly temperature variations and climatic fluctuations for the past 200 years or so on the basis of the analysis of ice cores derived from mountain ice sheets in the tropical and subtropical areas.

The **evidences of periglacial features** and deposits found in such areas which at present do not have periglacial environment, indicate earlier periglacial climate of those areas. The term **periglacial** literally means around the ice or peripheral to the margins of the glaciers but now this term is used for both **'periglacial landscape'** and **'periglacial climate'**. Periglacial areas are those which are in permanently frozen condition but without permanent ice cover on the ground surface. The periglacial climate is characterized by mean annual temperature ranging between -1^0C and -15^0C and mean annual precipitation of 120 mm to 1400 mm (mostly in solid form). Many parts of Europe and South-West USA presently do not have periglacial climate but have relict periglacial features which demonstrate that such areas were under periglacial climate in the past.

4. Tectonic Indicators

The tectonic movements involving plate movements, pole wandering, continental drifts, orogenesis, palaeomagnetism, topographic features etc. and seafloor spreading and sea level changes are significant indicators of palaeoclimatic changes. A. Wegener, a German meteorologist, was primarily concerned with the problem of past climatic changes. It may be pointed out that there are ample evidences, as discussed above, which indicate widespread climatic changes throughout the past history of the earth. Infact, the continental drift theory of Wegener 'grew out of the need of explaining the major variations of climate in the past'. The climatic changes which have taken place on the globe may be explained in two ways as follows :

(1) If the continents remained at their places throughout geological history of the earth, the climatic zones might have shifted from one region to another region and thus a particular region might have experienced varying climatic conditions from time to time.

(2) If the climatic zones remained stationary, the landmasses might have been displaced and drifted.

Wagener opted for the second alternative and postulated the concept of 'continental drift' or 'displacement hypothesis' to explain the global climatic changes on the basis of a number of geographical, geological, palaeontological etc. evidences. The plate tectonic theory as an outcome of post-Second World War advancement (mainly in the 1960s) in geotectonics, the evidences of palaeomagnetism and seafloor spreading have validated the concept of polewandering (shifting of the positions of the poles) which help in the reconstruction of climochronology mainly global climatic changes during Carboniferous and Pleistocene Ice Ages and widespread glaciation.

It has been demonstrated that plate movements during Cenozoic era displaced major continental blocks in the middle and high latitudes in the northern hemisphere and thus such northward displaced continental masses were subjected to the dominance of cold climate resulting into widespread glaciation (such as major parts of North America and Eurasia) during Pleistocene period (known as Pleistocene Ice Age and Pleistocene glaciation). On the other hand, mountain ranges of Tertiary period, formed due to collision of convergent plates and consequent subduction of heavier plate and lateral compression, and high plateaus, became effective barriers in controlling the global atmospheric circulation and generating a few new climatic types such as monsoon climate of South Asia (due to relief barriers of the Himalayas and Tibetan plateau). The investigations regarding the impacts of tectonic movements on climatic conditions have revealed strong relationship between horizontal plate movements leading to seafloor spreading along divergent plate boundaries and orogenesis along the convergent plate boundaries, vertical movement (tectonism) leading to upliftment and subsidence and climate change. The changes in global pattern in plate motions cause changes in climates at global scale.

5. Geomorphological Indicators

The geomorphological processes and landforms resulting therefrom have been directly related to particular climatic type on the concept that each climatic type produces its own characteristic assemblage of landforms and set of geomorphological processes which shape them on the basis of the following themes :

(1) Landforms differ significantly in different climatic regions.

(2) Spatial variations of landforms in different climatic regions are because of spatial variations in climatic parameters (e.g. temperature, humidity, precipitation etc.) and their influences on weathering processes, erosion dynamics and surface runoff.

(3) Quaternary climatic changes could not obscure relationships between landforms and climates.

In other words, there are certain diagnostic landforms which clearly demonstrate climate-landforms relationships.

Thus, on the basis of diagnostic landforms, the inference of climatic conditions at the time of the formation of such landform, is drawn which helps in the reconstruction of palaeoclimates.

The climatogenetic or climatically controlled landforms are identified and differentiated in two ways, e.g. (i) general observation and acquaintance of whole landscape of each climatic region, and (ii) identification of typical or distinctive landforms which represent the controls of particular climate. The typical landforms are, in fact, main tools of climatic geomorphologists which help them in determining climate-landforms relationships in different climatic regions. Such distinctive landforms are designated as diagnostic landforms which include duricrusts, inselbergs, pediments, tors, glaciated valleys, glacial boulders or erratics, sand dunes etc.

Duricrusts are indurated hardened surfaces of different kinds such as **laterites, silcretes, calcretes, alcretes, ferricretes** etc. and are normally supposed to have been formed in hot and humid climate of tropical and subtropical areas and hence they are indicative of warm and moist climate. The presence of lateritic crusts in certain parts of Europe (e.g. U.K., Germany etc.) clearly demonstrates the fact that these are not the result of present climate. 'Such crusts are often interpreted as of Tertiary age, or as having been under continuous formation since the end of the Mesozoic. Exposures of silcretes and calcretes are often related to past rather than present climatic conditions' (*D. R. Stoddart,* 1969).

Inselbergs representing steep sided residual hills are considered to be the representative landforms of hot and arid and semi-arid climates. It is argued that inselbergs are structurally controlled rather than climatically controlled and most of the present inselbergs were formed before Quaternary period, 'hence present climates are not necessarily those in which inselbergs were formed' (Stoddart, 1969). It may be possible that inselbergs might have been formed when the climate was warm and arid or semi-arid which might have changed after their formation.

Pediments, characterized by low-angle rock-cut surfaces surrounding mountains, are also considered to be the representative landforms of warm arid and semi-arid climates. Pediments are also found in a variety of climatic conditions e.g. tropical wet and dry climate, subtropical and temperate climates. A few geomorphologists argue that pediments are structurally and tectonically controlled rather than climatically controlled. L.C. King has opined that the process of pediplanation and pedimentation is universal and occurs in all environmental conditions. In fact, 'many arid zone pediments are clearly polycyclic, developed during the complex sequence of Pleistocene pluvials (period of prolonged rainfall) and interpluvials : Many appear to be being destroyed under present climatic conditions, rather than being formed' (*D.R. Stoddart*, 1969).

Tors, 'one of the most controvercial landforms, are piles of broken and exposed masses of hard rocks particularly granites having a crown of rock-blocks of different sizes on the tops and clitters (trains of blocks) on the sides' (*Savindra Singh*, 1977). Tors have been considered of periglacial origin by J. Palmer and *R. A. Neilson* (19€2), of fluvial origin by *D. L. Linton* (1955), whereas *L.C. King* has opined that tors are the result of universal processes of pediplanation in different climatic conditions. In fact, the presence of tors right from the Dartmoor of England through Nicargua to India has complicated the problem of the origin of tors rather than solving it.

It may be concluded that the aforesaid diagnostic landforms are older than Pleistocene climatic changes, so they are definitely not related to present climates where they are found. It may be pointed out that climatic relation of landforms at least in glacial, periglacial and warm desert climates is undoubtedly confirmed. So, such landforms may provide definite clues to reconstruct past climates.

It is an established fact that different geomorphological processes work in different climatic regions because the geomorphic processes originate from the atmosphere and their nature (type, e.g. whether fluvial, or glacial, or periglacial or aeolian etc.) depends on the combinations of temperature and precipitation. Thus, the nature of geomorphological processes in the past geological history of the earth helps in deciphering the climatic conditions in which a particular process was predominant.

The presence of glacial boulders or **erratics** in a region presently having other than glacial climate, may it be warm tropical or temperate climate, reminds us the fact that the region was glaciated at the time of formation and deposition of these erratics. Similarly, the presence of frost-riven cliffs, tors, altiplanation terraces, patterned grounds (having stone rings, polygons, garlands, stripes etc.), thermokarst lakes, nivation hollows, involutions, pingos, congelifluctate landforms, blockfields (blockmeers), boulderfields etc. tells us the dominance of periglacial processes under periglacial climate at the time of the development of such landforms. The presence of glacial boulders and erratics in the coal seams of Talcher of Orissa (India) of Gondwana period clearly indicates an earlier cold and glacial climate in India having presently warm monsoon climate.

6. Sea Level Fluctuations

Fluctuations in sea levels are considered significant indicators of past climatic changes. Sea level changes are of two types, namely **positive change** marked by rise in sea level above datum line, and **negative change** denoting fall in sea level below datum line. Changes in sea level are effected by (i) tectonic movements, and (ii) climatic changes. The tectonic movements cause rise in sea level when there is upward movement of sea floor (ocean bottoms) or down warping of coastal areas whereas fall in sea level is caused by downwarping leading to subsidence of sea floor or upwarping of coastal lands. It may be mentioned that tectonically induced changes in sea levels are very slow. The climatically induced changes in sea levels are rapid and are effected by glacial age and advancement of glaciers and ice sheets (fall in sea levels) and deglaciation leading to retreat of glaciers and ice sheets (rise in sea levels). The sequences of rise and fall in sea levels during Pleistocene Ice Age have revealed several phases of glacial periods (Gunz, Mindel, Riss and Wurm in Europe, and Nebraskan, Kansan, Illinoin and Wisconsin glacial periods in

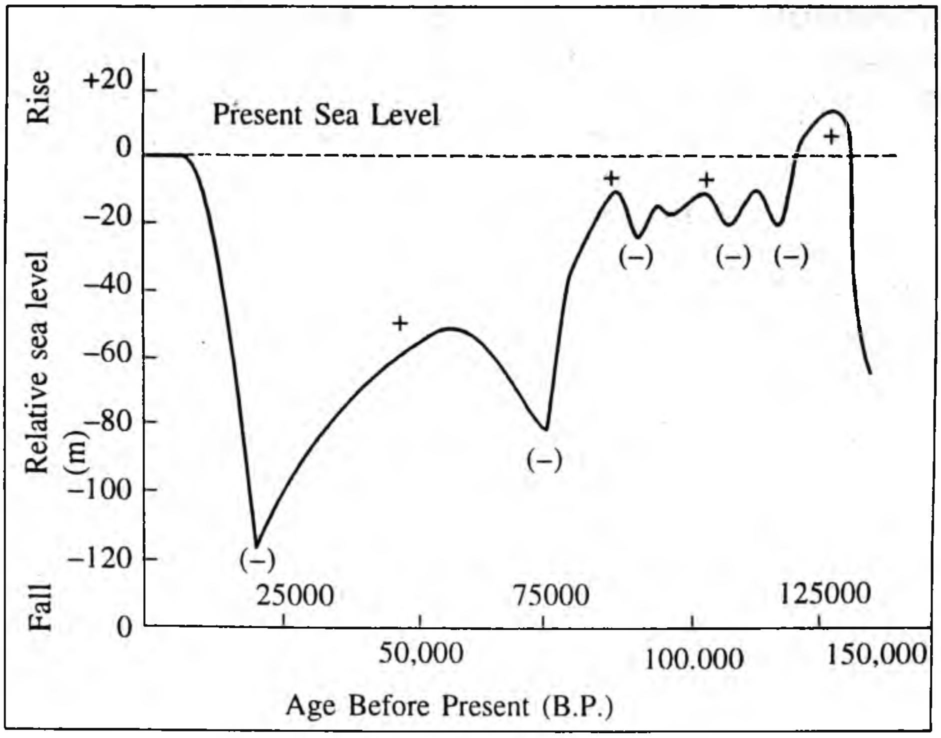


Fig. 15.2 : Fluctuations in sea level during last 150,000 years based on raised coral terraces and core oxygen 18 isotope data from deep sea deposits. Source : after : K.K. Turekian, 1996, in Oliver and Hidore, 2003.

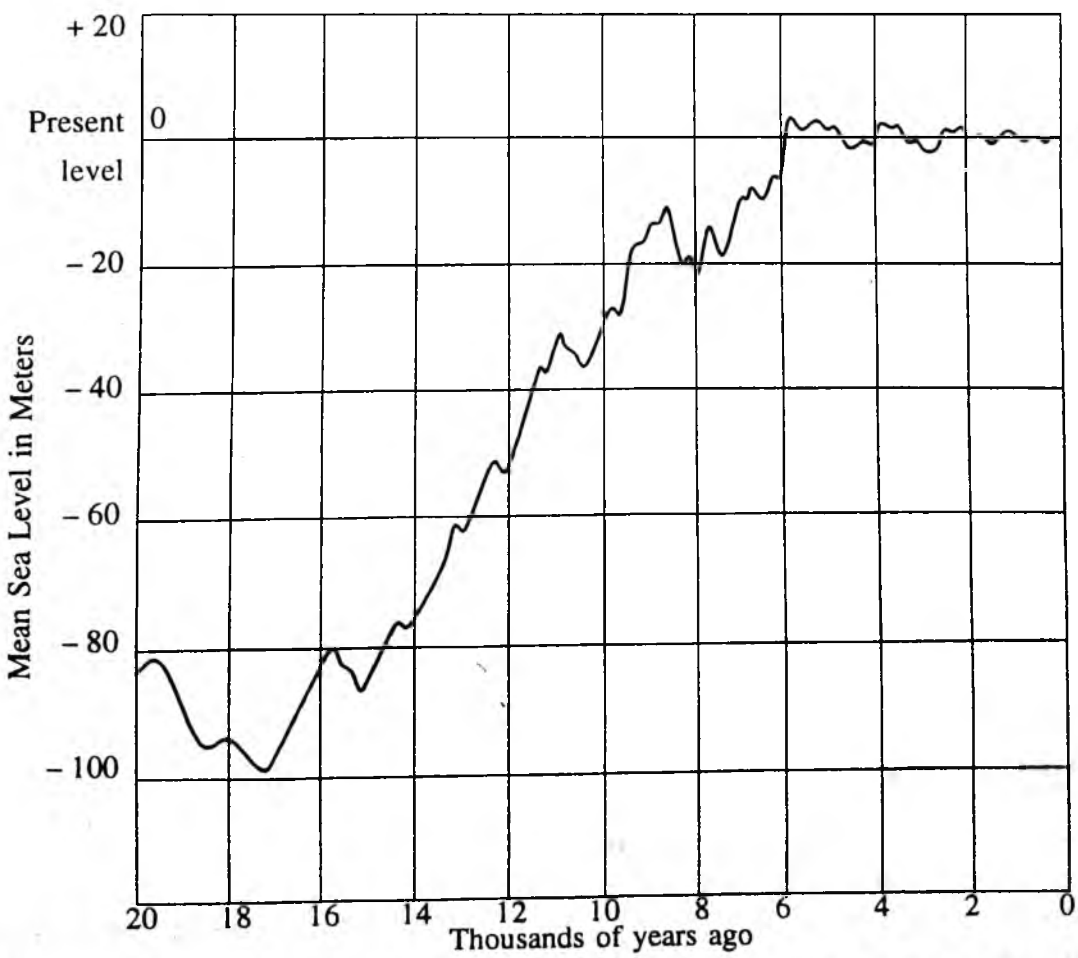


Fig. 15.3 : Fluctuations in sea level with reference to present sea level (present datum line at o meter). Source : after Fairbridge, in H.J. Critchfield, 2002.

North America and interglacial periods (relatively warm periods) separating two glacial (cold) periods. Figures 15.2 and 15.3 denote fluctuations of sea level (rise and fall) with reference to present sea level (i.e. present datum line at o meter) about 150,000 ybp and 20,000 ybp (years before present).

7. Indicators of Historical Records

The recorded events during the existence of human species provide valuable data for reconstructing the palaeoclimatic history (**palaeochimochronology**) for the past 6000 years. It may be mentioned that the recorded past events are related mostly to extreme events of weather conditions rather than regular weather conditions. Such extreme weather events include freezing of rivers and lakes, unprecedented floods and droughts leading to famines, mass exodus of human migration deserting their settlements etc. A few examples will be sufficient to demonstrate the significance of such indicators of climatic changes. The records of temperatures of the Thames (U.K.) from 9th century A.D. to 18th century A.D. denote increasing trend of frequencies of freezing of the Thames river per 100 years e.g. the Thames was frozen only once or twice per 100 years from 800 to 1500 years ago, 4 times during 16th century, 8 times during 17th century, and 6 times during 18th century. This denotes cooling of U.K. and environs from 800 to 1800 years before present (YBP). The recorded data from Iceland from 900 to 1900 YBP also demonstrate cooling of North Atlantic Ocean between 900 and 1900 YBP. The records of high floods in the Nile Valley since 640 A.D. reveal increase in rainfall in the source regions of the Nile river. The records of droughts in the south-western arid and semiarid United States of America and Sahel region or Sub-Sahara region denote acute deficiency in normal rainfall and resultant extreme aridity.

15.4 RECONSTRUCTION OF CLIMOCHRONOLOGY

Climochronology may be defined as systematic description of climatic conditions and climatic changes in terms of geological history of the earth i.e. past climates of each period of the earth's history. The reconstruction of palaeoclimates i.e. climochronology means rearranging of climatic history of the globe or part thereof on the basis of indicators/evidences of plaaeoclimates. The description of climochronology of the world may be attempted in the following heads.

(1) Climatic changes during geological periods,

(2) Climatic changes during Quaternary period, and

(3) Climatic changes in the recent past (about past 1000 years or so).

1. Climatic Changes Through Geological Periods

The geological history of the earth or the 'geological clock' refers to the reconstruction of evolutionary sequences of the geological events involving the information of various zones (crust, mantle and core) of the earth, formation and evolution of geomaterials (rocks), formation and development of mountains and faults, evolution of different lives etc. The whole geological history right from the origin of the earth to its present form has been divided into major and minor periods on the basis of forms of life (organic remains), characteristic rock deposits, places of rock formation, major tectonic events etc. The whole geological history of the earth has been divided into five eras (the largest time division of the earth's history has been termed Era) based on five major groups of deposits as follows:

Major Groups of Deposits	Eras (from youngest to oldest)
Cenozoic group	Cenozoic (era of recent life)
Mesozoic group	Mesozoic (era of medieval life)
Proterozoic	Proterozoic (era of earlier life)
Archeozoic	Archaeozoic (era of primeval life)

Each era is numbered in sequence as first (primary), second (secondary), third (tertiary) and fourth (quaternary) epoch. Further, each epoch is

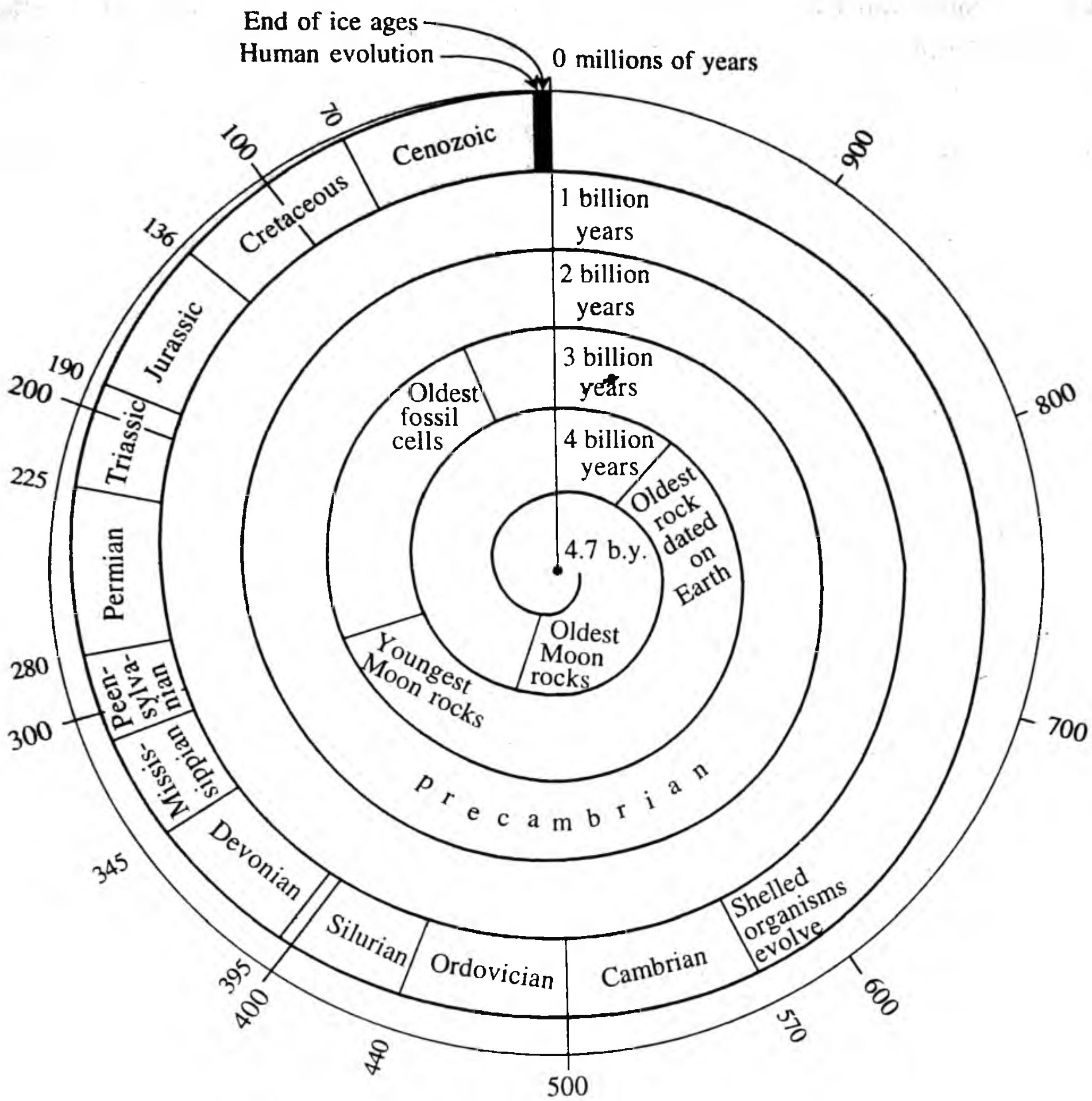


Fig. 15.4 : The geological clock (modified after F. Press and R. Siever, 1974). Numbers denote years in millions before present.

divided into several periods. The names of periods have been assigned on various grounds e.g. names of the places of characteristic systems of deposits, the names of tribes, the characteristics of deposits, dominance of certain elements and minerals etc. as follows :

Palaeozoic	palaeo (ancient), zoe (German)-life
Mesozoic	mesos (German) means middle
Cenozoic	Kainos (German) means new
Cambrian	Cambria or Wales (place) in U.K.
Ordovician	Ordovices (a British tribe in N. Wales)
Silurian	Silurs (a British tribe in S. Wales)
Devonian	Devonshire (place and region in U.K.)
Carboniferous	dominance of carbon (coal)
Permian	perm (a province in erstwhile USSR

Triassic	three-fold division of deposits in Germany, 'trias' means triple
Jurassic	after Jura mountains in Switzer-land
Cretaceous	creta (Latin) means chalk, domin-ance of abundant deposits of white writing chalk
Eocene	Eos means day break
Oligocene	Oligos (German) means little
Miocene	Meion (German) means smaller
Pliocene	Pleion (German) means greater
Pleistocene	Pleistos means most
Holocene	Holo means complete

Some scientists have put together all the geological events of the past history of the earth in the form of a clock. Thus, the spiral system representing the whole geological and geomorphic history together is called as **'geological clock'** wherein one billlion years represent each revolution of the clock's arm. Each revolution is further subdivided into **'hours'** where each division (hour) corresponds to 100 million years and **'minutes'** represent the time period of 10 million years. Fig. 15.4 represents the geological clock suggested by Frank Press and Raymond Siever (1974).

Table 15.1 : Geological Time Table (from youngest to oldest)

Eras	Epochs	Periods	Duration (million years)	Ice Age	Starting time before present (million years)
Neozoic	Quaternary	2. Holocene or Post-glacial		Pleistoecene	
		1. Pleistocene	0.990	ice age 4	1.000
Cenozoic	Tertiary	4. Pliocene	10.000		11.000
		3. Miocene	14.000		25.000
		2. Oligocene	15.000		40.000
		1. Eocene	30.000		70.000
Mesozoic	Secondary	3. Cretaceous	65.000		135.000
		2. Jurassic	45.000		180.000
		1. Triassic	45.000	3	225.000
Palaeozoic	Primary	6. Permian	45.000	Carboniferous	270.000
		5. Carboniferous	80.000	ice age	350.000
		4. Devonian	50.000	age	400.000
		3. Silurian	40.000	2	440.000
		2. Ordovician	60.000	Ice age	500.000
		1. Cambrian	100.000	(450-430 m ybp)	600.000
Pre-Palaeozoic		Pre-Cambrian or Algonican	-	Pre-Cambrian ice age (850-	700.000
Azoic or Archaean		Archaean	-	600 m ybp)	800.000

Pre-Palaeozoic Era

Very few geological evidences are available to reconstruct the climatic history of early pre-Palaeozoic era. Inferences have been drawn on the basis of lithological evolution and evidences thereof, numerical models and deductions. The earth changed from gaseous state to liquid state after its origin. The solid crust was formed due to cooling and solidification of liquid materials. This phase was followed by the formation of dense atmosphere surrounding the earth. Due to gradual but continued cooling and contraction of the earth and resultant condensation of water vapour there began the precipitation process which ultimately resulted into the development of rivers and seas. It is assumed that the earliest climatic phase of the earth's atmosphere was warm with average (assumed) atmospheric temperature of 37°C about 4250 MYBP (million years before present) which is supposed to have dropped to 25°C about 2500 MYBP. Such assumptions and calculations are based on the estimate that the concentration of carbon dioxide (CO_2) might have been much higher in the earliest atmosphere than at present and thus the pre-Palaeozoic climate might have been very warm due to **green house effect** of the early atmosphere.

The sequence of warming was broken by many glacial periods as indicated by glacial deposits, a few glacial features, striated surfaces, sedimentary data etc. found from Gowganda, Ramsey lakes, Bruce formations etc. in the Ontario province of Canada. These indicators reveal the existence of probably the **first ice age**, known as **Huronian Glaciation** (on the basis of Lake Huron of Canada and USA) which is supposed to have occurred about 2700 MYBP and might have continued upto 1800 MYBP. The earth again experienced warm climatic phase which continued upto 950 MYBP.

The late pre-Cambrian period is supposed to have been again under cold climatic phase wherein three glacial periods might have occurred when most of the earth's surface was glaciated.

Precambrian Period

The geological characteristics of rocks of pre-Cambrian period which started about 700 MYBP (million years before present) denote that dense atmosphere was formed around the earth. Due to gradual but continued cooling and contraction of the earth and resultant condensation of water vapour there began the process of precipitation which ultimately resulted into the development of rivers and seas. The sequence of warm climate was broken by many glacial periods resulting into the beginning of perhapse the first ice age known as **pre-Cambrian ice age** having a time span from 850 MYBP to 600 MYBP. Among the plant kingdom only marine grasses were evolved. The three pre-Cambrian glacial periods known as Gnejso, Sturtian, and Varangian glacial periods, continued from 950 to 650 MYBP.

Palaeozoic Era (650-600 to 250 MYBP)

The early Cambrian period is supposed to have been in cold climatic phase leading to **ice age** during which the glaciation was more widespread than pre-Cambrian ice age. This connotation is validated on the basis of the presence of ancient early Cambrian morainic deposits in Greenland, Scottland, Scandinavia, China, South America southern parts of Africa, Australia etc. representing both the hemispheres. This cold phase was followed by warm climatic phase which became responsible for the evolution of life mainly plants in water bodies i.e. seas. Most of the vertebrate animals including 1000 species were evolved in the seas but these are not found at present. These animals depended on marine grasses for their food. Though evidences from ancient organisms and sedimentary deposits suggest warm climatic phase during Cambrian and early Ordovician periods but some evidences from Sahara indicate **little ice phase**, if not ice age, during late Ordovician period. The Silurian period again became warm and this phase continued into Devonian period. The evidences denote warm tropical climate of most of the northern hemisphere including North America, Europe and China, characterized by warm and semi-arid climate. The Devonian period was also characterized by the evolution of green land plants and a large number of species of fish. Amphibians were evolved towards the end of Devonian period. There was dispersal of vertebrate animals from seas to land areas due to such flora on land areas which could provide them food.

The Carboniferous period experienced contrasting climatic conditions in the northern and the southern hemispheres. Most of the coals of North America and Europe were deposited during this period. The northern hemisphere was characterized by warm tropical climate having both warm dry and warm wet climates which became responsible for dense vegetation cover in the northern hemisphere. On the other hand, most of the southern hemisphere, say Gondwanaland, was under cool climatic phase leading to widespread glaciation known as **Carboniferous Ice Age** which is supposed to have continued from middle and late Carboniferous period to early Permian period. The climatic hazard of such widespread glaciation became responsible for extinction of numerous plant and animal species. With increasing seasonal variations in the climatic conditions the ratio of evergreen trees continued to decrease. Consequently, the deciduous trees which could resist dry weather and frost, were evolved. The number and species of land animals further increased and numerous species of mammal-like reptiles were evolved but these soon perished. By the end of Permian period the southern hemisphere recovered from Carboniferous glaciation due to retreat and ablation of ice sheets.

Mesozoic Era (225-70 MYBP)

The climatic condition during Triassic period was warm and dry but it became wet by the end of this period. Consequently, coniferous trees and ferns were developed in the northern hemisphere. For the first time, mammals evolved from reptiles on land areas. The Jurassic climate became subtropical. The rainfall was such that dense vegetation could be evolved and developed in many areas. For the first time, flowering plants (angiosperms) were evolved during this period. Land areas were dominated by forests and swampy plains having lakes and meandering rivers. Cretaceous period was marked by warming of high latitudes which made the growth of vegetation possible upto Greenland. Deciduous trees flourished because of seasonal regime of climate. The **oxygen isotope analysis** of deep sea cores having benthic and plankton fossils (300 planktons) provide ample data for inferring temperatures of oceans in both low and high latitudes. The later half of Cretaceous period witnessed cooling of high latitudes due to northward displacement of land areas of Angaraland. 'This time of earth history saw the world in its **greenhouse mode**, when climate was predominantely warm, polar ice caps nonexistent, and sea level high. The change from this to an eventual **ice house mode** may not have been smooth, but rather episodic' (Oliver and Hidore, 2003).

Cenozoic Era

The early Tertiary witnessed drop in temperatures but still the climate remained warm. In the **Eocene period** (70 to 40 MYBP) or early Tertiary epoch England was characterized by tropical vegetation similar to present Malaysia. Warm climate extended upto Greenland and hence tropical palm trees grew upto Greenland. During **Oligocene period** (40 to 25 MYBP) most of the areas were dominated by warm and temperate climate but the cycle of cold climate also started in this period. The onset of cold climate caused disappearance of forests in some areas mainly in high latitudes but there was expansion in grasslands which became responsible for the evolution of many species of grass eater mammals. During **Miocene period** (25-11 MYBP) the earth's surface was characterized by varying climatic conditions as these varied from dry and desert climatic conditions to wet and cold climate. Humid climate became responsible for the growth and development of deciduous forests having species of maple, oak and poplar in North America and Europe while cedar grew in highlands. The plains of North America were covered by prairie grasses. The **Pliocene period** (11-1 MYBP) witnessed wide range of fluctuations in temperatures i.e. repetition of warm and cold phases. The glaciers began to form over Antarctica. The continued lowering of temperature culminated into the formation of continental glaciation and onset of ice age in Pleistocene period of Quaternary epoch. This is being discussed in the following heading.

2. Quaternary Climate Changes

The Quaternary epoch of Cenozoic era started about one million years before present and continues at present. This epoch comprises Pleistocene and Holocene (post-glacial period) periods. The

Pleistocene witnessed most pronounced climatic changes for which much authentic data derived through different techniques such as pollen analysis, isotope analysis, carbon dating, potassium-argan dating etc. are available and the sequences of events are well documented. Major parts of North America and Europe were extensively glaciated during Pleistocene ice age which comprised of four glacial and four interglacial periods.

The Pleistocene glaciation of North America (Fig. 15.5) witnessed four periods of cooling and resultant formation of glaciers and ice sheets and their equatorward advancement. The glacial periods have been identified and named as Nebraskan (300,000-260,000 YBP), Kansan (205,000-167,000 YBP), Illinoin (135,000 -100,000 YBP) and Wiscconsin (70,000-10,000 YBP). These four glacial periods were separated by warmer periods, called as interglacial periods, namely Aftonian interglacial period between Nebraskan and Kansan glacial periods (260,000 to 205,000 YBP), Yarmouth interglacial period between Kansan and Illinoin glacial periods (167,000-135,000 YBP), Sangamon interglacial period between Illinoin and Wisconcin glacial periods (100,000-70,000 YBP) and recent Holocene interglacial period. The ice sheets advanced from 3 major sources (ice caps) e.g. (1) Labrador ice sheet; (2) Hudson Bay or Keewatin ice sheets, and (3) Cordillarean or Rocky ice sheets. Two ice sheets of Labrador ice caps and

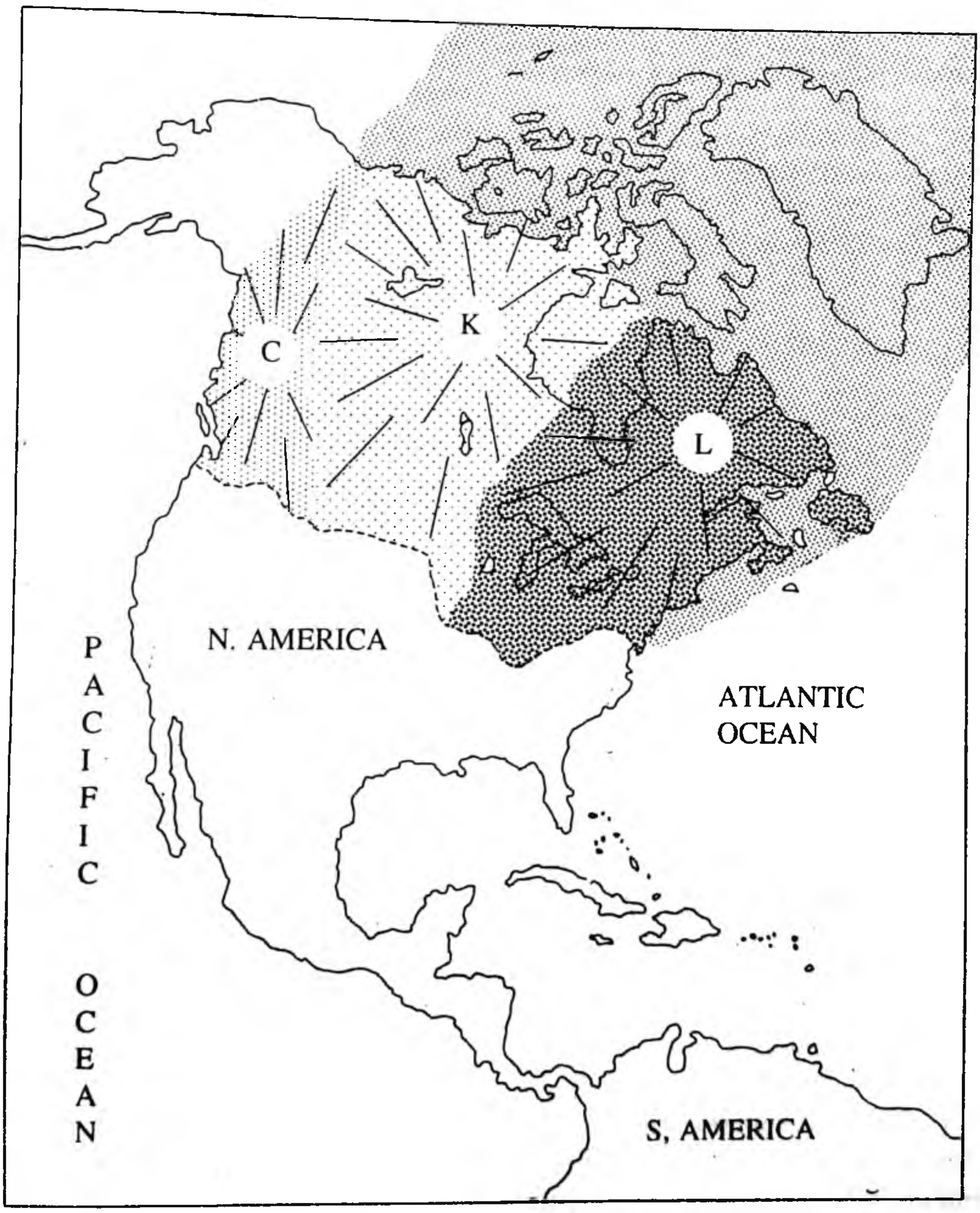


Fig. 15.5 : Glaciation of North America during Pleistocene Ice Age; C-Cordillarean ice sheet, K-Keewatin ice sheet, and L-Labrau ice sheet.

Keewatin ice caps after their initial southward advance combined together and became much wider and extensive ice sheets which moved as far south as upto the province of Nebraska. The combined ice sheets were called as Laurentide ice sheet. The St. Lawrence Valley and central lowland were completely covered by Laurentide ice sheet. Its eastward movement covered the Appalachians. Besides, Alaska, western Canada, Washington, Idaho, Montana etc. were also covered by thick ice sheets measuring 1000 meters to 1500 meters in thickness. The withdrawal or retreat of ice sheets during interglacial periods left behind numerous terminal moraines. Several lakes mainly the Great Lakes (comprising Superior, Michigan, Huron, Erie and Ontario) are the legacy of Pleistocene Ice Age and consequent glaciation.

Table 15.2 : Pleistocene Glaciation of North America

Glacial and Interglacial Periods	Duration (years before present)
1. Nebraskan	300,000-260,000
1. Aftonian (inter glacial)	260,000-205,000
2. Kansan	205,000 - 167,000
2. Yarmouth (inter glacial)	167,000-135,000
3. Illinoin	135,000-100,000
3. Sangamon (inter glacial)	100,000-70,000
4. Wisconcin	70,000-10,000
4. Holocene (inter glacial)	10,000

Europe was glaciated during Pleistocene ice age by the advancing ice sheets from three major sources of snow fields (i.e. caps), namely Scotland, Scandinavia, and the Alps. The advancing ice sheets from Scotland and Scandinavia covered Great Britain, Scandinavian countries, Denmark, Belgium, Luxemberg, Netherlands, Germany while Switzerland, Austria, Italy, France, southern Germany etc. were glaciated by ice sheets advancing northward from the ice caps of the Alps. Like glacial and interglacial periods in North America, four glacial periods have also been identified and named in Europe, e.g. Gunz, Mindel, Riss and Wurm glacial periods wherein two glacial periods were separated by warmer interglacial period. The tropical and subtropical regions of the globe remained warm.

The last but most recent early Wisconcin glacial period started about 70,000 YBP but main Wisconcin glacial period in North America is supposed to have started about 30,000 YBP (years before present) and retreated about 12,000 YBP. The then temperature was about 4^{0}C less than the present temperature.

3. Climate in the Post-Glacial Period

The final retreat and withdrawal of recent ice sheets started about 18,000 YBP and continued upto 10-12,000 YBP when most of the ice covers were withdrawn from the USA. On the other hand, the margins of retreating ice sheets in Scandinavia and Scotland (Europe) started to expand and advance about 10,200 YBP and thus there was reappearance of short period glacial phase involving limited areal extent. This little short-period glacial phase is known as **Younger Dryas but this** temporary glacial phase soon came to an end as the ice sheets melted and finally withdrew. The period ranging from 18,000 to 5,500 YBP is considered as a **period of deglaciation** denoting rapid changes in climate and rise in temperature.

It may be mentioned that the Pleistocene Ice Age caused lowering of sea level at least by 100 meters about 18,000 YBP and the deglaciation during Holocene period resulted in the recovery of sea level to its present level about 5000-6000 YBP (fig. 15.3). As mentioned above after Younger Dryas the warming of previously glaciated areas resulted in complete withdrawal of ice sheets from North America and Europe by 5,500 YBP. Greenland and Antarctica still remained under thick ice sheets. 'All evidence points to this being a time when the mean atmospheric temperature of the mid-latitudes was 2.5^{0}C (4.5^{0}F) above that of the present. This time has been described as the **Climatic Optimum** a term originally applied to Scandinavia when temperatures were warm enough to favour more varied flora and fauna' (Oliver and Hidore, 2003).

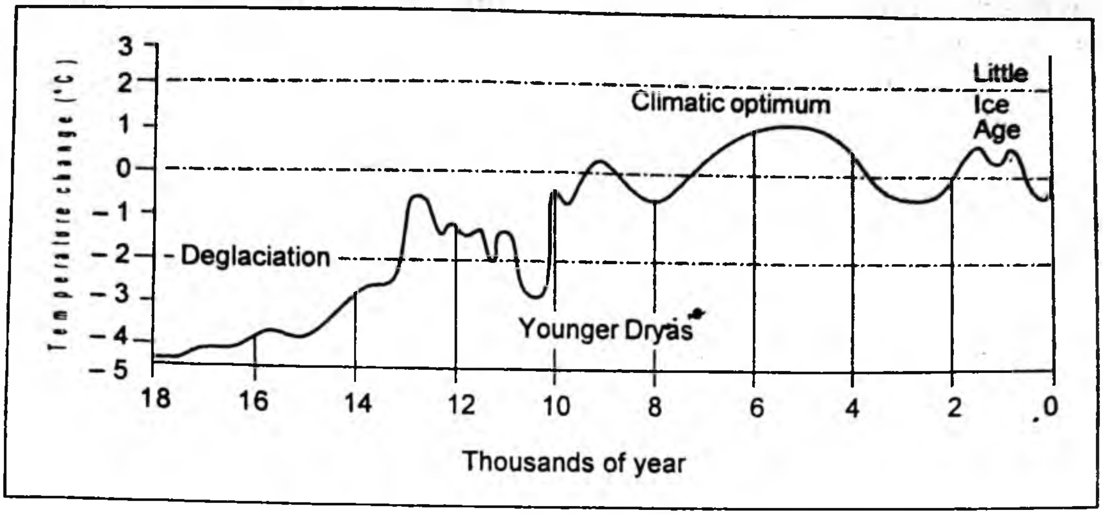


Fig. 15.6 : Trend of changes in surface temperature for the past 14,000 years. The temperature change is from present average global temperature. After J.E. Oliver and J.J. Hidore, 2003.

4. Climatic Changes in the Recent Past (Christian Era)

The proxy data from geological and biological sources and indicators, instrumental records, historical records, documentation etc. provide ample authentic information to reconstruct yearly climatic fluctuations since 1st century A.D. The records show that the temperature and precipitation conditions of European continent and Mediterranean regions were similar to presentday climatic conditions in the 1st century of Christian era. These areas experienced further more humid conditions characterized by increased precipitation and ameleorating temperature upto mid 4th century A.D. (i.e. by 350 A.D.). Europe and North America experienced dry phase resulting into semi-drought condition in the 5th century A.D. The increased aridity caused drying of several lakes in the western USA. The climate in the northern hemisphere became further harsh during 600-700 A.D. when climate became warmer and drier. The increased aridity resulted in melting of valley glaciers in the Alps of Europe and opening of frozen passes allowing free movement of people across the Alpine mountains. It may be mentioned that these passes are again in frozen condition at present time due to reestablishment of valley glaciers. The moist condition returned again in the 9th century A.D.

The period from 950 to 1250 A.D. i.e. 300 year period is called as **Phase of Little Climatic Optimum** in the climatic history of the earth when climate became warm and relatively dry as average temperature increased by 1^0 to 2^0C from the present-day global average temperature. The climate of Greenland and Iceland became mild and attracted the Vikings from Iceland to settle in Greenland. It may be mentioned that Vikings migrated from Europe to settle in Iceland in the 9th century A.D. because of favourable conditions characterized by warmer climate. The climatic conditions in southern Greenland allowed the growth of stunted vegetation, pasture and agriculture to support newly settled human population.

The period from 1250 A.D. to 1450 A.D. was characterized by the reversal of mild climate of 10th to 13th centuries A.D. as referred to above as temperature began to drop causing accumulation of more ice over Greenland, drifting of ice sheets and numerous icebergs in the North Atlantic Ocean. The drifting icebergs disrupted human physical connection of Greenland with Iceland and Europe. The 13th century saw very stormy weather in the Atlantic Ocean and the north Sea while extreme arid condition leading to severe drought prevailed in the western USA.

The trend of worsening climatic conditions in the middle and high latitudes of the northern hemisphere continued and the climate became further harsh for another period of around 400 years (i.e. from 1450 A.D. to 1880 A.D.) as the temperature fell below freezing point giving birth to another glacial period known in the climatic history of the earth as **Little Ice Age**. The climate of Greenland became so cold that the earlier settled people perished and their settlements and other infrastructures were buried under thick cover of ice sheets. The Alpine glaciers became more active, all the glacial valleys were covered with thick ice sheets, the advancing glaciers engulfed several villages at the foot-hills of the Alps mountain chains, several lakes and rivers were frozen, which are presently unfrozen etc. for example, the Thames river of England was frozen 4 times in the 16th century, 8 times in the 17th century, and 6 times in the 18th century. The historical records and Icelandic sagas very much indicate the severity of climate in Iceland. Extreme cold condition led to human deaths due to severe famines. It may be mentioned that glacial period (i.e. Little Ice Age) from 1450 to 1880 A.D. was not always characterized by continuous extreme cold condition and advancing glaciers rather it was punctuated by several cold and warm intervals. It is believed that each cold period continued at least for 30 years in each century (between 15th and 19th centuries) and two cold periods were separated by relatively warm period. The coldest period culminated in the year 1816 when major parts of northern Europe and the USA did not experience summer season. The year 1816 is known as '**the year without a summer**' in the climatic history, when the glaciers became most active after Pleistocene Ice Age, thereafter climate began to improve due to rise in temperature and by the end of 19th century the ice age was terminated.

The records of global temperatures since Industrial Revolution (1860) denote slow but irregaular trend of rise of temperature i.e. ranging between 0.3^{0}C and 0.6^0. Following R.G. Barry and R.J. Chorley (2002) the phases of rise in temperatures after 1860 have been identified as follows:

(i) Highly irregular trend of rise in temperature ranging between 0.2^{0}C to 0.4^{0}C between 1860-1920 A.D.

(ii) Consistent trend of rise of temperature of mean value of 0.4^{0}C between 1921 and 1945.

(iii) Oscillating trend of rise of temperature between 1946 and 1975 A.D. around 0.4^{0}C. The northern hemisphere was warmed while the temperature in the southern hemisphere remained more or less constant i.e. neither increase nor decrease.

(iv) Overall warming trend continued between 1976 and 1989 A.D. when temperature registered an upward rise by 0.2^{0}C.

(v) The global rise of temperature reached its peak in the last decade of 20th century (i.e. 1990s). Six out of seven warmest years on record occurred since 1980.

It may be summarised that overall increase in the surface air temperature in the 20th century has been about 0.5^{0}C to 0.7^{0}C against an average rate of increase of 0.3^{0}C per 1000 years at global level. According to another view the average air temperature in the northern hemisphere increased by 0.4^{0}C between 1880 and 1940 because of rapid rate of combustion of fossil fuels during this period but the temperature dropped after 1940 inspite of continued rapid rate of combustion of fossil fuels due to fast industrial growth but soon after 1940 air temperature in the southern hemisphere showed rising trend which registered an overall increase of 0.6^{0}C between 1940 and 1960.

Another source has indicated an increase in air temperature by 1.5^{0}C upto 1995 while other sources have shown general air temperature rise ranging between 0.3^{0}C and 0.6^{0}C. It may be mentioned that a rise of 2^{0}C temperature from the normal temperature was recorded in the Indian Ocean during 1997-98 which caused catastrophic **coral bleaching** leading to 70 per cent death of corals in the Andman Nicobar and Lakshwadeep inlands.

Various models have been developed to predict global rise in air temperature. S.H. Schneider (1950) pointed out that the temperature could rise upto 1.5^{0}C to 3^{0}C if the concentration of atmospheric carbon dioxide could be doubled from the 300 ppm (by volume) level to 600 ppm. The General Circulation Model (GCM) developed by S. Manabe and R.T. Wetherald (1975) predicts that if the present amount of carbon dioxide (1975 level) of the atmosphere is doubled, the temperature of the earth's surface wil increase by 2.9°C.

The major sources and processes of global warming, for example, ozone depletion and greenhouse gases, will be discussed in the succeeding chapter.

15.5 CAUSES AND THEORIES OF CLIMATIC CHANGES

As mentioned earlier climatic changes are effected by changes in atmospheric circulation and interactions among five components of the earth-atmosphere system, namely atmosphere, hydrosphere, lithosphere, biosphere, and cryosphere (frozen surface of the earth) wherein the amount of received solar energy, and the process of distribution, redistribution, and absorption of solar radiant energy at the earth surface are important considerations of the state of climate of an area in specific time period. The causes for such interactions leading to climatic changes are related to (1) **outside sources**, say **extraterrestrial sources**, and (2) **inside sources**, say eath-atmosphere system or **terrestrial sources**

The causes and theories of climatic changes are viewed in terms of periodicity of climatic changes which are generally of two types, namely (1) **short-term climatic changes**, and (2) **long-term climatic changes.** Since the nature and patterns of climatic changes vary temporally and hence the causes of such changes are also of varied nature. This is why no single theory can explain all types and patterns of climatic changes and thus we have a host of causes and theories of climatic changes.

Since the Industrial Revolution (1860 A.D.) the man's increased economic activities and the application of advance technologies are introducing significant modifications and changes in climatic conditions. This has led to the emergence of a new dimension in climatic changes and an additional source thereof. Thus, the sources of climatic changes may be grouped in the following 3 broad categories :

(1) Outside or extra-terrestrial sources

(2) Inside or terrestrial sources

(3) Anthropogenic sources

The significant causes and related theories of climatic changes may be stated as follows:

(1) Solar irradiance (variation in solar radiation),

(2) Sunspot cycles,

(3) Astronomical theories (eccentricity of earth's orbit, obliquity of the ecliptic, precession of the equinoxes, earth-sun relationship) etc.,

(4) Atmospheric dust hypothesis (mainly volcanic eruptions and dusts thereof),

(5) Carbon dioxide hypothesis,

(6) Continental drift and pole wandering,

(7) Tectonic and topographic control theory,

(8) Oceanic variation hypothesis,

(9) Extra terrestrial bodies collision theory, and

(10) Anthropogenic sources (changes in the earth's surface and atmospheric composition).

Solar Irradiance Theory

Solar radiative forcing is considered to be a significant factor of climatic changes. It is important to note that there are fluctuations in the energy radiated from the sun's outer surface (photosphere). It may also be mentioned that the amount of solar energy received at the earth's surface determines the nature and pattern of energy exchanges and atmospheric circulations which in turn determine temperatures and precipitation. The amount of solar radiant energy received at the earth's surface is also subject to changes due to (i) changes in the composition of the atmosphere in terms of its transparancy to incoming shortwave solar electromagnetic radiation waves, (2) changes in the relative distances between the sun and the earth, (3) the amount of the energy radiated from the earth's surface, (4) changes in the surface covers of the earth's surface etc. The variations in solar irradiance are viewed as (i) long-term change, and (ii) as short-term or periodic change (i.e. sunspots cycles).

It is a common belief that increase in solar radiation for longer duration will cause warming of the atmosphere leading to onset of warm climate and melting of ice sheets and glaciers. It may be mentioned that regular measurement of temperatures of the sun's surface started at the Kitt Peak National Observatory in Arizona, USA, from 1975. It is believed that even 0.1 per cent decrease in the average annual solar radiation for a decade in continuation may introduce measurable climatic changes in terms of changes in temperature and precipitation. The recorded data of sun's surface temperature revealed a drop of temperature by 11°C in January, 1977. If the solar radiation drops by even one to two per cent, the temperature at the earth's surface in the middle and high latitudes may come down and may cause climatic changes similar to Little Ice Age which occurred from 1450 to 1880 A.D. The year 1816 was known as the **year without summer** in the USA. The computer model has further revealed that the drop in solar radiation by 2-3 per cent for 50 years in continuation may cause regeneration of glaciation and may reactivate older glaciers, and if the solar radiation decreases by 5 per cent or more, the earth may experience new ice age and widespread glaciation.

The expansion and contraction of the core of the sun has been accepted by a few scientists as basic cause of changes in the amount of energy radiated from the outer surface of the sun. According to E.J. Opik the core of the sun expands after long intervals. The sun consumes a portion of its energy to expand its outer surface to cope with the expansion of its core. In such circumstance the radiant solar energy decreases because of consumption of substantial portion of solar energy by the sun itself. The decrease in solar radiation results in lowering of atmospheric temperature of the earth and consequently cool phase of climate is introduced, which causes ice age. Conversely, when the core of the sun contracts, the internal consumption of solar energy is remarkably reduced. Consequently, the solar radiation increases, which results in the increase of temperature of the earth's surface, termination of glacial period and beginning of interglacial period.

Simpson Theory

Contrary to the general view of the warming of the earth's surface and its atmosphere during the period of increased solar radiation, Sir George Simpson presented an entirely different concept related to variations in solar radiation and climatic changes in 1938 A.D. According to Simpson during the period of moderate increase in solar irradiance, the middle and high latitudes will experiencre extension in glaciers and their advances while decrease in solar radiation and resultant decrease in air temperatue would cause melting of ice sheets and glaciers and their retreat, resulting into onset of interglacial period. Simpson propounded the concept of cyclic pattern of increase and decrease in solar radiation. According to him the atmospheric temperature increases with increase in solar radiation. The increase in atmospheric temperature causes increase in evaporation and cloudiness, strong meridional air circulation and increased precipitation in higher latitudes. The precipitation in higher latitudes is in the form of snowfall which allows more accumulation of ice and extension of ice sheets and glaciers. The greater cloudiness during summer season prohibits melting of accumulated snow and ice rather protects the ice cover. On the other hand, during the phase of decrease in solar radiation, the atmospheric temperature decreases, meridional air circulation is weakened, evaporation and precipitation remarkably decreases in high latitudes, melting of ice sheets causes their retreat. 'Thus, paradoxically a lowering of mean atmospheric temperature might cause a recession of ice sheets, whereas temperature increase would lead to their advance. Although the Simpson theory appears not to fit recent instrumental evidence, it is a warning against oversimplified explanations of complex processes' (H.J. Critchfield, 2002).

Sunspot Theory

The sunspot activity has been related to variations in solar irradiance. The increased sunspot activity (increase in the number of sunspots) causes warming of the earth's surface and its atmosphere whereas decreased sunspot activity (decrease in the number of sunspots) causes lowering of atmospheric temperature. Sunspots are darker and cooler areas in the photosphere of the sun. The increased sunspot activity means increase in the number of sunspots while decreased sunspot activity is related to decrease in the number of sunspots. The study of sunspot activity for the last 200 years has revealed cyclic pattern of increase and decrease in sunspot activity. On an average, 11 years cycle has been accepted where as the period of one cycle may be as short as 8-9 years and as long as 16 years. Certain subcycles of sunspot activity at longer period have also been postulated e.g. 35 years cycle, 80 years cycle etc. It has been estimated that the output of ultraviolet radiation from the sun's surface at the time of maximum sunspot activity (maximum number of sunspots) is 20 times more than during the period of minimum sunspot activity. The prolonged period of minimum sunspot activity, called as **Maunder Minimum,** is supposed to introduce cooling of the earth's surface and its atmosphere, whereas the prolonged period of maximum sunspot activity may cause warming. It may be mentioned that perfect correlation between sunspot activity and atmospheric temperature has not been substantiated. It may be that periodic fluctuations in sunspot cycles may introduce some sort of weather changes at shorter temporal scale. 'Repeated studies trying to correlate rainfall with the fluctuation in sunspot cycles have not yet produced statistically significant results' (Oliver and Hidore, 2003).

Atmospheric Dust Hypothesis

The atmospheric solid particulate matters include dust particles, salt particles, pollen, smoke and soot, volcanic dusts and ashes etc. Most of the solid particles are kept in suspension in the atmosphere. It is an established fact that these solid particulate matters (SPM) present in the atmosphere reduce the amount of solar radiant energy reaching the earth's surface by scattering, reflection and absorption of incoming shortwave electromagnetic solar radiation. About 23 per cent of incoming solar radiation is scattered by dust particles and haze, of which 6 per cent energy is sent back to the space while 17 per cent energy reaches the earth's surface as diffuse day light, of course much later. The scattering of incoming solar radiation waves by dust particles when the diameter of such particles is longer than the wavelengths of incoming solar radiation waves, is called diffuse reflection which sends some portion of incoming solar energy back to space while some portion remains in the lower atmosphere.

It is also an established fact that sudden increase in dust particles caused by violent powerful volcanic eruptions reduces the temperature of the earth's surface at its lower atmosphere remarkably and introduces fluctuations in weather and climatic conditions atleast at shorter temporal scale. It may be remembered that the stratospheric temperature increases at the time of greater volcanic activity because most of the scattered, reflected and absorbed energy remain there, but the temperature of the lower troposphere and the earth's surface drops significantly, and it is the temperature of the lower atmosphere that controls weather and climate at the earth's surface. This corollary may be substantiated with a few examples of volcanic eruptions and resultant cooling of the earth's surface and its atmosphere.

(1) There was annihilating violent explosive eruption of a volcano on 27 August, 1883 in Krakatoa island located in the Sunda Strait between Java and Sumatra in the East Indies. The powerful volcanic blast was 9TNT equivalent of about 100 million tons (2×10^{11} pounds). Nearly 20 cubic kilometers (some sources put it 53 cubic kilometers) of fragmental materials, ashes and dusts were thrown in the air upto 32 kilometers in the atmosphere (upto middle of stratosphere), which were later on distributed, due to their fall, on an area of 700,000 square kilometers. The fine dusts were ejected upto 32 kilometers in the atmosphere which produced global decrease in solar radiation received at the earth's surface by 10-20 per cent, there was total darkness in the sky because the dusts and ashes blotted out the sun for several days, the effect of total darkness was observed upto the distance of 150 kilometers from the center of eruption. The ejection of fine dusts and ashes in the stratosphere and their circulation and drifting around the earth by upper air atmospheric circulation produced brilliant red sunsets for several years. The reduced solar radiation received on the earth's surface and resultant drop in temperature matches with cold years from 1884 to 1886.

(2) The violent eruption of Mt. Asoma in 1783 in Japan is correlated with severe cold years of 1784, 1785 and 1786. The exceptionally cold year of 1816 A.D., known as **a year without summer** in the climatic history of the world, followed the famous explosive eruption of Mt. Tamboro in Dutch East Indes in the year 1815. The

volume of dusts ejected from the violent eruption of this volcano was so enormous that thick dust veil covered the sun resulting into complete darkness for 3 days in continuation, which extended upto a distance of 500 kilometers from the center of eruption.

(3) The explosive eruption of Mt. Katmai in 1912 in Alaska (USA) ejected about 21 cubic kilometers of volcanic materials and dusts in the atmosphere resulting into 20 per cent reduction in the amount of solar radiation received at the earth's surface. About 2 percent drop in solar radiation was noted at the Mauna Loa Observatory in Hawaii at the time of the eruption of Mt Agung in Bali in the year 1963.

Contrary to the general belief of correlation between major volcanic eruptions and lowering of temperatures, the empirical studies of a few recent volcanic eruptions such as El Chichon eruption of 1982 in Mexico, Mt. St. Helens eruption of 1980 (USA) a few earlier explosive eruptions such as Mount Cosequina eruption of 1835 in Nicaragua show no such correlation. It may be mentioned that the impact of volcanic eruptions in lowering the temperature depends on a variety of factors, numely the penetration of the stratosphere by ejected volcanic dusts and gases, the volume of sulphur dioxide, the amount of dusts etc. If the eruption is very explosive and powerful, the volume of ejected sulphur dioxide is very large, and the amounts of dusts are very high, definitely these materials will reach the stratosphere and will reduce the temperature at the earth's surface and its atmosphere. The ejected sulphur dioxide gas after combining with atmospheric water vapour forms tiny droplets of sulpluric acids. These tiny sulphuric acid droplets remain in the atmosphere for longer period and reflect sizeable portion of incoming solar radiation and thus the amount of solar radiation received at the earth's surface is remarkably reduced resulting into the lowering of earth's surface temperature.

Recently, two indices related to volcanic eruption and its impact on climate change, namely (1) **Volcanic Explosive Index** (VEI) and (2) **Dust Veil Index** (DVI), have been prepared. It is argued that high VEI would indicate powerful and effective penetration of the stratosphere by volcanic dusts and gases and thereby would cause lowering of temperature. Similarly, high DVI would be indicative of reduction in solar radiation received at the earth's surface and consequent drop in temperature. It may be mentioned that resident period of volcanic dusts and gases is very important factor for glacial climate. If the resident period of volcanic materials is for longer duration i.e. if the volcanic materials remain in the atmosphere for longer period, the resultant lowering of temperature may initiate glacial period. On the other hand, short-term resident period would cause only local effects on weather and climate.

Carbon Dioxide Theory

It is important to note that it is the receipt of solar energy at the earth's surface and absorption of incoming solar radiation and outgoing terrestrial radiation by the atmosphere which has significant control on weather and climate, and the amount of energy received at the earth's surface depends on (1) changes in the composition of the atmosphere, (2) changes in the transparency of the atmosphere, (3) modification of energy in the transit (i.e. flowing through the atmosphere) etc. The changes in the gaseous composition of the atmosphere are effected by both natural and anthropogenic sources. The increase of relative proportion of greenhouse gases (e.g. carbon dioxide, methane, nitrogen oxides etc.) in general and carbon dioxide in particular causes global warming and initiates warm climate while decrease in their relative percentage causes global cooling and helps in initiating cold climate if other factors remain constant. Thus, the carbon dioxide theory states that increase and decrease in temperatures of the earth's surface and its atmosphere is effected by increase and decrease of its (CO_2) relative percentage in the gaseous composition of the atmosphere respectively.

It may be remembered that the increase of earth's temperature by absorbing outgoing terrestrial infrared radiation by certain gases (mainly carbon dioxide) is called **greenhouse phase** of the atmosphere whereas **icehouse phase** refers to lowering of earth's temperature leading to beginning of glacial period. The **greenhouse effect** means 'progressive warming-up of the earth's surface due to the blanketing effect of man-made carbon dioxide in the atmosphere' (Oxford Dictionary). 'In a green house, visible sunlight passes through the glass and heats up the soil warming the plants. The warm soils emit radiation in longer wavelengths particularly in the infrared band. Because the glass is opaque to these wavelengths (long wavelengths of infrared radiation waves), it absorbs and reflects (reradiates back to the soils) the infrared (radiation)' (D.B. Botkin and E.A. Keller, 1982). This mechanism keeps the greenhouse warmer than the outside environment. In nut shell it may be summarized that a greenhouse is a body which allows the shortwave incoming solar radiation to come in but does not allow the longwave outgoing terrestrial infrared radiation to escape. Carbon dioxide and water vapour act as greenhouse in that these allow visible sunlight to reach the surface of the earth but absorb and reflect back (reradiate) the longwave outgoing terrestrial radiation mainly infrared radiation (back to the earth's surface) and thus help in keeping the earth's surface warmer.

The most significant greenhouse gas is carbon dioxide which is released to the atmosphere by burning of fossil fuels (coal, mineral oil and natural gas) for different purposes in various ways, burning of firewoods etc. Deforestation also helps in increasing the concentration of carbon dioxide in the atmosphere. The pre-industrial level of atmospheric content of carbon dioxide was fixed at 280-290 ppmv (part per million by volume) or 0.028 per cent to 0.029 per cent (the base year of the beginning of industrial revoltuion in 1860A.D.) It is also important to note that there are certain natural processes and sources which regulate the atmospheric concentration of carbon dioxide, namely vegetation covers and oceans are major sinks(absorbers and users) of atmospheric carbon dioxide. Deforestation and burning of forests for shilfting cultivation remarkably reduces the use of carbon dioxide by vegetation covers and hence helps in increasing the concentration of carbon dioxide in the atmosphere.

The atmospheric content of carbon dioxide increased from the pre-industrial level of 280-290 ppmv to 350-360 ppmv during 1998, registering an overall increase by 25 per cent from the pre-industrial level. It is believed that the rate of increase of atmospheric carbon dioxide through anthropogenic sources will be accelerated due to uncheked industrial development and increasing urbanization worldover.

Different models have been developed to reveal the relationships between the increase in the concentration of atmospheric carbon dioxide through anthropogenic sources and climate changes but the predictions of these models are very much confusing and contradictory. 'If there is uncertainty in the prediction of carbon dioxide trends, then the predictions of the resulting climatic effects are even more uncertain' (J. E. Hobbs, 1980).

(1) **Schneider Model (1950) ;** S.H. Schneider while reviewing the results of various climatic models dealing with the predictions in the change of thermal conditions of the atmosphere and the earth's surface resulting from the increased content of atmospheric carbon dioxide concluded that the temperature could rise upto 1.5C-3.0^{0}C if the concentration of atmospheric carbon dioxide could be doubled from 300 ppmv level to 600 ppmv. He further predicts that increased temperature would cause increase in evaporation and cloudiness which would reduce incoming solar radiation (because of increased albedo i.e. more clouds would reflect more solar radiation back to space). Thus, the reduced solar radiation reaching the earth's surface would counteract the warming of the earth's surface. It is obvious that such feedback mechanisms negate the impact of greenhouse effect of increased atmospheric carbon dioxide and the whole process of the heating or cooling of the lower atmosphere and the earth's surface becomes highly complicated. Another model envisages cooling of the earth's surface due to enormous increase in the atmospheric carbon dioxide.

(2) General Circulation Model (GCM) : The general circulation model by S. Manabe and R.T. Wetherald (1975) predicts that if present amount (1975 level) of carbon dioxide of the atmosphere is doubled, the temperature of the earth's surface will increase by 2.9^{0}C and there will be 7 per cent increase in the activity of hydrological cycle but there will not be any feedback and thus there will not be either increase or decrease in the amount of cloudiness as predicted by S. H. Shneider. In other words, the increase in surface temperature caused by increase in the atmospheric carbon dioxide will not be negated by feedback mechanism and hence increased greenhouse effect would certainly introduce climate change (warming of the earth's surface and its lower atmosphere).

(3) **Atmospheric-Oceanic General Circulation Model (AOGCM)** : As per the report of the Intergovernmental Panel on Climate Change (IPCC, 2001) if the concentration of atmospheric CO_2 increases to 540-970 ppmv by the end of the 21st century, the average surface air temperature at global level would register an increase between 1^0C to 5.8^0C. This increase in average air temperature has been estimated in relation to average air temperature during 1990-2000 A.D.

The trends of probable future climatic change due to increase in average surface air temperature at global level have been estimated on the basis of increase in the concentration of greenhouse gases in the atmosphere in future.

It has been estimated that the overall increase in surface temperature over the past one hundred years (upto 2000 A.D.) has been about 0.5^0C to 0.7^0C. According to another view the average air temperature in the northern hemisphere increased by 0.4^0C between 1880 and 1940 because of rapid rate of combustion of fossil fuels during that long period but the temperature dropped after 1950 inspite of continued rapid rate of combustion of fossil fuels due to fast industrial development after 1960. The air temperature in the southern hemisphere showed rising trend which registered an overall increase of 0.6^0C between 1940 and 1960. It is evident that though there is maximum consumption of fossil fuels in the northern hemisphere and consequent increase in the concentration of atmospheric carbon dioxide but the air temperature dropped whereas there is minimum consumption of fossil fuels in the southern hemisphere but air temperature increased. It does not mean that there is no direct impact of increasing carbon dioxide on air temperature rather some other factors might have dominated over the factor of greenhouse effect. It is opined that large amount of volcanic dusts thrown into the atmosphere through the eruptions of Heckla (Iceland) in 1947, Mt. Spurr (Alaska, USA) in 1953, Agung (Bali) in 1963, Mount Taal (Philippinse) in 1965, Mayon and Fernandina in 1968 etc. might have reduced air temperature in the northern hemisphere between 1940 and 1970.

Inspite of contrasting opinions about the impact of increasing concentration of atmospheric carbon dioxide due to greenhouse effect on air temperature it may be conclusively opined that there is definite positive effect of increased greenhouse effect due to increased concentration of carbon dioxide in the atmosphere. The increase in temperature introduces several changes in climatic conditions at local, regional, and global levels as fallows:

(1) According to A.B. Pittock (1972) the change in global mean temperature by a few degrees celcious caused by greenhouse effect would greatly change climate.

(2) Increased temperature due to increased greenhouse effect would cause decrease in precipitation and soil moisture content.

(3) In case of global warming oceans would be required to absorb more and more carbondioxide, this will raise normal level of acidity of the oceans, which would decrease biological activity in the oceans and oceanic plant cover, which ultimately would alter the albedo of ocean surface.

(4) It may be possible that the carbon dioxide concentration in the atmosphere may increase to such an extent that the total atmospheric pressure would increase. Such increase in atmospheric pressure would broaden the absorption bands and increase the opacity of the atmosphere to the outgoing terrestrial radiation which would in turn increase the surface temperature to such an extent that all the atmospheric processes may come to grinding halt.

(5) Recently, **atmospheric black clouds** (ABC), as a result of concentration of pollutants in the atmosphere due to burning of fossil fuels, have been related to unprecedented snowfall in Dubai, heavy snowfall in the lower altitudinal areas of Jammu and Kashmir, Himachal Pradesh and

Uttaranchal Himalayas (India) etc. during December (2004) and January (2005).

Continental Drift and Polewandering

The plate tectonic theory, based on the evidences of palaeomagnetism and seafloor spreading, the result of post-1950 advancement in geophysical researches worldover, has validated the concept of continental drift. It has now been proved that different plates are in constant motion and hence the continents and ocean basins change their relative locations. The plate tectonics have two major implications, namely changes in relative positions of the continents (and ocean basins) due to continental displacement (drift), and origin of mountains of varying heights due to convergence of destructive plate boundaries (the effects of the later on climate will be discussed under the next heading). It is believed that the relative locations of continents in relation to the poles have paramount control on climatic changes. The clustering of continental masses around the pole causes glaciation of major land areas while scattering of continents away from the poles causes deglaciation of the land areas which are places at greater distances from the poles, as 'the primary requirement for the formation of great ice caps is the polar location of continents' (J.E. Oliver and J.J. Hidore, 2003).

A lot of convincing evidences are available for two great ice ages e.g. Permo-Carboniferous ice age, and Pleistocene ice age. It is believed that about 350-250 million years B.P. (before present) i.e. during Carboniferous-Permian periods all the landmasses were united in one landmass which has been named as Pangaea II. Most of the land areas of Gondwanaland (comprising present South America, Africa, India, Australia and Antarctica) clustered around south pole which was located near the present position of Durban in Natal (South Africa). Thus, the south pole was located almost in the middle of Pangaea. Consequently, ice sheets might have spread out from south pole at the time of glaciation and Brazil, southern South America upto Falkland, southern Africa, peninsular India, Australia, Antarctica etc., which were closer to south pole, might have been covered with thick ice sheets. At much later date, these land masses might have parted away due to disruption of Pangaea and consequent movement to present locations because of plate movements, and finally might have experienced deglaciation and termination of Permo-Carboniferous ice age.

The Pleistocene glaciation of northern land areas of the northern hemisphere is supposed to have occurrred around one million years B.P. due to closer location of North American and Eurasian landmasses to north pole. The Pangaea began to break during early Jurassic about 180 million years B.P. and the disruption was completed by 70-100 million years B.P. Consequently, the northern part of North America upto present Nebraska in the south (in USA), Greenland, Iceland, Europe and Siberia were covered with ice sheets during Pleistocene period (about one million years B.P.). As mentioned in the preceding section the Pleistocene Ice Age comprised of four glacial periods separated by four interglacial periods of warmer climate. It may be mentioned that interglacial periods within a comprehensive ice age cannot be explained on the basis of continental drift and plate tectonics. It may also be remembered that glaciers of the Rockies, Alps, Himalayas etc. were more extensive than their present position. The glaciation of high mountains, which were far away from the location of pole also cannot be explained on the basis of plate tectonics and continental drift.

Tectonism and Topographic Controls

It is a commonly agreed fact that topographic factor (relief) plays an important role in shaping weather and climate at regional and global levels. High mountains control temperature and upper air circulation patterns. This is why efforts have been made to correlate ice ages with active tectonism and mountain building, 'as with increasing height of landmasses, the potential for ice formation is greatly increased' (Oliver and Hidore, 2003). The advocates of tectonic theory of ice ages and glaciation have tried to demonstrate close relationship between Permo-Carboniferous ice age and Pleistocene ice age and glaciation with large-scale vertical tectonic movements and orogenesis (mountain building) as these two great periods of ice age and widespread glaciation preceded large-scale mountain building activities. In other words, the Caledonian mountain building was followed by Permo-Carboniferous ice age and late Cenozoic mountain building, leading to the formation of Alpine-Himalayan mountain chains, North American cordillera, upliftment of Tebatan plateau, western North America including Great Plains etc, was followed by Pliocene-Pleistocene ice age when major parts of North America and Eurasia were glaciated. Rudiman and Kutzbach (1989) have also demonstrated such relationships through computer models wherein they used the models with 'no mountains', 'half mountains', and 'full mountains' to predict the patterns of general atmospheric circulation and their impact on producing cool climate to introduce glaciation. The computer models based on 'half mountains' and 'full mountains' during late Cenozoic period predicted colder climate over North America, North-Western Europe, and northern Asia during Pliocene-Pleistocene periods and likely ice age and glaciation. The actual occurrence of Pleistocene ice age after late Cenozoic mountain building validates the prediction of computer models, as 'in general 2 to 4 km of late Cenozoic surface uplift in Tibet and the Himalayan mountains, and at least one kilometer uplift across a broad area of the western North America, including the Sierra Nevada, Basin and Range province, Colorado Pleateau, Rocky Mountains, and the western Great Plains, successfully produced changes in the model climates that are comparabie to, although less extreme than, the inferred actual climate changes of the late Cenozoic Era' (A.L. Bloom, 2002).

Vertical tectonic movements leading to origin of mountains and their further uplift results in high reliefs which augment erosional and weathering processes which in turn affect atmospheric carbon dioxide. It has already been stated earlier that decreased content of atmospheric carbon dioxide cools the earth's surface and its lower atmosphere to such an extent that glacial climate is induced. The weathering of rocks has been correlated with climatic cooling. In other words, chemical weathering requires dissolution of atmospheric carbon dioxide. The increased rate of chemical weathering results in decrease in the concentration of atmospheric carbon dioxide and resultant reduction in greenhouse effect, with the result cooling of the earth's surface and its lower atmosphere induces glaciation.

Astronomical Theories

The astromical theories are related to three variables, namely (1) earth's orbital **eccentricity**, (2) **obliquity** (tilt) of the earth's rotational axis relative to the plane of earth's orbit, and (3) **precession of equinoxes**, which determine the amount of solar radiation received at the earth's surface and its temporal variations. The earth's orbital eccentricity refers to a ratio between the elliptical orbit of the earth around the sun and a true circle. It may be remembered that the earth revolves around the sun in an elliptical orbit, thus, the eccentricity of the earth's orbit is derived by comparing the orbital elliptical path of the earth to theoretical circular path.

(1) The **eccentricity** of the earth's elliptical orbit simply means deviation of its elliptical orbital path from true circular path. The present position of earth's orbital path has been shown to be closer to circular path. When the earth's orbit is nearest to a circle, the earth's eccentricity becomes almost zero. It has been demonstrated through measurement for the past million years on the basis of inferred data that variations in the earth's eccentricity take place in cyclic manner. The variations in eccentricity during the past 1,000,000 years have changed between a minimum value of 0.001 to maximum value of 0.054. It takes about 95,000 years for the earth's eccentricity to attain its maximum value of 0.054. This is called 95,000 years cycle or **Milutin Milankovitch cycle** (after the name of Serbian scientist M. Milankovitch). The temporal variations in the earth's eccentricity influence the amount of solar radiation to be received by the earth's surface and also determine the temporal variations in solstices and equinoxes. It has been estimated that the maximum variation in the earth's eccentricity (0.054) 'results in a maximum variation of the incoming annual radiation of only 0.2 per cent of the total over a cycle of about 95,000 years' (Berger, 1988, quoted in A.L. Bloom, 2002).

(2) **The obliquity** of the earth's rotational axis or tilt of the earth's rotational axis 'refers to the angle of the axis (of the earth's rotation) in relation

to the plane in which the earth revolves around the sun' (Oliver and Hidore, 2003). The obliquity or tilt of the earth's rotational axis varies temporally between 22^0 and 24^0 27'. The net angular variation is 1.5^0 which oscillates around mean obliquity value of 23.1^0. The present angle of the earth's rotational axis is 66.5^0 giving an obliquity of 23.5^0 i.e. the tilt angle of the earth's rotational axis with respect to the plane of its orbital path is 23.5 degree. The significance of the obliquity factor lies in the fact that it controls the latitudinal distribution of solar radiant energy and the intensity and duration of different seasons. It may be mentioned that if the obliquity angle is zero (i.e. if the rotational axis of the earth is perpendicular to its plane of orbital circle) the length of day, and night would be of equal duration throughout the year, there would be no seasonality i.e. the same season would prevail throughout the year, and the horizontal distribution of climatic zones would be static but such situation is not possible because no such evidences could be found in the climatic history of the earth. It has been demonstrated through computer models, and manual calculation by Milutin Milankovitch that there have been angular variations in the earth's obliquity in the past and such variations, though small (maximum value of 1.5^0), are sufficient enough to induce changes in the climatic conditions and its world distribution. The change of the earth's obliquity from the minimum angle value of 22^0 to the maximum value of 24^0 27' takes about 41,000 years. Thus, the complete change in the earth's obliquity occurs in cyclic manner and one cycle is completed in a period of 41,000 years. There is direct relationship between the amount of angular variation of the earth's obliquity and seasonal contrasts i.e. difference of temperature in summer and winter seasons. The smaller the changes in the inclination of the earth's rotational axis (obliquity), the smaller is the change of temperature between summer and winter seasons and vice versa. It may be mentioned that warmer winters induce more snowfall and accumulation of ice due to increased evaporation and resultant condensation, while cool summers taboo melting of ice sheets. Thus, it is apparent that if the temperature difference between summer and winter seasons is minimised and if such condition persists for longer duration, the climate would be cold enough to induce glacial period.

(3) **Precession of equinoxes :** The dictionary (Webster) meaning of precession denotes 'slow, conical motion of the earth's axis of rotation, caused by the gravitational attraction of the sun and the moon, and to a smaller extent, of the planets, on the equatorial bulge of the earth,' while the precession of equinoxes 'refers to earlier occurrences of the equinoxes in each successive sidereal year because of the slow retrograde motion of the equinoctial points along the ecliptic, caused by the precession of the earth's axis of rotation' (Webster Dictionary). In more simple words, the precession of equinoxes may be defined as the time of a year or say the days of the year on which the earth's position is nearest to the sun (perihelion) or farthest to the sun (aphelion) due to varying motions of the earth. Thus, the precession of equinoxes denotes 'the regular change in time when the earth is at given distance from the sun.' '**Climatic precession** is a complex variable with principal periods of 23,000 and 19,000 years. The climatic precessional parameter refers to the time of year when the earth is at perihelion, or closet to the sun, which is now in early January (more precisely 3 January). Climatic precession controls the difference in the length of the seasons and has an opposite effect on each hemisphere' (A.L. Bloom, 2002). In other words, at the time of perihelion position of the earth during northern hemispheric winter, the winters in the northern hemisphere become much longer and 7 per cent more warmer while in the southern hemisphere the summers become much longer and 7 per cent less warm.

Presently, the earth's perihelion position with respect to its distance from the sun is in the northern hemispheric winter. The astronomical calculation denotes that this position will be reversed after about 10,000 years from present i.e. the perihelion position of the earth will change to northern hemisphere summer season, with the result winter season will be more extreme and cold due to receipt of less amount of solar radiant energy. The scientists have made successful attempts in computing the dates of occurrences of perihelion and aphelion positions in the past and have tried to reconstruct palaeoclimates on this basis.

Milutin Milankovitch, a Serbian scientist, manually calculated the dates of occurrences of perihelion and aphelion positions of the earth for the past thousands of years (600,000 years) and presented a mathematical model based on the aforesaid three astronomical variables (e.g. eccentricity of the earth's elliptical orbit, obliquity including of the earth's rotational axis, and precession of equinoxes) to explain the advancement (expansion) and retreat (contraction) of ice sheets during Pleistocene Ice Age. His model or theory is popularly known as **'Milankovitch Theory'** or **'orbital variation theory.'** The earth's orbital variations are known as **'Milankovitch cycles'.** The salient features of Milankovitch theory are stated as follows :

(i) The change of obliquity angle of the earth's rotational axis from 22.1^0 to 24^0 27' (say 24.5^0) is completed in a cycle of 41,000 years. Such variations in the inclination of the earth's rotational axis affect the amount of radiant solar energy to be received at the earth surface, temperature distribution, general atmospheric circulation and seasons.

(ii) The change in the eccentricity of the earth's orbit from minimum value of 0.001 to maximum value of 0.054 takes place in a cycle of 95,000 years. Such variation causes variations in the distance of the earth from the sun which in turn affects the amount of insolation and temperature distribution on the earth's surface.

(iii) The precession of equinoxes in terms of the perihelion position of the earth with respect to the sun is completed in about one-half cycle of 11,000 years duration. It is believed that 'in about one-half cycle or 11,000 years from now, the northern hemisphere winter season will be cooler, and more than 23 days longer than the summer season, because the northern hemisphere winter will occur while the earth moves more slowly from the sun' (Berger, 1978, quoted by A.L. Bloom, 2002). The above view is based on the calculation of past events that about 10,500 years before present the northern hemisphere winter was at the time when the earth was farthest (aphelion position of the earth) from the sun.

According to Milankovitch orbital theory cool summers and relatively warmer winters in the latitudinal zone of 50^0 to 70^0 in the northern hemisphere are prerequisite conditions to induce cold phase of the climate leading to continental glaciation because cool summers prevent melting of annual accumulation of snow while relatively warmer winters induce more evaporation and condensation leading to more snowfall and accumulation of ice sheets.

It may be concluded that the eccentricity of the earth's orbit affects the receipt of insolation at the earth's surface while the obliquity of the earth's rotational axis and precession of equinoxes determine the horizontal (latitudinal) distribution of temperature over the earth's surface and length and intensity of summer and winter seasons in terms of temperature. All such changes and variations induce climatic changes.

It has been argued by the critics of Milankovitch orbital theory of climatic changes that 'the amplitude of the fluctuations of solar energy inferred by Milankovitch theory are inadequate to produce the documented climatic changes of ice ages' (A.L. Bloom, 2002). The advocates of this theory are of the opinions that the aforesaid three astronomical variables, known as Milankovitch orbital variables, have operated throughout past geological periods and may be effective in explaining climatic fluctuations at least during ice ages with minor corrections and improvements. They argue that 'other tectonic, atmospheric, oceanographic, and biological changes of the late Cenozoic Era, also created an environment in which the relatively weak orbital parameters could be expressed as major climate changes' (A.L. Bloom) and may act as **climatic pacemaker.**

15.6 IMPORTANT DEFINITIONS

Atmospheric black clouds (ABC) : simply means formation of layers of pollutants in the atmosphere due to burning of fossil fuels (coal, petroleum, natural gas etc.).

Climochronology : Climochronology may be defined as a systematic description of climatic conditions and climatic changes in geological history of the earth.

Climatic precession : 'Climatic precession is a complex variable with principal periods of 23,000 and 19,000 years. Climatic precessional parameter refers to the time of year when the earth is at perihelion or closet to the sun, which is now in early January (more precisely January, 3)' (A.L. Bloom, 2002).

Duricrusts : Duricrusts are indurated hardened surfaces of different kinds such as laterites, silcretes, calcretes, alcretes, ferricretes etc.

Eccentricity : of the earth's elliptical orbit simply means deviation of its elliptical orbital path from true circular path.

Evaporites : Evaporites are the deposits represented by salt deposits in warm and arid climatic conditions when evaporation exceeds precipitation.

Glaciology : The science dealing with glaciers and glaciation is called glaciology.

Greenhouse effect : Greenhouse effect means 'progressive warming-up of the earth's surface due to blanketing effect of carbon dioxide in the atmosphere.'

Greenhouse phase : Greenhouse phase means increase in earth's temperature by the absorption of outgoing terrestrial infrared radiation by certain gases i.e. greenhouse gases, mainly carbon dioxide.

Icehouse phase : The icehouse phase refers to lowering of earth's temperature leading to beginning of glacial period.

Maunder minimum : The prolonged period of minimum sunspot activity is called **Maunder** minimum.

Milankovitch cycle : The earth's orbital variations are known as Milankovitch cycles.

Palynology : The science of the study of pollen grains and spores of plants is called palynology.

Obliquity : of the earth's rotational axis, or inclination of the earth's rotational axis 'refers to the angle of the axis in relation to the plane in which the earth revolves around the sun.'

Precession of equinoxes : may be defined as the time of the year or say the days of the year on which the earth's position is nearest to the sun (perihelion position of the earth) or farthest to the sun (aphelion position) due to varying motions of the earth.

Proxy data : Proxy data refer to inferred data as substitutes for real data.

Varves : Varves are the alternate sequences of layers of fine silts and clays deposited at the floors of lakes and large ponds in such an area which is characterized by alternate freezing and thawing during winter and summer seasons respectively.

Year without summer : The year 1816 is known as the year without summer in the climatic history of the earth when the glaciers became most active after Pleistocene ice age due to extreme cold winter and cool summer mainly in North America.

16

GLOBAL WARMING AND CHANGE IN ATMOSPHERIC CHEMISTRY

16.1 MAJOR GLOBAL PROBLEMS

The most significant global environmental problem faced by the world community is related to **global environmental changes** (GEC) consequent upon **global warming** resulting from a host of causal factors mainly anthropogenic factors such as changes in atmospheric chemistry, ozone depletion, emission of greenhouse gases at alarming increasing rate, urbanization, land use changes mainly deforestation etc. The probable net result of global warming and changes in atmospheric chemistry through air pollution and other natural sources would be **climatic changes** (also discussed in the preceding chapter) at local, regional and global levels including both short-term and long-term changes in weather and climate.

The international communities are scared of catastrophic adverse effects of future climatic changes on different spheres of man and nature e.g. deglaciation and sea level changes, submergence of island nations and major coastal lowlands, atmospheric dynamics including evaporation and precipitation, global radiation balance, photosynthesis and ecological productivity, plant and animal community, human health and wealth and many more. The major sources of global environmental problems have been identified as changes in atmospheric chemistry through air pollution (both gaseous and solid particulates pollution) through rapid rate of industrialization and urbanization, population growth at alarming rate, advances in productive technology, major land use changes mainly deforestation etc. and efforts are afoot for tackling the problem of global warming leading to climatic changes at international level.

It is, thus, necessary to discuss the evidences of global warming, trend of global warming, processes of global warming including ozone depletion and emission of greenhouse gases, effects of global warming, air pollution leading to changes in atmospheric chemistry, and related environmental problems and international cooperations to tackle the problems of global warming and climatic changes.

16.2 EVIDENCES OF GLOBAL WARMING

Global warming refers to gradual rise in atmospheric and ground surface air temperatures and consequent changes in global radiation balance caused mainly by anthropogenic processes (although natural processes also cause global warming and cooling) leading to climatic changes at different levels (e.g. local, regional and global levels). It may be pointed out that the pattern of global rise in air temperatures has been studied and reported by different scientists and agencies, and a few computer models have been constructed, but their results are not uniform, rather a few are contrasting. The **radiative forcing** and **global warming potential** (GWP) are used by the Inter-governmental Panel on Climate Change (IPCC) to compare the relative warming effect of different gases. The radiative forcing as defined by the IPCC refers to 'the effects which greenhouse gases have in altering the energy balance of the earth-atmosphere system'. On the other hand, the global warming potential is used as a tool to compare the relative warming effect of various gases emitted from anthropogenic sources such as carbon dioxide, carbon monoxide, nitrogen oxides, methane, sulphur dioxide, chlorofluorocarbon etc. (these will be discussed under the heading 'air pollution').

The scientists have attempted to identify convincing evidences to demonstrate the rising trend of air temperatures at least since the beginning of industrial revolution (1860 A.D.), though systematic recording of temperatures at different meteorological centers in the world started since 1880 A.D. It may be mentioned that only those evidences may yield fruitful results in demonstrating any trend of rise in air temperatures (which is the only indicator of global warming) which are temperature-dependent evidences. The following evidences support the theory of gradual rise in air temperature and consequent global warming :

1. Temperature records.
2. Melting of mountain and continental glaciers,
3. Warming of ocean water at global level,
4. Rise in sea level,
5. Thawing of permafrost areas,
6. Upward shifting of snow lines of the tropical and subtropical mountains,
7. Spreading of tropical diseases towards temperate and polar regions.
8. Shifting of seasonal weather phenomena and changes in precipitation patterns etc.

Increase in Air Temperature

It has been stated that the overall increase in the air temperature in the 20th century has been about 0.5 to 0.7°C. The last country *i.e.* the 20th century has been the warmest century in the last 2000 years. The last two decades of the 20th century (1980's and 1990's) have been warmest decades since the systematic recording of air temperature began in 1880. All the ten warmest years have occurred since 1980. The last decade of the 20th century (1990's) was the warmest single decade in the historical record of temperature, as seven out of ten warmest years occurred in this decade wherein the year 1998 was the warmest year of the millennium.

According to another view the average air temperature in the northern hemisphere increased by 0.4°C between 1880 and 1940 because of rapid rate of combustion of fossil fuels during this period but the temperature dropped after 1950 inspite of continued rapid rate of combustion of fossil fuels due to fast industrial growth but soon after 1940 the air temperature in the southern hemisphere showed rising trend which registered an overall increase of 0.6°C between 1940 and 1960. Another source has indicated an increase in air temperature by 1.5°C upto 1995 while other sources have shown general air temperature rise ranging between 0.3°C and 0.6°C. It may be mentioned that a rise of 2°C temperature from the normal temperature was recorded in the Indian Ocean during 1997-98 which caused catastrophic **coral bleaching** leading to 70 per cent death of corals in the Andaman-Nicobar and the Lakshwadeep islands.

Various models have been developed to predict global rise in air temperature. S.H. Schneider (1950) pointed out that the temperature could rise upto 1.5°C to 3°C if the concentration of atmospheric carbon dioxide could be doubled from the 300 ppmv level to 600 ppmv. The General Circulation Model developed by S. Manabe and R.T. Wetherald (1975) predicts that if the present (1975 level) amount of carbon dioxide of the atmosphere is doubled, the temperature of the earth's surface will increase by 2.9°C.

The global circulation models (GCM) have shown a temperature rise between 0.4°C to 0.8°C in the 20th century and have predicted warming of high latitudinal zones mainly arctic regions. The early melting of winter snow in the Great Britain, Norway, Canada, the U.S.A. *etc.* has resulted in early beginning of spring season at least by 15 days as evidenced by flowering of plants of spring season two weeks in advance. The flowering of mango trees in Uttar Pradesh, India in December 2004, also indicates warming trend. The temperature records of a few American and European countries have shown that the diurnal range of temperature or say difference of temperatures between days and nights has been reduced. The increase in the frequency of El Nino events between 1970 and 2000 A.D. also denotes warming of the earth's surface and its atmosphere. On the basis of aforesaid trend of temperatures in the past century it may be said that rising trend of temperatures denotes global warming. It is argued by some scientists that the temperature data are deceptive and confusing because most of the temperatures have been recorded in urban areas which become locally warmer than the surrounding countryside because of urban pollution, and we lack in sufficient temperature data from ocean surfaces, so nothing precisely could be said about either global warming or global cooling.

Projection of temperature and sea level rise due to global warming

	2025	2050	2100
CO_2 concentration	405-460ppmv	445-640ppmv	540-970ppmv
Global mean temperature change from the year 1990	0.4-1.1°C	0.8-2.6°C	1.4-5.8°C
Global mean sea level rise from the year 1990	3-14 cm	5-32 cm	9-88 cm

Source : Climate Change, Synthesis Report, IPCC, 2001.

Melting of Ice Sheets and Glaciers

The recent evidences have shown that the ice sheets of Antarctica and Greenland are breaking, the permanent ice covers of the arctic regions are melting, and continental and mountain glaciers are shrinking in both size and length as evidenced by their regular retreat. It may be mentioned that the Antarctica is well instrumented continent in terms of the study of various aspects of the continent e.g. surface and air temperatures, ice core analysis, size and thickness of ice sheets and glaciers, contraction and shrinking rate of ice sheets etc. The regular monitoring of Antarctic ice sheets has shown about 100 m annual rate of their shrinking. A rise of temperature of winter season by 4°C has been reported since 1950 in the west Antarctic Peninsula. There are ample evidences to demonstrate regular breaking of ice shelves and formation of giant icebergs which are floating masses of ice. It may be mentioned that ice shelf is floating huge mass of ice but is attached to the landmass while icebergs are floating masses of ice independent of ice shelves. In other words, the icebergs are formed when the ice shelves are disintegrated, thus huge voluminous mass of ice known as iceberg measuring several hundred square kilometers in area, floats independently in the sea. It is significant to point out that melting of ice-bergs does not make any change in sea level because these have already occupied places in the sea but melting of ice shelves and glaciers causes rise in sea level. The disintegration of Antarctic ice shelves is rapidly increasing *e.g.* Larsen iceshelf disintegrated in 1995 while many Antarctic iceshelves including Larsen B and Wilkes iceshelves broke away during 1998-1999.

Recording of ice covers over Bering Sea and Arctic Sea has revealed gradual but regular shrinking of their areas, e.g. (i) there has been decrease in areal coverage of Bering sea ice covers by 5 per cent since 1960, (ii) the sea ice area over Arctic sea has decreased by about 90,00 square kilometers since 1978 etc.

There are ample evidences to demonstrate the melting and retreat of mountain glaciers i.e. Alpine, Himalayan and Andean glaciers etc. A few examples would be sufficient enough to validate the melting and retreat of mountain glaciers upward e.g. (i) European Alpine glaciers have been reported to have shrunk in their length and volume by more than 50 per cent in the past century, (ii) the rate of upward retreat of Andean glaciers in Peru increased seven times in the last 3 decades of the 20th century, more precisely between 1978 and 2000 A. D., (iii) the Russian Caucases mountain glaciers have been shortened in their length by about 50 per cent due to melting since 1960, (iv) the glaciers of Chinese Tien Shan Mountains have lost their ice volume by 25 per cent on melting since 1960, (v) the glaciers of Southern Alps of New Zealand have moved upward by about 100 meters due to their retreat caused by thermal melting of ice, (vi) Mt. Kenya has lost its most extensive glacier in the past century etc.

Different studies have demonstrated faster rate of melting of the Himalayan glaciers in India, resulting into their upward retreat and negative mass balance. A recent study of 19 glaciers of the Baspa basin of Himachal Pradesh by the scientists of Marine and Water Resource Group of Space Application Center (SAC), Ahmedabad during 2000-2002 on the basis of weekly satellite images and field data provided by the Geological Survey of India (GSI) has revealed that their mass balance during 2001 and 2002 registered negative trend (i.e. $-90m^3$ in 2001 and $-78m^3$ in 2002). The study revealed that if the current rate of retreat continues, these glaciers would disappear by 2040 A.D. The study by SAC scientists from 1962 to 2001 also revealed loss of 24 per cent of glacial ice cover at the altitude of 5000 meters and of 14 per cent at the altitude of more than 5000 meters. The latest findings of SAC studies published in Current Science (Vol. 86, No1, 2004) as reported in Down to Earth (March 31, 2004) revealed the fact that continuous melting and retreat of glaciers in Himachal Pradesh resulting into decrease in the mass of ice of glaciers would result in marked reduction in runoff causing serious shortage of water supply in future. The rapid rate of retreat of glaciers in the Garhwal and Kumaon Himalayas has also been reported.

According to the latest survey of the Himalaya by Chinese scientists there is reduction in the height of Himalaya since 1966. The measured height of Mt. Everest was 8849.75 meters in 1966 which dropped to 8848.45m in 1999, thus registering a drop of 1.3m height in 33 years. The rate of lowering of its height was 0.1m per year from 1966 to 1975, 0.01m between 1975 and 1992 and again 0.1m from 1992 to 1999.

Other Indicators

The gradual spread of a few tropical and subtropical diseases poleward such as malaria, cholera, plague, dengu fever, yellow fever etc. is indicative of global warming. It may be mentioned that the insects, bacteria, viruses of such diseases flourish in extreme weather conditions e.g. extreme heat and cold, and extreme wet and dry seasons. The global warming is supposed to bring extreme weather conditions in the middle and high latitudes. The cases of outbreaks of cholera (in 1991 in Peru), dengu fever (e.g. during 1994 in Australia) and malaria in the temperate countries demonstrate the warming of middle latitude areas. According to an estimate, presently tropical diseases cover about 42 per cent area of the globe which may increase to 60 per cent if the average earth's surface temperature rises by 2^0C.

Decrease in the Antarctic penguins population by 40 per cent during the past 3 decades of the 20th century, due to their deaths from starvation because rise in sea temperature causes marked decrease in zooplanktons which are main sources of penguine feeding, is indicative of global warming. Mass destruction of corals due to coral bleaching is another significant indicator of global warming. The coral bleaching during 1997-98 has been recorded as the most catastrophic event as it accounted for large-scale deaths of corals in the tropical oceans of 60 countries and island nations. Though coral bleaching was observed by Alfred Mayer as back as 1991 but it was the year 1998 when large-scale coral bleaching accounting for 70 per cent deaths of corals off the coast of Kenya, Maldives, Andman and Lakshadeep islands in the India Ocean and 75 per cent deaths in the Seychelles Marine Park System and the Mafia Marine Plant of Tanzania was reported by Clive Wilkinson of the Global Coral Reef Monitoring Network (GCRMN) of Townsville (Australia). The coral bleaching is related to 2^0C rise in temperature from the normal temperature in the Andman Sea in 1997-98.

The analysis of recorded temperatures at the sea surface and below upto the depths ranging between 800 meters and 3000 meters has revealed the fact that the average sea temperature has risen by 0.6°C in the later half of the 20th century which caused rise in sea level by 10-25 centimeters. It has been estimated that if the current rate of increase of sea temperature continues upto the end of the present century i.e. by 2100 years, the sea level would register an increase of one meter.

The continued thawing of permafrost areas in Alaska and Siberia is another testimony of global warming. The studies by various scientists have indicated rise of temperatures of the upper layer (active layer) of permafrost ranging between 0.6°C and 1.5°C in Alaska resulting into the thawing of the upper layers of permafrost.

16.3 PROCESSES OF GLOBAL WARMING

Major sources and processes of global warming include ozone depletion and greenhouse effects. Thus, it is necessary to understand the mechanism of creation, destruction and maintenance of ozone layer and sources and processes of intensification of greenhouse effects by increasing emission of carbon dioxide and methane for evaluation of global warming.

16.4 OZONE DEPLETION

The mechanism of ozone depletion includes the aspects of creation of ozone, destruction of ozone and recreation or maintenance of ozone layer in the stratosphere. It is desirable to understand the mechanism of formation of ozone layer first so that the processes of its destruction and its impacts on global warming can be properly understood. It may be mentioned that the thinning of stratospheric ozone layer allows more ultraviolet solar radiation to reach the earth's surface and thereby increases the temperature of the earth's surface.

The stratospheric ozone layer mostly concentrated between the altitudes of 12km to 35km, is considered as a protective shield and earth's umbrella because it prevents ultraviolet solar radiation from reaching the earth's surface. Thus, the presence of ozone layer in the stratosphere is of vital significance for all biota including plants, animals and man in the biosphere. In the absence of this layer no life is possible in the biosphere because all the ultraviolet rays of the sun will reach the earth's surface and consequently the temperature of the earth's surface and the lower atmosphere will rise to such an extent that the **'biological furnace'** of the biosphere will turn into a **'blast furnace'**. It is, thus, desirable to study the various aspects or.

1 Creation of Ozone Layer

Ozone defined as 'a three-atom isotope (one of a set of chemically identical species of atoms which have the same atomic number but different atomic weight is called isotope) of oxygen (O_3)', or 'merely a triatomic form of oxygen (O_3) is a faintly blue irritating gas with a characteristic pungent odour. Ozone is a strong oxidizing agent which can at high concentrations decompose with an explosion'. There are contrasting opinions about the altitudes of the concentration of ozone. It may be pointed out that ozone is present almost at all altitudes in the atmosphere but the bulk of its concentration is present in a layer from 10km to 50km up in the atmosphere and within this ozone the highest concentration of ozone is between the altitudes of 12km and 35km in the stratosphere. This zone (12km-35km) of ozone is called **ozonosphere** or **ozone layer** or **stratospheric ozone layer.**

The ozone gas is unstable because it is created as well as destroyed or disintegrated. In other words, the creation and destruction of ozone gas is a gradual and continuous natural process. The oxygen molecules are broken up or separated in the atmospheric layer between the altitudes of 80 to 100 km by ultraviolet solar radiation or by an electric discharge in oxygen or air during a thunderstorm in the troposphere in the following manner.

$$O_2 \rightarrow O + O$$

(oxygen breaks up into two separate oxygen molecules)

These separated oxygen atmos (O) are then combined with oxygen molecules (O_2) and thus ozone (O_3) is formed.

$$O_2 + O + M \rightarrow O_3 + M$$

or

$$O_2 + O \ldots\ldots\ldots\ldots O_3 \text{ (ozone)}$$

Where M denotes energy and momentum balance produced by the collision of oxygen molecules (O_2) with another individual atom or molecule. It may be pointed out that the collisions of 3 atoms or molecules or the collisions of oxygen

(O_2) with the third atom are not very common feature of regular occurrence between the altitudes of 80 to 100 km (though O_2 is very frequently broken up into individual atom or molecule in this layer as referred to above) because of very low density of gases in this part of the atmosphere and such collisions are also very rare in the atmosphere below the altitude of 35 km because most of the solar ultraviolet rays have already been absorbed above this height. Thus it is obvious that the formation of ozone (O_3) due to collision of 3 atoms (O_2 + O) through the process of **photomechanical reaction** triggered by the sunlight is more active in the atmospheric zone of 30 to 60 km height from the sea level. It is further important to note that the **ozone mixing ratio** (ozone mixing ratio = mass of ozone per unit mass of dry air) is maximum at the height of about 35 km but the maximum **ozone density** (ozone density = mass of ozone per unit volume) is found between the height of 20 km to 25 km. This is because of the fact that ozone is transported to lower height (upto 12 km) by some upper air atmospheric circulation mechanisms which allow the ozone gas to accumulate between the height of 12 km to 35 km.

It is also important to note that most of the stratospheric ozone is formed in the atmosphere over the tropical areas from where some ozone is transported by the atmospheric circulation to the polar areas up in the atmosphere. The ozone (O_3) is also transformed back into oxygen by further collision of ozone with monatomic oxygen (individual molecule of oxygen, O) in the following manner.

Ozone (O_3) + O $\rightarrow$ Oxygen (O_2) + Oxygen (O_2)

Ozone is also transformed into oxygen by **photochemical processes** (by the actions of solar radiation on ozone).

In a very simpler term the process of the formation of ozone may be described as the production of ozone by the actions of ultraviolet rays on ordinary oxygen atoms by the photochemical process which is responsible for the constant transformation of oxygen (through the collision of 3 atoms of oxygen i.e. O_2 + O) to ozone and from ozone back to oxygen. Thus the constant formation or production and destruction of ozone is a natural process which maintains an approximate equilibrium level of ozone in the atmosphere if not interfered by human activities.

Though ozone layer contributes only about 3 to 4 mm of thickness to the total atmospheric thickness of 8m (if the whole of atmosphere may be compressed to sea level temperature and pressure) but this layer is a life-saving protective cover for all the biota of the biosphere.

2. Depletion of Ozone Layer : An Environmental Concern

There has been much hue and cry about the depletion of stratospheric ozone in the last one or two decades (of the 20th century) and the issue now has assumed a global dimension because the problem of ozone depletion and its adverse consequences have threatened the existence of all forms of life in the biosphere. The presence of ozone layer in the atmosphere is very crucial and significant for plants and animals in general and human beings in particular because it provides a protective cover, known as earth's umbrella, to all of the organisms (including plants, animals, micro-organisms and man) in the biospheric ecosystem against their exposure to ultraviolet solar radiation. Infact, the ozone layer filters the solar radiation by absorbing unwanted ultraviolet rays and allowing only those radiation waves to reach the earth's surface which are essential for the maintenance of life of the planet earth. Any change in the equilibrium level of ozone in the atmosphere will adversely affect the life in the biosphere. Thus, the growing concern for the depletion of stratospheric ozone is not without reason and scientific evidences. The following evidences and efforts of scientific communities and governments are sufficient enough to demonstrate the growing awareness about the importance of ozone and possible adverse effects arising out of its sharp depletion.

Perhaps the first concious effort to sound a warning about the depletion of ozone layer was made in the Western World by M. Molina and S. Rowland of the University of California (U.S.A.) in 1974-75 when the result of their published theoretical computer studies using a unidimensional linerar model predicted the accumulation of man-made ozone destroyer chemicals known as chlorofluorocarbons in the atmosphere of the earth and rapid rate of depletion of ozone because of the presence of these chemicals. On the other hand, the efforts to collect information and data of the variations in the ozone level in the earth's atmosphere based on satellite monitoring on regular basis started in Russia as back as 1967. The data of ozone level variations coming through satellite monitoring since 1967 have revealed sharp depletion of ozone layer. The monitoring from NIMBUS 3, NIMBUS 4 satellites and EXPLORER 5 and TYROS 4 of the former U.S.S.R. indicated definite variations in the ozone level. The sharp decline in the ozone level during 1960's was attributed to the discharge and transport of nitrous oxides caused by numerous nuclear tests carried out by the developed nations like the Russia, the U.S.A., France etc. into the atmosphere. The original level of ozone was restored and the depleted ozone layer was gradually stabilized soon after the banning of nuclear tests in the atmosphere.

The British Antarctic Survey Team led by Josepth Farman provided first hand evidence of ozone depletion over the Antarctica in 1985. Joseph Farman reported 40 per cent loss in the spring time ozone layer in the atmosphere lying over Antarctica (reported in Nature, 1985).

Following the startling findings of ozone depletion over Antarctica by the British team a Multinational Expedition was launched during the spring season (March to October) of 1987. This expedition involving scientists from several countries conducted satellite, aircraft, baloon and terrestrial measurements to find out the level of the ozone in the atmosphere over Antarctica involving an area twice as large as the U.S.A. The findings of this multinational expedition team revealed that (i) the average natural concentration of ozone dropped by 50 per cent between August, 15 (1987) to October 7, 1987, and (ii) in some patches of the observed area the ozone concentration dropped by 100 per cent or ozone totally disappeared which resulted into the formation of ozoneless patches now called as **ozone hole** in the ozone layer or the **ozonosphere.**

Thus following the startling revelations by the British Antarctic Survey Team in 1985 and the Multinational Expedition of Antarctica in 1987 about the depletion of ozone layer and the creation of **ozone hole** over Antarctica the **Montreal Protocol** on substances that deplete the zone layer was signed in September 1987 by 35 countries. This first international agreement to limit the production and consumption of ozone depleting chemicals such as CFC (chlorofluorocarbon) was made possible due to sincere efforts made by the developed countries and leading scientists under the United Nations Environment Programme (UNEP).

The World Watch Institute (U.S.A.) released the first authentic and well documented detailed research monograph on the threat to the ozone layer authored by Cynthia Pollock Shea in 1988. It may be pointed out that prior to the release of the report of the NASA Ozone Trend Panel in 1988 there was a common belief that the depletion of ozone was a seasonal phenomenon and was confined to the atmosphere laying over Antarctica alone but the report of the said *NASA OTP* (NASA Ozone Trend Panel) based on the conclusions of more than 100 scientists of 10 countries revealed that the previous orthodox hypothesis of ozone depletion only over Antarctica was erroneous and therefore not tenable and concluded that the depletion of ozone layer was a global affair.

The **World Watch Institute** further released a detailed report on the **State of the World** in 1989 wherein several crucial factors responsible for environmental degradation such as the depletion of ozone layer, greenhouse effects, soil erosion, deforestation and population growth were listed and detailed immediate action plans at global scale were suggested inorder to safeguard the earth from the perilous effects of these man-made environmental diseases so that the future generations might not curse the present human society.

A three-day international conference involving a large number of ministers, senior officials, leading international scientific societies, scientists and industrialists of over 150 countries was organised between March 5 to 7, 1989, at London at the behest of the United Nationas Organisation. The central theme of the conference was to search ways and means to save the endangered ozone layer. The basic issues were concerned with limiting the production and consumption of ozone depleting chemicals such as chlorofluorocarbons not only in the developed countries but also in the developing countries. The deleberations and decisions of the London Conference on 'Save Ozone Layer' as referred to above will be discussed in the next subsection of this topic (maintenance of ozone layer).

3. Factors and Mechanisms of Ozone Depletion and Creation of Ozone hole

Combining of atmospheric oxygen (O_2) with individual oxygen molecule (O) results in the creations of ozone ($O_2 + O \rightarrow O_3$) whereas the breaking of ozone (O_3) into O_2 and O or re-creation of oxygen due to collision of ozone (O_3) with monatomic oxygen (O) results in the depletion or destruction of ozone ($O_3 \rightarrow O_2 + O$ or $O_3 + O \rightarrow O_2 + O2$). The collective process of constant metamorphosis of oxygen into ozone (ozone formation) and ozone back into oxygen (ozone destruction or ozone depletion) is triggered by photochemical processes. If this is true, there must be maximum formation of ozone during June near the equator but the distributional pattern of ozone denotes its maximum concentration in the high latitudes (beyond 50^0 latitude in both the hemispheres) and minimum concentration over the equator. This anomalous distribution of ozone may be explained if we consider transport of ozone by the atmospheric circulation towards the polar areas.

It is believed that ozone having maximum concentration between the altitudes of 30 km to 40 km during summer months mainly during June in the low latitudes (equatorial zone) is transported during winter months towards high latitudes (polar areas) between the altitudes of 20 to 25 km. Thus the accumulation of ozone in the polar areas during winter season results in the development of rich ozone layer during early spring season.

It may be pointed out (as referred to earlier) that the creation and destruction of ozone is a regular natural process which never disturbs the equilibrium level of ozone in the stratosphere but when the destruction of ozone exceeds the level of ozone creation, serious repurcussions are bound to crop up in the lower atmosphere and at the earth's surface, due to disequilibrium in the level of ozone.

In the beginning there was a lot of controversy about the causes and factors of ozone depletion but now a consensus has been reached that the main culprits of ozone depletion are halogenated gases called chlorofluorocarbon, halons, and nitrogen oxides. The world Meteorological Organisation's (WMO) statement on anthropogenic modification of the stratospheric ozone layer issued in 1976 maintained that a continuous release of chlorofluoromethanes into the atmosphere may be capable of destroying ozone to a considerable extent. Contrary to this opinion M.L. Parry maintained in 1977 that the ozone concentration in the stratosphere might be rising and chlorine does not necessarily cause depletion of ozone. But the latest *NASA* report has set aside the controversy about the factors and causes of ozone depletion as chlorofluorocarbons (CFCs) and halons have been recognised by most of the scientists as the main culprits of ozone depletion.

The chlorine-containing chlorofluorocarbons were discovered by U.S. scientist Thomas Midgley Jr in 1930 while Ralph J. Cicerone and Richard S. Stolarski, the scientists of the University of Michigan (U.S.A.), reported that chlorine atoms could deplete the ozone in the same manner as nitrogen oxides. Thus it may be concluded that nitrogen oxides, chlorofluorocarbons and halons are the main sources of the depletion of stratospheric ozone.

It may be pointed out that the chlorofluorocarbons are neither toxic nor flamable at ground level but when these reach the stratosphere they become potent destroyer of the ozone layer through a set of chemical reactions. The chlorofluorocarbons (popularly known as CFCs), belonging to the category of synthetic chemicals, are relatively simple compounds of the elements chlorine, fluorine and carbon and are initially stable compounds which do not have any toxic effect on life processes in the biosphere at the ground level. These synthetic chemicals are widely used as propellants in spray can dispensers, as fluids in airconditioners and refrigerators, as blowing agents in insulations foams (popularly known as styrofoam) and as industrial solvents. It is estimated that about 35 per cent of the total world production of chlorofluorocarbons is used to propel personal care products such as deodorants, hair sprays, shaving creams and numerous other cosmetic products. The most important of the chlorofluorocarbons- hydrocarbons are the trichlorofluoromethane (trade name FREON 11) and dichlorofluoromethane (trade name FREON 12).

Bromine containing halons were developed by the U.S. Army Corps of Engineers at the end of Second World War as a means of fire fighting in tanks and armoured personnel carriers. Now halons are widely used in fire fighting devices. The world wide production of Freons 11 and 12 continued to rise at the rate of 10 per cent per year upto 1974 but the production of F-11 and F-12 dropped by 15 per cent in 1975 and 1976 wherein 3000 million cans ejected more than 5,00,000 tonnes of fluorocarbons and the total production of F-11 and F-12 was about 7,00,000 tonnes in 1975. Since then the production of chlorofluorocarbons increased by 1985 when the Montreal Protocol was signed to reduce the production of these villain chemicals. There are more than 24 major producers of chlorofluorocarbons. It is reported that the major world producers of CFCs excluding socialist countries produced 10,00,000 tonnes of CFCs in 1987. It may be pointed out that the atmospheric concentrations of chlorofluorocarbons are increasing rapidly at the rate of 13 to 28 per cent (Freon 11) per annum.

The mechanisms of ozone depletion include both (i) the **natural processes,** and (ii) the **anthropogenic process.** The natural processes of ozone depletion involve the conversion of atmospheric nitrogen into nitrous oxides due to solar activity because of maximum sunspots at the end of every 11-year cycle. According to latest estimate the level of nitrous oxides rises from 30 to 60 per cent at the end of 11-year cycle in the middle latitudes of the southern hemisphere. This mass of nitrous oxides is transported to the stratosphere at the polar areas during winter season (polar night). These nitrous oxides then deplete the ozone layer through photochemical reactions. These nitrous oxides also augment the rate of ozone depletion triggered by chlorine molecules. Secondly, ozone (O_3) is also split into oxygen (O_2) and single oxygen molecule because of ultraviolet solar radiation. The natural mechanisms of ozone depletion do not necessarily upset the ozone equilibrium in the atmosphere because the loss of ozone caused by natural processes is suitably compensated by the creation of ozone through natural processes. Thirdly, the dynamic mechanism involves the redistribution of ozone by the atmospheric circulation. It has been suggested that the upper air atmospheric circulation transports ozone from over south pole and accumulates it in a belt between 60^0 to 70^0S. This transport of ozone from over south pole results in the thinning of ozone layer and thus the formation of ozone hole.

The **anthropogenic mechanisms of ozone** depletion include a few processes on which the following hypotheses have been postulated viz. (1) **Chlorine hypothesis** - The Chloro-fluorocarbon and halon gases are released during the maintenance or operation of several devices using these synthetic chemicals (such as refrigerators, airconditioners, spray-can dispensers etc.), shredding of foam insulation and fire fighting into the atmosphere. Initially, these gases are chemically inert and nontoxic at the ground level and in the troposphere. These gases also do not break down in the troposphere. These are transported upward into the stratosphere. The transport of chlorofluorocarbons and halons by vertical atmospheric circulations to the stratosphere normally takes 6 to 8 years or even more (about 10 years). These gases are further transported to the south polar stratosphere. The depletion of ozone due to chlorofluorocarbons and halons involves the following steps.

(i) A swirling polar vortex is formed over the south pole (in the atmosphere) during long Antarctic winter (from March to September).

(ii) This swirling south polar Antarctic vortex causes considerable lowering of temperature.

(iii) The meagre amount of vapour present in the dry upper atmosphere is frozen due to markedly low temperature below freezing point. This frozen upper atmospheric moisture forms upper atmospheric or stratospheric clouds.

(iv) The chlorine and bromine of chlorofluorocarbons and halons are converted from their initial non-reactive form to reactive form because of the chemical reactions on the ice crystals. It may be mentioned that chlorofluorocarbons and halons are transported to the stratosphere by vertical atmospheric circulation. Thus the transformed form of non-reactive chlorine and bromine, as reactive molecules, becomes very much sensitive to sunlight.

(v) The nitrogen oxides generally inactivate chlorine but the lowering of stratospheric temperature because of polar Antarctic swirling vortex transforms nitrogen oxides into frozen form which then becomes non-reactive nitric acid.

(vi) During the next spring sunlight breaks down chlorofluorocarbons and halons through the mechanism of photochemical processes and thus chlorine and bromine are released to the atmosphere. These halogen molecules then disintegrate ozone (O_3) into ordinary oxygen (O_2+O) and thus the process of destruction or depletion of ozone starts.

2. Sulphate hypothesis : In 1986 it was established by the scientists that the chemistry of cloud surface is of paramount significance in the destruction of ozone. It is believed that the sulphate aerosols emitted through volcanic eruptions (natural) and numerous constantly active human volcanoes (chimneys of factories) accumulate in the atmosphere at all latitudes between the altitudes of 15km to 22 km. It has been discovered that the concentration of sulphate aerosols is most prevalent over the populated and industrialised areas of the northern hemisphere. This trend further validates the belief that most of the sulphate aerosols present in the atmosphere are contributed by human (industrial) activities. These sulphate aerosols catalyse the transformation of ozone to ordinary oxygen (O_2+O). If this **sulphate hypothesis** of ozone depletion is accepted, the destruction of the ozone layer thus becomes global phenomenon and the depletion of ozone would be accelerated more than anticipated on the basis of **chlorine hypothesis** (depletion of ozone due to chlorine molecules released from the breakdown of chlorofluorocarbon).

(3) The **nitrogen oxides hypothesis** states that nitrogen oxides emitted from supersonic jets in the higher altitudes deplete ozone. The supersonic transport aircrafts (SST) flying at the speed of more than twice the speed of sound at the altitude of 18 to 20 km release significant amount of nitrogen oxides from their exhausts (the first commercial flights of Concorde and Super Sonic Transport aircrafts started on January 22, 1976). The study of impact of nitrogen oxides released from the exhausts of a large fleet of Super Sonic Transport (SST) aircrafts on the stratospheric ozone conducted by Harold H. Johnston, an atmospheric scientist at the University of California, Berkeley (U.S.A.), demonstrated that 'a fleet of 500 Boeing SSTs would reduce global ozone by a value between 3 and 23% over all the earth's surface, and by as much as 50% near areas of intensive air travel' (A.N. Strahler and A.H. Strahler, 1976). The **Climatic Impact Assessment Programme** (CIAP) launched by the U.S. Department of Transportation (DoT) to study the impact of nitrogen oxides on ozone depletion confirmed the initial conclusion of considerable impact of nitrogen oxides released from the exhausts of Super Sonic Transport aircrafts on ozone as drawn by H.H. Johnston as referred to above. Further studies to assess the impact of nitrogen oxides on stratospheric ozone conducted by the U.S. National Academy of Sciences and the U.S. National Academy of Engineering have confirmed the potential impact of nitrogen oxides on ozone depletion.

(4) **Polar stratospheric clouds hypothesis :** The research team of the Cambridge University, U.K. reported in March, 2005 that the concentration of stratospheric ozone over Arctic region decreased upto 50 per cent between November, 2004 to March, 2005. According to Markus Rex of the Alfred Wegener Institute, located in Potsdam, Germany, the Arctic ozone layer was depleted upto 30 per cent by 2005. The question arises, as to why the ozone layer got depleted over the Arctic region inspite of substantial reduction in the production and consumption of CFCs under Montreal Protocol? It may be mentioned that the depletion of ozone layer continues though there is gradual decrease in the production and consumption of ozone depleting substances. It means that besides CFCs being major factor of ozone depletion, there are also other factors which contribute in the depletion of stratospheric ozone layer. According to John Pyle (2005) of the research team of the Cambridge University there has been maximum depletion of Arctic stratospheric ozone between 1965 and 2005. It was believed by the scientists that after the implementation of Montreal Protocol there would be substantial decrease in ozone depletion but this could not happen. Now the scientists believe that the increase in the number of clouds in the Arctic stratosphere leads to reduction in the concentration of stratospheric ozone. The green house effect causes warming of lower atmosphere but there is cooling of stratosphere. This phenomenon causes formation of ice clouds at the height of 14-26 km in the stratosphere. It may be remembered that there is also maximum concentration of ozone within this zone of the atmosphere. There are fast chemical reactions due to such ice clouds in ozone zone which cause depletion of ozone layer. According to Markus Rex the cloud covers in the stratosphere over the Arctic region increased four times in 2005 in comparison to Arctic stratospheric cloud covers during the decades 1960 and 1970 due to marked cooling of the stratosphere. This led to record depletion of Arctic ozone layer upto the tune of 50 per cent during 2004-2005.

4. Ozone Depletion and Global Warming

According to one school of thought the net effect of ozone depletion mainly because of the impact of chlorofluorocarbons on thermal conditions of the earth's surface and the lower atmosphere would be highly complicated and unpredictable because of two facts arising out of ozone depletion viz. (i) Because of weakening of ozone layer there will be less absorption of ultraviolet solar radiation and hence more ultraviolet rays will reach the earth's surface and consequently the temperature of the earth's surface will be increased. (ii) On the other hand, the heating of the stratosphere will be reduced because of reduced absorption of ultraviolet rays. This phenomenon would result in cooling of the earth's surface because of less thermal radiation from the stratosphere to the earth's surface. These two factors will certainly complicate the effects of ozone depletion due to the effects of chlorofluorocarbons. This hypothesis is not tenable because without doubt it has now been established that ozone depletion would result in the increase of surface temperature of the earth and its lower atmosphere.

It is believed that the depletion of ozone layer would result in 5 to 20 per cent more ultraviolet radiation reaching the populated areas of the world. The substantial increase in the surface temperature of the earth would cause global warming and climate changes at regional and global levels. The overall warming of the environment would cause melting of continental glaciers and ice sheets such as those of Antarctica and Greenland. This would in turn cause rise in sea level and consequent submergence of coastal lowlands.

Chlorofluoromethanes, besides depleting ozone layer, are also supposed to enhance the greenhouse effect of carbon dioxide because these halogen gases are effective absorbers in the 8-13 microns wavelength band but water vapour and carbon dioxide may not effectively absorb these radiation waves. Thus, the increased temperature would induce several climatic changes in various parts of the globe. It is also believed that the depletion of ozone in the stratosphere would result in the increase of the amount of hydrogen peroxide in the troposphere which would ultimately induce acid rain. Ozone depletion and increased ultraviolet solar radiation would also increase photochemical processes which in turn would create poisonous urban smogs.

5. Protection and Maintenance of Ozone Layer

The depletion of ozone layer and consequent imminent danger to biological communities in general and human society in particular have become a matter of serious environmental concern to governments, scientific communities and general public at local, regional and global levels. With the result serious attempts are being made at international level to heal the already wounded stratosphere by protecting and maintaining the precious ozone layer. The signing of Montreal Protocol in 1987 to reduce the production and consumption of chlorofluorocarbons and the organization of International Conference known as London Conference hosted by the British Government and collaborated by the United Nations Environment Programme (UNEP) during March 5-7, 1989 at London to study the level and causes of ozone depletion and to involve more international participation to tackle the problem of ozone depletion clearly indicate the level of the seriousness of the problem and keenness of the world communities to protect the gradually depleting precious ozone layer. The remedial measures of ozone depletion at international level are being taken at two levels viz. (i) to promote reduction in the production and consumption of emissions of ozone depleting chemicals, and (ii) to make serious efforts to produce and propagate the use of alternative chemicals which do not deplete ozone in the stratosphere.

(i) **Reduction in the production and consumption of CFCs and halons** : The emissions and spread of chlorofluorocarbons and halons do not care for any international boundary as about 95 per cent emissions of these ozone depleting chemicals occur in the northern hemisphere (because of the location of all of the developed countries in this hemisphere) whereas the concentration of these chemicals is only 5 to 10 per cent less in the southern hemisphere because of their rapid spread through the troposphere by the atmospheric circulations. According to a survey conducted in 1976 the concentrations of Freon-11 and Freon-12 in the southern hemisphere were 120 p.p.m. and 220 p.p.m. respectively which were expected to increase to 700 p.p.m. and 900 were p.m. by the turn of the 20th century. It is reported that the major world producers of CFCs (chlorofluorocarbons) excluding socialist countries produced 1,000,000 tonnes of CFCs in 1987. It may be further pointed out that most of the world production of CFCs is consumed in the developed countries where the annual per capita consumption of CFCs is 1 to 1.2kg in the U.S.A., European countries and Japan.

The first and foremost task before the world communities is to stop or markedly reduce the production and consumption of ozone depleting synthetic chemical compounds like CFCs (chlorofluorocarbons) and halons. The Montreal Protocol signed in September 1987 at Montreal, Canada, by 35 developed countries of the world is the first concrete step in this regard. The signing of this Montreal Protocol was made possible because of continued efforts and negotiations made by the United Nations Environment Programme (UNEP). The following provisions were commonly agreed by the countries which signed the said protocol.

(i) To freeze the production of CFCs (chlorofluorocarbons) at 1986 level by 1989.

(ii) To decrease the production of these synthetic chemical compounds by 20 per cent by the end of 1993.

(iii) To allow further 30 per cent cut in the production of these chemicals by 1998.

(iv) To freeze the production of halons at 1986 level starting from 1992.

(v) Thus the total production of ozone depleting chemicals (mainly CFCs and halons) would be reduced, according to the Montreal Protocol, by 50 per cent by the beginning of 1999 but this could not be achieved.

The aforesaid Montreal Protocol suffers from certain lacunae viz. (i) the provisions for phase out reduction in the production of CFCs and halons, and (ii) the provisions of exemption to developing countries to implement the reduction programme from 1999.

It is argued that the phase out programme of the reduction of CFCs and halon production by 50 per cent by the end of 1998 or the beginning of 1999 was not sufficient to stop the depletion of ozone because it would only slow down the pace of ozone depletion. Secondly, there are also some other chemical compounds which contain chlorine and bromine such as methyl chloroform and carbon tetrachloride which contribute in the depletion of ozone layer but these chemicals were not covered by the Montreal Protocol. It may be pointed out that these chemicals are used as solvents which, according to an estimate, contributed about 13 per cent of the total depletion of the stratospheric ozone in 1987, the year when the Montreal Protocol was signed.

The Montreal Protocol also granted exemption to developing countries to implement the phase out programme of the reduction of ozone depleting chemicals say chloroflurocarbons and halons 10 years later i.e. from 1999. It may be pointed out that at present (1987) the per capita consumption of CFCs and halons in the developing countries is very low but in view of the large populations of these developing countries the per capita consumption of CFCs and halons is expected to increase enormously in the 21st century. According to a survey conducted in 1986 the developing countries consume about 16 per cent of the total world consumption of CFCs and halons per year. So, the developing countries have been allowed by the Montreal Protocol to increase the consumption of CFCs and halon upto 1999 but the per capita consumption of CFCs and halons must not exceed 0.3 kg which is only one third of the present rate (1988) of per capita consumption (1 to 1.2 kg) by the developed industrialized countries. The developing countries were asked to freeze the production of CFCs and halon from 1999 and then to effect 50 per cent reduction in the production of these chemicals in a phased manner as was applicable to the developed countries. It may be pointed out that most of the developing countries have not singed the Montreal Protocol.

According to the survey report of the U.S. Congress Office of Technology Assessment (OTA) if only the eight major developing countries e.g. China, India (has now signed), Brazil, Indonesia, Iran, Mexico, Saudi Arabia, and South Korea could not sign the Montreal Protocol and did not participate in the phase out programme of the production and consumption of CFCs and halon as envisaged in the said protocol, the consumption of CFCs at global level would fall by only 15 to 30 per cent of the present level (1987) by 2000 A.D. It may be further pointed out that the Montreal Protocol envisaged, if all the provisions of the treaty were implemented in toto, only 2 per cent loss in the present level of (1987) the stratospheric ozone by 2075 A.D. but ozone has already been depleted by 2 per cent at present (1987). According to the report of the survey conducted by the U.S. Environmental Protection Agency (EPA) the total concentration of chlorine in the atmosphere would increase three fold even if all the nations of world sign the Montreal Protocol and implement all of its provisions in letter and spirit.

(ii) **Search for alternative technology :** Besides reducing the level of production and consumption of ozone depleting CFCs and halon, attentions are focussed on improving the use and maintenance of existing CFCs and halon and on searching substitute chemicals which can replace dangerous CFCs and halons. New techniques should be developed so that leakage of these gases may be stopped and efficient equipments may be used to handle these gases. A few substitute chemicals claimed to be chlorine free have been developed. For example, a U.S. based petroleum company has developed Bioact EC-7, a biodegradable non-toxic, and non-corrosive chemical known as HFC-134 (a trade name) which may be used in place of Freon-12 in airconditioners and refrigerators. This chemical is claimed to be free from chlorine. A new chemical called CFC-22 has been developed in the U.S.A. as a substitute for Freon-11 and Freon-12. But the researches on the use and effects of CFC-22 conducted by the U.S. scientists have revealed that the CFC-22, a monochlorofluoromethane considered to be best among the fluorocarbons, also depletes ozone more than CFC-11 (Freon-11) and CFC-12 (Freon-12). The research laboratories of some companies have discovered that HCFs or CFCs with an added extra hydrogen atom may be used in airconditioners. Attempts are also being made in the developed and the industrialized countries to search for chlorine free substances that do not have ozone depletion potential but can be used in refrigerators.

16.5 GREENHOUSE EFFECTS AND GLOBAL WARMING

1. Meaning of Greenhouse Effect

A greenhouse is meant for plants mainly in the cold countries where total insolation at least during winter season is not sufficient enough to support plant growth. The glasses of greenhouse are such that these allow the visible sunlight to enter but prevent the longwave infrared rays to go out. A greenhouse also does not have any provision for artificial heating. The greenhouse effect means 'progressive warming-up of the earth's surface due to the blanketting effect of man-made carbon dioxide in the atmosphere' (Oxford Dictionary).

'In a greenhouse, visible sunlight passes through the glass and heats up the soil and warms the plants. The warm soils emit radiation in longer wavelengths particularly in the infrared. Because the glass is opaque to these wavelengths (long wavelengths of infrared radiation waves), it absorbs and reflects the infrared (radiation waves)' (D.B. Botkin and E.A. Keller, 1982). This mechanism keeps the greenhouse warmer than the outside environment. In nut shell it may be summerized that a greenhouse is the body which allows the shortwave incoming solar radiation to come in but does not allow the longwave outgoing terrestrial infrared radiation to escape. Carbon dioxide and water vapour act as a greenhouse in that these allow visible light of the sun to reach the surface of the earth but absorbs and reflect back the longwave outgoing terrestrial radiation mainly infrared rays back to the earth's surface and thus help in keeping the earth's surface warmer. The gases with the properties of greenhouse are called **greenhouse gases** such as carbon dioxide. Halogenated gases such as chlorofluorocarbons are also greenhouse gases because these absorb longwave terrestrial radiation in the 8-13 microns band and thus help in enhancing the carbon dioxide greenhouse effect. It may be, thus, concluded that the net result of greenhouse effect of carbon dioxide, water vapour and halogenated gases is the increase in the temperature of the earth's surface and the lower atmosphere because these gases allow solar radiation to reach the earth's surface but absorb most of the longwave terrestrial radiation and reradiate back to the earth and thus regularly warm the earth's surface and its immediate atmosphere.

Table 16.1 : Emission of Green House Gases (GHG) (in million tonnes), 1995

Developed Countries			Developing Countries		
1.	U.S.A.	1,433	1.	China	846
2.	Russia	414	2.	India	250
3.	Japan	308	3.	South Korea	104
4.	Germany	241	4.	South Africa	95
5.	U.K.	151	5.	Mexico	94
6.	Canada	115	6.	Iran	76
7.	Italy	107	7.	Brazil	65
8.	Poland	95	8.	Saudi Arabia	63
9.	Ukraine	92	9.	Indonesia	62
10.	France	91	10.	Kazakhastan	48
11.	Australia	87	11.	Taiwan	48
12.	Spain	60	12.	Turkey	38

Source : Down to Earth, April 30, 1998.

2. Major Sources of Greenhouse Gases

The most significant greenhouse gas is carbon dioxide which is released to the atmosphere by burning of fossil fuels for different purposes in various ways e.g. (i) Electric power stations based on fossil fuels mainly coal and mineral oil emit huge amount of carbon dioxide which reaches the atmosphere every year. These power stations are the most significant and widespread major sources of man-induced carbon dioxide. (ii) Numerous factories spread all over the world burn immense quantity of coal, mineral oil and natural gas and spew huge amount of carbon dioxide together with other undesirable gases through their chimneys into the atmosphere. (iii) The third major source is the transport sector which includes various types of vehicles run on coal and petroleum. For example, railways are large consumers of coal mainly in the developing countries, in India coal operated locomotives have been phased out and many developing countries are trying to phase out coal operated rail engines. Similarly, large fleets of automobiles (trucks, buses, cars and two wheeler-motor cycles, scooters etc.), agricultural implements like tractors, combines etc. and aircrafts all over the world burn immense quantity of diesel and petoleum each year. (iv) The fourth major source of the production of carbon dioxide is deforestation and burning of firewoods. The people are acquainted with the first three major sources of carbon dioxide as they directly spew carbon dioxide but the mechanisms of the release of carbon dioxide through deforestation are little understood by common man.

It is important to note that the vegetation, mainly forests of trees, and soil of the earth are very large storage pools of unoxidised carbon as according to an estimate they contain about 2 trillion tons of carbon in them. The trees release carbon as carbon dioxide after carbon is oxidised in two ways e.g. (i) through the decay and decomposition of felled or naturally fallen trees or parts thereof, and (ii) through burning of wood for various domestic purposes or through large-scale forest fires either kindled by deliberate or inadvertent actions of man or through natural forest fires due to lightning. The vegetation is a very large sink of carbon dioxide because carbon dioxide is used by plants to prepare their food during the process of photosynthesis and thus huge quantity of carbon dioxide is fixed among the plants. If the forest cover is reduced through large-scale deforestation for different purposes (for increase in agricultural lands, for urban and industrial expansion, for commercial purposes etc.) the consumption of extra amount of carbon dioxide released through anthropogenic sources (e.g. human volcanoes-chimneys of factories, transport vehicles, thermal power stations etc.) to the atmosphere will be reduced and thus the concentration of carbon dioxide in the atmosphere will increase. It is believed that the deforestation has added 90 to 180 billion tonnes of carbon to the atmosphere whereas the total contribution of carbon from the burning of mineral oil and coal has been 150 to 180 billion tonnes (the base year of the beginning of the Industrial Revolution).

Minor greenhouse gases like halogenated gases (chlorofluorocarbons) and halons are released to the atmosphere during the operation and maintenance of appliances and equipments using chlorofluorocarbons as coolants and propellants (e.g. airconditioners, refrigerators, several cosmetic goods, plastic foam, fire extinguishers etc.). Besides, methane, nitrous oxides, and ozone are also green house gases.

3. Emissions of Carbon Dioxide

The climatic changes caused by global greenhouse effect due to higher concentration of carbon dioxide in the atmosphere are primarily related to the pattern of energy transfer and uses the world over. It may be pointed out that here only that part of climatic changes is being considered which is caused by greenhouse effect only. It is significant to note that the pre-industrial level of atmospheric content of carbon dioxide (CO_2) was fixed at 280 to 290 p.p.m. (parts per million) or 0.028% to 0.029%) by volume (the base year of the beginning of the industrial revolution in 1860 A.D.). Thus the atmospheric content of carbon dioxide increased from the pre-industrial level of 280-290 p.p.m. (1860 A.D.) to 350-360 p.p.m. during 1988, registering an overall increase by 25 per cent from the pre-industrial level. It is believed that the rate of increase of atmospheric carbon dioxide through anthropogenic sources as referred to above will be accelerated due to relentless march of developing countries towards industrial development and urbanisation. It is, therefore, necessary to examine the pattern of emission of carbon dioxide through the use and burning of fossil fuels (coal, petroleum and natural gas). The following trends of consumption of fossil fuels and emission of carbon dioxide may be highlighted.

(1) According to the report of the Oak Ridge National Laboratory (Tennessee, U.S.A.) based on the analysis of the 37-year time series of emission, the total emissions of carbon dioxide through the burning of fossil fuels were dominated by a few developed and highly industrialized countries by 1950 (e.g. U.S.A. former U.S.S.R., U.K., Germany, France etc.). Only the U.S.A. contributed about 42 per cent of the total world emissions of carbon dioxide in the year 1950. The former U.S.S.R., U.K., Germany and France occupied 2nd, 3rd, 4th and 5th positions in the global output of carbon dioxide through the burning of fossil fuels. The contributions of the developing countries towards the total emissions of carbon dioxide upto 1950 was negligible because of exceedingly slow pace of industrialization in such countries. For example, India stood only 13th in the hierarchy of carbon dioxide emitting countries.

(2) The situation drastically changed by 1986, that is after a lapse of 36 years from 1950 base. The relative percentage of the contribution of carbon dioxide from the burning of fossil fuels by the developed and highly industrialized countries declined while the relative contribution of the emissions of carbon dioxide by the developing countries increased because of rapid rate of industrial development taking place in the developing countries after 1950. The data of the emissions of carbon dioxide from the burning of fossil fuels during 1986 reveal that the U.S.A. and the former U.S.S.R. (first and second respectively) still remained the largest contributors of atmospheric carbon dioxide but a few developing countries like China (advanced to 3rd place from the 10th place during 1950) and India (occupied 7th place in comparison to its 13th place in 1950) became major contributors of atmospheric carbon dioxide during 1986. Japan (4th place) has also become a very significant comtibutor of carbon dioxide. It may be pointed out that South Korea, a fast developing country, has moved from its 53rd position during 1950 to 20th place during 1986 in the hierarchical order of carbon dioxide emitting nations.

(3) It is important to state that though the relative contributions of carbon dioxide from the combustion of hydrocarbons by developed and highly industrialized nations have declined because of the increase of carbon dioxide emissions from the developing nations but the total emissions based on per capita basis are still dominated by the developed nations. The per capita emission of carbon dioxide is highest in the U.S.A. (5 tonnes per person per year). If we compare this figure with the figure of a major developing nation, say India (occupying 7th place among the carbon dioxide emitting nations and producing 0.2 tonnes of carbon dioxide per capita per year), the U.S.A. still emerges the main culprit followed by Russia.

(4) On a regional basis of the emission of carbon dioxide it is clear that the total emissions are steadily increasing in China, most of Asia and Latin America.

The IPCC (Intergovernmental Panel on Climate Change) constituted by the United Nations Environment Programme (UNEP) and World Meteorological Organisations (WMO) in 1988 has been assigned the main task on the study of climatic changes, and of presenting reports on the effects of greenhouse gases on the earth from time to time (the IPCC submits its reports after every four-year period).

Table 16.2 shows the trend of concentration of greenhouse gases and aerosols in the decade 1980-89.

Table 16.2 : Trend of concentration of greenhouse gases and aerosols during 1980-89

1. The concentration of atmospheric carbon dioxide increased at the rate of 1.5 ppmv per year (i.e. increase of 0.4% or 3.2 billion tonnes of carbon per year) due to human economic activities. This increase is equivalent to approximately 50 per cent of anthropogeneic emission during 1980-89.
2. The rate of increase of atmospheric methane declined but again registered increase in 1993. The atmospheric methane increased at an average rate of 13 ppmv per year (0.8% or 37 million tonnes).
3. Nitrous oxides registered an increase of 0.75 ppmv (0.25% or 3.7 million tonnes of nitrogen per year.)
4. The rates of increase of atmospheric concentrations of several ozone-depleting hydrocarbons have fallen, demonstrating the impact of Montreal Protocol and its amendments and adjustments.
5. The trends of increase in tropospheric ozone during 1980-89 were variable and uncertain.
6. Anthropogenic aerosol and precursor emissions have increased over 150 years but no clear picture emerged during 1980-89.

Source : Climate Change 1994 : Report of the Intergovernmental Panel on Climate Change (IPCC), 1994, ppmv = part per million by volume.

Table 16.3 depicts the trend of concentration of greenhouse gases and climate changes as per reports of the IPCC, 1996.

Table 16.3 : Report of Intergovernmental Panel on Climate Change (IPCC), 1996

1. The concentration of atmospheric major green-house gases (GHG) viz carbondioxide, methane and nitrous oxide (N_2O) has increased by 30, 145 and 15 per cent respectively, largely due to burning of fossil fuel, land use changes and agriculture.
2. 'Many greenhouse gases like CO_2 and N_2O remain in the atmosphere for centuries, hence it takes a long time to reverse their effect on climate.'
3. If the emissions of carbon dioxide at 1994 level are stabilized, the atmospheric concentration of carbon dioxide would be doubled from the preindustrial level of atmospheric carbon dioxide by the year 2000.
4. 'Global mean surface air temperature has increased between 0.3^0 and 0.6^{0}C since the late 19th century. The global sea level has risen by 10-25 cm over past 100 years (upto 1994).

Source : Down to Earth, August 15, 1996.

Table 16.4 shows reactions of oil producing countries and industrialized countries to the report of IPCC in 1996.

Table 16.4 : Reactions to IPCC Report, 1996

1. Oil producing countries opposed the above report (table 16.3) on the fear that any reduction on oil production or tax on fossile fuel, which has been held responsible for global warming and climate change, would adversely affect their economic conditions.
2. The industrialized countries advocate the imposition of **carbon tax** on fossil fuel (like mineral oil) but are not willing to share the burden.
3. On the other hand, industrialized nations could not implement the agreement for reducing and bringing back their CO_2 emissions to 1990 level by 2000 AD.
4. Industrialized nations are not agreeable to come to any agreement for reduction in carbon emission target beyond 2000 AD as agreed upon at Berlin Summit on Climate Change in 1995, while IPCC has recommended to stabilize CO_2 emission at a level of 450 ppmv to keep the rise in temperature at global level upto 2^0C by the end of 21st century.

Source : Down to Earth, August 15, 1996, p.3, ppmv = part per million by volume.

Table 16.5 denotes trend of concentration of other greenhouse gases such as methane, atmospheric nitrous oxides, stratospheric ozone, tropospheric ozone, in the atmosphere according to the Report of the IPCC, 1996.

Table 16.5 : Trend of concentration of other greenhouse gases in the atmosphere.

1. The concentration of atmospheric methane gas (CH_4) registered a phenomenal increase from the preindustrial level of 700 ppmv to 1724 ppmv in 1992.
2. Atmospheric nitrous oxide (N_2O) increased from the preindustrial level of 275 ppmv to 311 ppmv in 1992.
3. The concentration of stratospheric ozone (O_3) at global level registered variable trends from 1970 to 1994, viz. (i) midlatitude areas of northern hemisphere, 10% depletion; (ii) tropical areas, 4-5% depletion per decade; (iii) maximum depletion in southern hemisphere. The formation of ozone hole over Antarctica during 1992-93 was of global concern as it accounted for 99% depletion in ozone. This phenomenal decrease in ozone has been ascribed to emission of sulphate aerosol from the Pinatubo volcanic eruption in 1991.
4. The concentration of tropospheric ozone has been reported to have doubled from preindustrial level to 1993 level in the northern hemisphere while it registered decrease over south pole.

Source : Report of the Intergovernmental Panel on Climate Change (IPCC), 1996. ppmv = part per million by volume.

The emission of carbondioxide has been held as the most dangerous and most significant greenhouse gas emission causing global warming. The total world emission of carbon in the year 1995 amounted to 22,700.2 million tonnes of which the United States accounted for 23% (table 16.6).

Table 16.6 : Share of world carbon dioxide emission, 1995, in percentage of the total world carbon emission of 22,700 million tonnes.

United States	23	Germany	4
China	13	India	4
Russian Federation	7	Brazil	1
Japan	5	Indonesia	1

Source : The Citizen's Fifth Report, Centre for Science and Environment, 1999, New Delhi.

Five worst carbon dioxide emitter countries are United States (5648.6 million tonnes), China

(3192.5 million tonnes), Russian Federation (7% of world total), Japan (5% of world total) and Germany (4% of world total) as regards annual emission of carbon dioxide during 1995. It may be pointed out that the data of the emission of greenhouse gases together and carbon dioxide separately released by different agencies and sources are not compatible. For example, there is vast variation in the data of emission of greenhouse gases (table 16.1 in the developed and developing countries (for 1995) as released by Climate Action Report of the Framework Convention on Climate Change (FCCC), U.S.A. and the data of carbon dioxide emission in 1995 as reported in the Citizen's Fifth Report of the Centre for Science and Environment, New Delhi, based on Anon, 1998, Knowledge for Development, World Development Report, 1998-99 (table 16.7) and hence it becomes very difficult for comparative analysis and understanding of real picture.

Table 16.7 : Emission of Carbon Dioxide during 1980 and 1995

Country	Total (Million tonnes)		Per capita emission (tonnes)	
	1980	1995	1980	1995
World	13,385.7	22,702.2	3.4 (w)	4.0 (w)
U.S.A.	4,515.3	5,468.6	19.9	20.8
China	1476.8	3,192.5	1.5	2.7
Canada	420.9	435.7	17.1	14.7
India	347.3	908.7	0.5	1.0
Australia	202.8	289.8	13.8	16.0
Regions				
East Asia and Africa	1,832.7	4,140.0	1.4	2.5
Europe and CentralAfrica	886.9	3,722.0	—	7.9
Latin America and Caribbean	850.5	1,219.8	2.4	2.6
Middle East and North Africa	500.5	982.9	2.9	3.9
South Africa	392.4	1,024.1	0.4	0.8
Sub-Saharan Africa	350.5	477.1	0.9	0.8

Source : Anon, Knowledge for Development Report, 1998-99, reported in the Citizen's Fifth Report, 1999, Centre for Science and Environmental, new Delhi, Vol. 2, p. 239. w = weighted mean.

Burning of mineral oil is another source of greenhouse gases. Increasing industrialization and urbanization and phenomenal increase in the number of automobiles (the number increased from 0.45 billion in 1985 to 0.6 billion in 1995, the projected figure upto 2030 AD is 1.05 billion) have accelerated the rate of annual consumption of mineral oil. The percentage of urban population to the total world population increased from 40 in 1980 to 45 in 1995 (table 16.8).

Table 16 .8: Urban population growth, 1980-1995

Region	Urban population as percentage of total population		Average annual growth rate
	1980	1995	1980-95
1. Sub-Saharan Africa	23	31	5.5
2. East Asia and Pacific	21	31	4.2
3. South Asia	22	26	3.4
4. Europe and Central Asia	58	65	1.6
5. Middle East and North Africa	48	56	4.2
6. Latin America and Caribbean	65	74	2.8
World	40	45	2.5

Source : Anon, 1997, The State in a Changing World, World Development Report, 1997, reported in the Citizen's Fifth Report, Centre for Science and Environment, New Delhi, vol. 2, p.243.

Rapid rate of deforestation also increases the concentration of carbon dioxide in the atmosphere because forests are the greatest source of carbon sink as forests consume carbon dioxide to prepare food with the help of sunlight through the process of photosynthesis and thus fix carbon in their biomass. Table 16.9 depicts the coverages of forests and pattern of deforestation in the world. The total world forest cover was 69.595 million km^2 in 1990 wherein Russian Federation accounted for the largest share (7.681 million km^2), followed by Brazil (5.61 million km^2), Canada (4.533 million km^2), United States (2.96 million km^2), Australia (1.456 million km^2), China (1.247 million km^2) and India (0.517 million km^2). About 0.3 per cent of the total world forest area was cleared during the decade 1980-89.

Table 16.9 : Forest area and deforestation

Country	Forest area Total area 1990 (000km^2)	(000 km^2)	Annual deforestation 1980-90 Percentage Change
World	69,595	133.4	0.3
Russian Federation	7,681	15.5	0.2
Brazil	5,611	36.7	0.6
Canada	4,533	–47.1	–1.1
United States	2,960	3.2	0.1
Australia	1, 456	00	00
China	1,247	8.8	0.7
India	517	3.4	0.6

Region			
Sub-Saharan Africa	522	40.7	0.7
East Asia and Pacific	3,986	43.5	1.0
South Asia	658	5.5	0.8
Middle East and North Africa	466	−1.4	−0.3
Latin America and Caribbean	9,786	74.8	0.7

Source : Anon, 1997, The State in Changing World, World Development Report, 1997, reported in The Citizen's Fifth Report, 1999, Centre for Science and Environment, New Delhi, Vol. 2, P. 238

It is heartening to note that global carbon emission, according to the U.S. based World Watch Institute, decreased by 0.5 per cent in 1998 which in real terms means decrease of around 6.32 billion tonnes because of delinking of carbon emission from economic growth, improved energy system and decrease in the use of coal (Down to Earth, September, 15, 1999). Even in China carbon emission dropped by 3.7% in 1998. Russia's emission dropped by 24% from 1991 to 1998.

Methane is another significant greenhouse gas which is produced from the biodegradation of organic matter i.e. biomass. The animal excreta and paddy fields have been accepted as major sources of methane. It may be pointed out that developing countries of tropical region account for 90 per cent of global rice production. Consequently, tropical developing (rice producing) countries have been held responsible for producing largest amount of global warming methane by the industrialized countries. The report of the Intergovernmental Panel on Climate Change (IPCC, 1992) released in 1994 contains the estimate of methane production from paddy fields as 37 million tonnes per annum. It may be mentioned that the IPCC estimated annual methane emission at 110 million tonnes in 1990, which it further revised to 60 million tonnes in 1992 and 37 million tonnes in 1994. Suresh K. Sinha, former Director of the Delhi-based Indian Agricultural Research Institute refuted the IPCC estimate of annual emission of methane on the basis of a series of experimental studies. He stressed that upper limit of methane production from world paddy fields could not be more than 13 million tonnes per year. His final studies revealed the fact that the estimate of world production of methane from world paddy fields could be as low as 7.08 million tonnes a year (Down to Earth, February, 28, 1995). In fact, the developed countries are deliberately shifting the responsibility of global warming from their shoulders to the developing nations.

4. Greenhouse Effect and Climatic Change

The carbon dioxide is, in fact, a natural constituent of the earth's atmosphere. It is not necessarily a pollutant at least in the lower atmosphere but its increased concentration in the atmosphere leaves adverse effects on biological communities through changes in the thermal conditions and global radiation and heat balance. As stated in the beginning the carbon dioxide, present in gaseous form in the atmosphere, has unique properties in that it allows the solar radiation to reach the surface of the earth but tends to prevent longwave terrestrial radiation (such as infrared heat radiation from the earth) from the earth surface from escaping into outer space. This mechanism results in the increase of temperature of the surface of the earth and the lower atmosphere. It may be pointed out that about 50 per cent of the total carbon dioxide produced by anthropogenic sources (combustion of fossil fuels and burning of wood) is dissolved into the oceans and fixed by the plants in their biomass whereas the remaining 50 percent is stored in the atmospheric storage pool and thus the concentration of carbon dioxide in the atmosphere steadily increases. The trend of increasing atmospheric carbon dioxide increases the greenhouse effect which raises the temperature of the earth's surface. This mechanism may be explained in simple term as given below.

The everincreasing proportion of carbon dioxide in the atmosphere through anthropogenic sources (as discussed earlier) changes the general composition of the atmosphere and overall heat balance because carbon dioxide is more or less transparent to incoming shortwave solar radiation but it absorbs most of the outgoing longwave radiation emitted from the earth's surface. Thus the supply of additional amount of carbon dioxide to the atmosphere every year enhances the absorption of radiation of more heat emitted from the earth's surface. This mechanism (absorption of more heat emitted from the earth's surface by the atmospheric carbon dioxide) results in the warming of the lower atmosphere. This warmed lower atmosphere again reradiates heat (counterradiation) to the earth's surface which further warms the earth's surface. The net result of all these mechanism is the gradual increase of the temperature of the earth's surface and the lower atmosphere which causes changes in the climatic conditions at local through regional to global levels.

It is important to note that different models have been developed to reveal the relationships between the increase in the concentration of atmospheric carbon dioxide through anthropogenic sources and the increase of surface temperature consequent upon the increase of the atmospheric carbon dioxide and the results and predictions of these models are very much confusing and contradictory. 'If there is uncertainly in the prediction of carbon dioxide trends, then the predictions of the resulting climatic effects are even more uncertain' (J.E. Hobbs, 1980). S.H. Schneider (1950) while reviewing the result of various climatic models dealing with the predictions of change in thermal conditions of the atmosphere and the earth's surface resulting from the increased content of atmospheric carbon dioxide concluded that the temperature could rise upto 1.5⁰ to 3⁰C if the concentration of atmospheric carbon dioxide could be doubled form the 300 p.p.m. level to 600 p.p.m. He has further pointed out that increased temperature would cause increase in cloudiness which would reduce incoming shortwave solar radiation (because of increased albedo i.e. more clouds would reflect more solar radiation back to outer space). Thus the reduced solar radiation reaching the earth's surface would counteract the warming of the earth's surface due to increased temperature caused by increased carbon dioxide. It is obvious that such feedback mechanisms negate the impact of greenhouse effect of increased atmospheric carbon dioxide and the whole process of the heating or cooling of the lower atmosphere and the earth's surface becomes highly complicated.

The **general circulation model** developed by S. Manabe and R.T. Wetherald (1975) predicts that if present amount of carbon dioxide of the atmosphere (1975 level) is doubled, the temperature of the earth's surface will increase by 2.9⁰C and there will be 7 per cent increase in the activity of the hydrogical cycle but there will not be any feedback and thus there will not be either increase or decrease in the amount of clouding as predicted by S.H. Schneider (as referred to above). In other words, the increase in surface temperature caused by increase in the atmospheric carbon dioxide will not be negated by feedback mechanisms.

It has been estimated that the overall increase in the surface temperature over the past one hundred years has been about 0.5⁰ to 0.7⁰C. According to another view the average' air temperature in the northern hemisphere increased by 0.4⁰C between 1880 and 1940 because of rapid rate of combustion of fossil fuels during that long period but the temperature dropped after 1950 inspite of continued rapid rate of combustion of fossil fuels due to fast industrial development but soon after 1950 the air temperature in the southern hemisphere showed rising trend which registered an overall increase of 0.6⁰C between 1940 and 1960. It is thus clear that though there is maximum consumption of fossil fuels in the northern hemisphere and consequent increase in the concentration of the atmospheric carbon dioxide but the air temperature dropped after 1950 whereas there is minimum consumption of fossil fuels in the southern hemisphere but air temperature increased. It does not mean that there is no direct impact of increasing carbon dioxide on air temperature rather some other factor or factors might have dominated over the factor of greenhouse effect. It is opined that large amount of volcanic dusts thrown into the atmosphere through eruptions of Heckla (Iceland) in 1947, Mt. Spurr (Alaska, U.S.A.) in 1953 and Agung (Bail) in

1963 and many eruptions of minor dimension might have reduced the air temperature in the northern hemisphere between 1940 and 1970. It is important to note that volcanic dust reflects and scatters the incoming shortwave solar radiation and does not block/prevent outgoing longwave radiation of the earth's surface and thus volcanic dust does not intensify the greenhouse effect but ultimately has cooling impact on air temperature.

Inspite of contrasting opinions about the impact of increasing concentration of carbon dioxide in the earth's atmosphere from the burning of woods and combustion of fossil fuels on the air temperature it may be conclusively opined that there is definite positive effect of the increased concentration of the atmospheric carbon dioxide, that is there is increase in the temperature of the surface of the earth and the lower atmosphere. This increase in temperature introduces several changes in the climatic conditions at local, regional and global levels.

(i) According to A.B. Pittock (1972) the change in the global mean temperature by a few degrees celsious caused by greenhouse effect would greatly affect the human society and agriculture,

(ii) It is believed by some scientists that increased temperature due to increased greenhouse effect would cause decrease in precipitation and soil moisture content in the most developed agricultural regions of the world. The plants, animals and insects may be able to adjust themselves to the changed environmental conditions caused by rise in the air temperature but the whole ecosystems may be adversely damaged.

(iii) If the concentration of carbon dioxide goes on increasing, the oceans would be required to absorb more and more carbon dioxide. More absorption and decomposition of carbon dioxide in the oceans would raise their normal level of acidity. Increased oceanic acidity would decrease biological productivity of the marine ecosystem and the decreased plant cover in the oceanic areas would change the albedo of the ocean surface.

(iv) The increased surface temperature would cause melting of continental and mountain glaciers and polar ice caps. The resultant melt-water would raise sea-level and thus would cause flooding of coastal areas of lowland countries. According to an estimate one-metre rise in sea-level may be possible by 2050 A.D. due to warming impact of greenhouse effect. This rise in sea-level may cause flooding of 15 percent of the agricultural lands of U.A.R. bordering the Mediterranean sea and thus about 8 million people would be displaced. Similarly, a major portion of the lower deltaic region of Bangladesh would be submerged under sea-water and consequently about 8 to 10 million people would lose their agricultural lands and homes.

(v) It may be possible that the concentration of carbon dioxide may increase to such an extent that the total atmospheric pressure would be increased. This increase in the atmospheric pressure would broaden the absorption bands and increase the opacity of the atmosphere to the outgoing longwave terrestrial radiation which would in turn increase the surface temperature to such an extent that all the atmospheric processes which are now responsible for the existence and sustenance of all life forms in the biosphere would come to grinding halt and every thing, then, would be over. But this is an extreme situation which is unlikely to occur and this should not occur.

(iv) The impact of greenhouse gases mainly carbon dioxide is also expected to influence rather intensify the depletion of ozone layer which would cause further rise in the temperature of the earth's surface.

(vii) It is also argued by some scientists mainly botanists that the increased concentration of carbon dioxide in the atmosphere would increase plant production. According to an estimate an increase of carbon dioxide between 300 to 600 p.p.m. would increase vegetative productivity by about 30 per cent. It may be pointed out that this positive response of the increased carbon dioxide on the vegetative productivity is only theoretically deduced conclusion because increase in temperature is believed to have serious adverse effects on vegetation communities mainly agricultural crops.

(viii) The publication of recent report of the US Climate Change Science Programme (CCSP), 2006 (May 2), the earlier report of the National Research Council (NRC), and IPCC report 2001 have demonstrated the fact that there was an overall increase in global average temperature by 1°C since 1950s. These reports have validated the theory of strong relationship between human activities and global warming. Thus, global warming and consequent climate change is human-induced. "They (the reports) showed a significant difference in the rise of global average temperatures in the lowest 8 km of the atmosphere (+0.05 ± 0.10°C per decade) and the global average surface temperature (+ 0.15 ± 0.05°C per decade) (Down to Earth, June 30, 2006)'. The recent report of the CCSP (2006) entitled 'Temperature trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences' has validated the findings of other scientists about warming near the earth's surface as well as in the higher atmosphere on one hand and has stengthened the link between anthropogenic greenhouse gases and global warming and related climate changes.

Impact of Climate Change in India

India, being a party of U.N. Framework Convention on Climate Change (F.C.C.C.) published its first official document on impact of emission of green house gases on present and future climate of the country on June 1, 2004. The total annual emission of GH gases amounted to one million tonnes giving per capita emission of 1.3 tonnes/year. The over all global rise of temperature of 0.4°C has caused 10–12% increase in monsoon rain in the west coast, northwest regions and north Andhra Pradesh but 6-8% decline in M.P. and adjoining areas, northeast regions and parts of Gujarat and Kerala. The temperature is likely to increase by 2-4°C from 1994 level by 2040 AD. Minimum temperature will rise by 4°C across the country by 2040. There will be decrease in rainy days by 15 days over major parts of the country. The rising temperature would dry up key river basins of India after 2040 AD (Down to Earth, July 31, 2004).

16.6 GLOBAL WARMING AND INTERNATIONAL COOPERATIONS

The international communities are well aware and are seized of the global environmental and ecological problems and various efforts have been initiated to control global warming and halt probable climatic changes. There are several organizations, government agencies, intergovernmental agencies, non-government organizations (NGO) which have undertaken various action plans and projects to study the relationships between man and environment, interactions between man and nature, the environmental problems resulting therefrom and remedial measures therefor. It is heartening to note that now international cooperations are forthcoming for the amelioration of the environmental and ecological problems. Efforts are being made to control ozone depletion and greenhouse effects at global level. The formulation of **Montreal Protocol** in September, 1987 under the leadership of UNO-sponsored **United Nations Environment Programme** (UNEP), the international conference on **'depletion of ozone layer'** in London, held from March 5 to 7, 1989, wherein government officials, scientists and industrialists of 180 countries participated, international conference on **ozone depletion** held in London in 1990 etc. for restricting the production and consumption of ozone depleting chlorofluorocarbons (CFCs) etc. are a few examples which reveal the seriousness of international communities for their active cooperations in tackling the global environmental problems but it is painful to pen down that still the political gimmicks, international politics, self interest and greed are the taboos of such efforts and cooperations.

Several international conferences, seminars, symposia, workshops etc. for the maintenance of environmental quality, ecological balance, ecosystem stability and biodiversity have been attended by different countries, United Nations, voluntary, non-government and government organizations and several agreements and declarations have been signed. The following are the important conferences, protocols, agreements and declarations.

1. (1979), first **World Climate Summit, 1979** in Geneva (Switzerland).
2. (1980), Conference on Industrieis and Climate, 1980, in Vienna (Austria).
3. (1985), **Vienna Convention** (Austria), 1985, for the protection and maintenance of ozone layer.
4. (1987), Agreement on **Montreal Protocol,** Montreal, Canada, 1987 (September) for reduction of the production and consumption of ozone depleting chlorofluorocarbons (CFCs) in order to check the depletion of ozone layer. The Montreal Protocol on substances that deplete the ozone signed in September, 1987 at Montreal, Canada, by 35 developed countries of the World was the first concrete step in this regard. This was initiated by United Nations Environ-

ment Programme (UNEP). The following provisions were commonly agreed by the countries which signed the protocol.

(i) To freeze the production of CFCs at 1986 level by 1989.

(ii) To decrease the production of these synthetic chemical compounds by 20 per cent by the end of 1993.

(iii) To allow further 30 per cent cut in the production of these chemicals by 1998.

(iv) To freeze the production of halons at 1986 level starting from 1992.

(v) Thus, the total production of ozone depleting chemicals (mainly CFCs and halons) would be reduced by 50 per cent by the beginning of 1999.

5. (1988), **Toronto Summit,** in Toronto city of Canada, for the reduction in the emission of carbon dioxide. The summit aimed at 20 per cent cut in the emission of carbon dioxide by 2005 AD but the developed countries backed out from the agreement on the pertext of non-availability of reliable data of emission of green house gases.

6. (1988), Constitution of **Intergovernmental Panel on Climate Change** (IPCC) for the study of climatic changes by United Nations Environment Programme (UNEP) and World Meteorological Organization (WMO) in 1988. This panel was assigned the main task of presenting report on effects of greenhouse gases on the earth from time to time.

7. (1990), **Second World Climate Summit** was held in 1990 to search effective measures to check the emission of greenhouse gases and Intergovernmental Agreement Committee was constituted.

8. (1992). The United Nations Conference on Environment and Development—UNCED, better known as **First Earth Summit** or **Rio Summit,** was organized in June, 1992 in Rio De Janeiro city of Brazil which was attended by 154 countries which signed the **Climate Change Convention.**

9. (1994), The signed climate change convention during 'first earth summit' was given practical shape which aimed at reduction in carbon emission and to stabilize the emission at 1990 level by 2000 AD but it could not be implemented in letter and spirit by the allotted time frame.

10. (1995), The first summit of the advocates of Climate Change Convention, better known as **Berlin Summit,** was held in June 1995 in Berlin city of Germany but no agreement could be arrived at for the fixing of amount of emission of carbon dioxide by different countries.

11. (1996), The second summit of the advocates of the Climate Change Convention was held in Vienna city of Austria in July 1996 but this summit also proved unsuccessful as no agreement on the amount of emission of carbon dioxide could be struck.

12. (1997), United Nations **Second Earth Summit,** was organized in New York city of the U.S.A. from June 23 to 27, 1997 and was represented by the representatives of 170 countries and 70 heads of the government. This summit aimed at the evaluation of the implementation of **Agenda 21** of the first earth summit organized in Rio De Janeiro in 1992.

13. (1997). The third summit of the advocates of the climate change was held from December I to 10, 1998, in the Kyoto city of Japan. After prolonged discussion an agreement, known as **Kyoto Agreement,** to 5.2 per cent cut in the emission of carbon dioxide by the developed countries, was signed.

14. The 10th climate change meet known as Tenth Conference of Parties (CoP-10) of the United Nations Framework Convention on Climate Change (UNFCCC) was held from Dec. 6 to 17, 2004 in Buenos Aires (Argentina) to combat global warming and implement Kyoto Protocol but nothing substantial could the achieved as 'political will for concerted global solutions (of global warming and climate change) has seriously waned' (Down to Earth, Jan 15, 2005, p. 22).

Besides, the **Stockholm Conference** in 1972 (Sweden), **Desertification Conference** in 1972 in Nairobi (Kenya), **Hague Declaration** of March, 1989, **Helsinki Declaration** of May 2, 1989 etc. are positive steps towards the maintenance of environmental quality. It may be mentioned that about 158 agreements, declarations, protocols etc. have been signed upto 1997.

First Earth Summit (Rio Summit)

United Nations Conference on Environment and Development (UNCED), better known as **Earth Summit** or simply **Rio Summit** was organized from June 3 to 14, 1992, in Rio De Janeiro city of Brazil under the aegis of United Nations for the protection of the earth and its environment, maintenance of ecological balance and to enrich bodiversity. The conference was attended by the representatives of 178 developed and developing countries. The primary objectives of the conference were to arrive at commonly acceptable agreements and their implementation to tackle the problems of global warming, depletion of ozone layer and ozone hole, deforestation, biodiversity, weather and climate change, acid rain, sustainable development etc. The following were five important agenda of the conference—(i) rise in global temperature (global warming), (2) forest protection, (3) biodiverisity, (4) agenda 21, and (5) Rio declaration. Only two aspects of global warming and forest conservation of Rio Summit are being discussed here as only these two are directly concerned with global warming and climate change.

1. Global Warming : A rise of 1.5^{0}C in the atmospheric temperature has been reported for the last 75 years (upto 1995). Some sources put this rise from 0.3^{0}C to 0.6^{0}C. Greenhouse gases (carbon dioxide, methane, chlorofluorocarbon, nitrous oxide etc.) have been identified as major factors of global warming. It is, thus, apparent that the global warming is due to anthropogenic economic activities. Greenhouse gases are emitted from industrial establishments, automobiles, domestic appliances etc. and these gases are concentrated in the lower atmosphere, thereafter they increase air temperature. The relative shares of carbon dioxide, chloroflurocarbon, methane and nitrous oxide were 51%, 20%, 16% and 16% respectively upto 1990. The detailed information of emission of greenhouse gases and global warming have already been presented in the preceding section 16.5 and the causes, mechanism and adverse effects of greenhouse gases and ozone depletion have been discussed earlier in this chapter. It may be pointed out that developed countries are themselves responsible for ozone depletion and creation of ozone hole.

An attempt was made at the time of earth summit for an agreement to reduce the emission of greenhouse gases at 1990 level by 2000 AD by the developed countries to tackle the problem of global rise in temperature and its consequential adverse effects in future but no concrete agreement could be arrived at. It was commonly agreed upon to cut the emission of greenhouse gases but neither any concrete formula nor any time limit could be decided for this purpose.

2. Forest Conservation : At the time of earth summit all the participants expressed deep concern and anger at the rapacious and reckless cutting of forests. It may be pointed out that according to an estimate about 8,000 years ago 8,000 million hectares of land were covered with forests which decreased to 3,000 million hectares by 1998. Thus, the modern society has already consumed two third of world forest cover. It may be remembered that one third tropical rainforests were cleared by 1972 and the loss of remaining rainforests began at the annual rate of 0.5 per cent (i.e. 100,000 km^2 forest area per year). The annual rate of loss of rainforest reached the figure of 170,000 km^2 by the year 1992. According to United Nations' data (1980) forest area is being lost at the annual rate of 2,000,000 hectares in Asia and Pacific region. Even in Brazil 620,000 km^2 of forest area was cleared in the decade 1980-90. India is losing its forest cover at the rate of 2.8 per cent per year. It may be pointed out that the developed countries have already consumed major portions of their forest covers. It may be underlined that the tropical rainforests are richest in biodiversity and have medicinal importance.

Developed countries plead for imposing restrictions on cutting of tropical rainforests in order to use them for medicinal purposes and as natural carbon sinks for the absorption of emitted carbon dioxide from their industrial establishments and thermal power plants. Keeping this fact in mind the United States presented a proposal of forest conservation which was strongly supported by the countries of European Communities at the time of first earth summit. The American proposal was based on the logic that forest wealth is the commonly shared property of the world community and hence an international law should be enacted for its conservation and maintenance. It may be mentioned that the United States cleverly excluded private forests from the purview of the proposed forest conservation law because most of forests in the U.S.A. come under private ownership. Thus, the U.S.A. on one hand tried to delink its forest resources from the proposed international law and on the other hand, attempted to claim right on the forest resources of the developing countries. The developing countries smelt the trick of the U.S.A. and under the leadership of India and Malasia rejected the U.S. proposal outrightly on the ground that forests are their national property and hence they cannot be brought under any international law. Developing countries strongly pleaded that the developed countries should control the emission of carbon dioxide in their own regions. Thus, the proposal of forest conservation was finally rejected.

Second Earth Summit

The second earth summit was held from June 23 to 27, 1997 in New York city of the U.S.A. in order to evaluate the progress and implementation of proposals and Agenda 21 which were agreed during the **First Earth Summit** organized in 1992 in Rio De Janeiro city of Brazil. The second earth summit was attended by representatives of 170 countries with 70 heads of government. This summit is also known as **Plus-5 Summit** because this summit was organized after 5 years from the second earth summit (Rio Summit) and the programmes and action plans (accepted during Rio Summit) were discussed and reviewed but ultimately no concrete and fruitful results could be achieved because no agreement could be made on any agenda. Various agenda which were endorsed during Rio Summit e.g. financial help for check on global rise in temperature, effective cut in the emission of greenhouse gases, law of forest conservation, sustainable agricultural development, conservation of biodiversity, eradication, of poverty etc. could not be sincerely implemented. It may be pointed out that the aforesaid problems could not be attended sincerely and hence could not be solved rather they were further aggravated during 5-year period (1992-97) because (a) the emission of carbon dioxide further increased from 1992 to 1997 (but slightly decreased in 1998), (b) the pace of deforestation got accelerated, (c) global warming could not be controlled, (d) poverty and population growth have increased etc. The U.S.A. became an effective barrier in endorsing the proposal for curtailing the emission of carbon dioxide and the agenda was postponed to be considered at **Kyoto Summit** to be held in December, 1997 in Japan. At the end of the summit a declaration of voluntary contribution of 0.7 percent of national product by the developed countries to developing countries was signed but the developed countries did not implement this declaration sincerely as they contributed only 0.27 per cent of their national product to aid fund. World Wild Fund (WWF) and World Bank assured to take the responsibility of forest conservation.

Kyoto Protocol

A summit to reduce global warming was held from December 1 to 10, 1997 in Kyoto city of Japan and an agreement to this effect was also signed. This summit was attended by the representatives of 149 countries. This agreement is popularly known as **Kyoto Protocol or Kyoto Thermal Treaty.** The following are the main items of this historic agreement :

(i) A proposal of 30 per cent cut in the emission of carbon dioxide by 2008-12 A.D. was presented by the island nations on the fear that the temperature is estimated to rise 2°C to 3.5°C at the present rate (1997 level) of global warming but the proposal was strongly opposed by the developed and industrialized countries. Ultimately an agreement on 5.2 per cent cut from 1990 level of carbon emission could be signed. This cut in carbon emission would be implemented by 11 industrialized countries. It may be pointed out that the U.S.A., European community and Japan agreed to curtail 7 per cent, 8 per cent and 6 per cent emission of carbon dioxide respectively but the developing countries did not agree for any cut in carbon emission.

(2) According to this agreement industrial countries can have mutual transfer of fixed quota of

cut in the emission of greenhouse gases. For example, if two countries have been allotted the quota of 6 per cent cut each in carbon emission, after mutual understanding one country may curtail only 4 per cent carbon emission while the second country will have to cut 8 per cent carbon emission and can claim royalty for additional 2 per cent cut from the first country. This is termed as **carbon trading** or **hot air trading.** As a consequence of Kyoto Protocol Russia and Japan have struck such deal between them. Japan found it difficult to implement the quota of 6 per cent cut in carbon emission from 1990 level. On the other hand, Russia can meet its target of zero per cent rise in carbon dioxide because of its economic recession. 'Under the agreement Japanese companies would invest in 20 Russian power plants and industries to cut greenhouse emission. These reductions of Russian emissions would be added to Japanese carbon dioxide balance sheet' (Down to Earth, July 31, 1998).

(3) The Kyoto Protocol and agreement would automatically be invalidated if at least 60 countries of conference of Parties (CoP) do not endorse and implement its provisions and resolutions. The protocol was to be effective from June, 1999. A fine would be imposed on those countries which do not adopt the protocol.

(4) **A Clean Development Fund** (CDP) would be established which would be funded by the fines realized from the countries which flout the protocol.

Review of Kyoto Protocol : One positive outcome of the Kyoto Conference on Climate Change and Kyoto Protocol is that the developed and developing countries accepted at least in principle that some concrete steps should be initiated to check climatic change due to rise in global temperature. The developing and poor countries succeeded in managing unanimity on the point that reduction in the emission of greenhouse gases would not be binding on them. It may be pointed out that the emission of greenhouse gases from a few big developing countries like China, India, Brazil etc. would also increase substantially in near future. It is to be remembered that at the time of Kyoto Protocol (1997) the per capita emission of greenhouse gases from the developing countries was 2.4 tonnes per annum against annual per capita emission of 11.9 tonnes from developed countries, thus, the developing countries should also be prepared for future cut in the emission of greenhouse gases. In fact, Kyoto conference could not be as much effective as expected because of rigid attitude of developed countries and futile efforts to blame each other for global warming. It may be pointed out that in order to transfer **environment friendly technologies** from developed countries to developing countries to check the emission of greenhouse gases **Global Environment Facility (GEF)** has been established with the help of World Bank, United Nations Development Programme (**UNDP**) and United Nations Environment Programme (**UNEP**) but no concrete steps could be initiated by 1998.

It may be concluded that 'the Kyoto protocol, agreed in December 1997, was the first step to curtail emissions of the industrialized world. It is now being used to set up a trading system to buy and sell carbon emissions. The Kyoto protocol is increasingly being understood not as an **environmental agreement** but **a trading agreement**' (Down to Earth, July 31, 1998).

Carbon Trading

As per Kyoto Protocol carbon trading simply means that in order to implement the mandatory cut in the overall carbon emission by at least 5 per cent below 1990 level between 2008-2012 A.D. the industrialized developed 'countries and their private corporations could invest in projects in developing countries which are carbon efficient. The net benefits of carbon reduction would accrue to the industrialized country or private corporation in its balance sheet of carbon accounting. Developing countries would be selling **'certified emission reduction" units'** (Down to Earth, July 31, 1998). It is proposed to set up a global Executive Board (EB) to superwise carbon trading and numerous certification agencies will be authorized by the Executive Board. Several organizations and establishments have floated various brokers for managing carbon trading. For example, Carbon Investment Fund by the World Bank, Portfolio of Projects of Interest by the Asian Development Bank, Emission Trading Corporation by the United Nations Conference on Trade and Development (UNCTAD), Intergovernmental Panel on Emission Trading by the United Nations Environment Programme (NNEP), Clean Development Mechanism (CDM) by the United Nations Development Programme (UNDP) etc. are a few efforts to manage carbon trading.

It may be remarked that 'after the Kyoto meet, one thing is clear, climate change has been taken out of the world of the environmental lobby to the big bad world of money. The key issue—between the buyers and sellers of this commodity (carbon emission) which has no clearly defined borders—is to trade without limits and without the interference of prickly issues of the property rights of the poor...... Rich nations want to reduce their emissions on the cheep......Politics is now driving science. The threat posed by global warming has been forgotten' (Down to Earth July 31 1998).

A conference known as **Bonn Convention** to deliberate climate-change affair was held in Bonn city of Germany in June, 1998 in order to make carbon trading effective. It may be mentioned that the industrialized countries in general and the U.S.A. in particular became frenzy about their greed to start carbon trading, say **trading in the atmosphere,** without further delay. The countries involved in negotiating carbon trading and rules for it have been identified to fall in three blocks viz. (1) **The JUSSCANNA Block,** comprising U.S.A. Australia, Canada, Switzerland, Japan, New Zealand and Norway, is led by the US. This block has now been joined by the Russian Federation and Iceland also. This block, better known as **The Free Raiders Group,** is over enthusiastic in the implementation of carbon trading and is demanding **meaningful participation** of developing countries in the programme to curtail carbon emission. (2) **The EU Block,** better known as **The Free Bubblers Group,** comprising the countries of European Union, desires to "bubble together" i.e. all the countries of EU can meet their target of cut in the emission of greenhouse gases together (in aggregate). (3) **The G-77 and China,** known as **The (Not) for Sale Group.** 'These countries do not have commitments to curtail their emissions but they are required to "assist" the industrialized nations meet their targets by selling carbon units' (Down to Earth, July 31, 1998).

These three blocks sharply differed on two basic issues of carbon trading viz. (i) approach towards carbon trading and (ii) approach towards three mechanisms of carbon trading as laid out in Kyoto Protocol (December 1997), e.g. (a) **Joint Implementation** (Article 6), (b) **Clean Development Mechanism**—CDM (Article 12), and (c) **Emissions Trading** (Article 17). There was a lot of discussion between trading and non-trading blocks but 'it would be right in a way to say that the meeting of Bonn did flag important issues and provided countries with an opportunity to size up the situation before they come to the negotiations in Buneos Aires city of Argentina at the Conference of Parties (CoP-4) to be held in November 1998' (Down to Earth July 31, 1998).

The convention of Conference of Parties-4 (CoP-4) held from November 2 to 12, 1998 in Buneos Aires (Argentina) fixed 2000 A.D. as the deadline for the implementation of Kyoto Protocol which envisaged reduction in the emission of greenhouse gases by 5.2 per cent below the level of 1990 emission by 2008-2012 A.D. It may be concluded that efforts are being made through periodic meetings of the UN Framework Convention on Climate Change (FCCC), Conference of Parties (CoP) and many other conventions and conferences to tackle the problems of global warming and related environmental problems and climate change.

Tenth CoP Meet (2004)

The Tenth Conference of Parties (CoP-10) of the United Nations Framework Convention on Climate Change (UNFCCC) was held from Dec. 6 to 17, 2004 in Buenos Aires (Argentina) 'to discuss the development, deployment and diffusion of technologies to mitigate climate change. What they agreed to was merely continue focussing its work on exchanging information and sharing experiences and views, among members, on practical opportunities and solutions to mitigate climate change' (Down to Earth, Jan. 15, 2005).

16.7 GLOBAL CHANGE IN ATMOSPHERIC CHEMISTRY

The chemical composition of the atmosphere refers to the gaseous composition of the atmosphere. The significant gases are nitrogen and oxygen which constitute 78 per cent and 21 per cent of total gaseous composition of the atmosphere respectively. The remaining one per cent is represented by argon (0.93%), carbon dioxide (0.03%), neon (0.0018%), helium (0.0005%), ozone (0.00006%), hydrogen (0.00005%), krypton (trace), xenon (trace), methane (trace) etc. The gaseous composition determines the receipt of insolation at the earth's surface and hence its temperatures, controls atmospheric circulation and weather phenomenon. The change in atmospheric chemistry refers to the changes in relative percentage of different gases in the atmosphere, in general and in the homosphere (upto 90 km altitude) in particular through air pollution caused by anthropogenic sources. Thus, it is necessary to discuss all aspects of air pollution which is responsible for changes in atmospheric chemistry which may lead to climatic changes due to either global warming or global cooling, namely meaning and definition of air pollution, sources and types of air pollutants, types of air pollution, air pollution in India, adverse effects of air pollution, acid precipitation, urban smog etc.

AIR POLLUTION

1. Meaning and Definition of Air Pollution

The atmosphere is a gaseous envelope which surrounds the earth from all sides and the air is a mechanical mixture of several gases, mainly, nitrogen (78.09%), oxygen (20.95%), argon (0.93%) and carbon dioxide (0.03%). Besides, other trace gases like neon, krypton, helium, hydrogen, xenon and ozone are also present. Air is very important for all types of life in the biosphere. Human life is not possible without air because man can live for a few days without water or for a few weeks without food but cannot survive even for a few minutes without air. It constitutes about 80 per cent of the total intake of all things by a person every day as a person breathes 22,000 times a day inhaling 25 gallons or 16 kilograms of air which he obtains from the oxygen-rich atmosphere surrounding the earth.

It may be pointed out that air is never pure because some gases such as sulphur dioxide, hydrogen suplhide, carbon monoxide; emissions from volcanoes and swamps; windblown dusts, salt spray, pollens from plants etc. are continuously added to the air by the natural processes. Thus the air becomes polluted when its natural composition is disturbed either by natural or man-made sources or by both. H. Perkins (1974) has defined air pollution as "the presence in the outdoor atmosphere of one or more contaminants such as dust, fumes, gas, mist, odour, smoke or vapour in quantities of characteristics and of duration such as to be injurious to human, plant or animal life and to property or which unreasonably interferes with the comfortable enjoyment of life and property". According to World Health Organization (WHO) air pollution is defined as limited to situation in which the outdoor ambient atmosphere contains materials in concentration, which are harmful to man and his surrounding environment.

In a general sense air pollution may be defined as the disequilibrium condition of the air caused due to introduction of foreign elements from natural as well as anthropogenic sources to the air so that the air becomes injurious to biological communities in general and human community in particular.

Air pollution is generally accomplished through the pollutants of gases and solid and liquid particles of both organic and inorganic chemical classification important being carbon dioxide, fluorocarbons, nitrogen oxides, sulphur compounds, waste heat, water vapour, ammonia, hydrocarbons, methane, peroxyacetylnitrates, methyl bromide, krypton-85, aerosol etc. It is significant to note that air pollution through natural sources including volcanic dusts, windblown dusts, vapour from plant leaves, rotting materials in the natural environment, pollens from plant flowers etc. does not warrant much concern because "such pollutants can be considered to be accommodated within the global ecology" (J.E. Hobbs, 1980) because they (natural pollutants) are distributed all over the globe but man-made pollutants are injected and concentrated in certain localities of their sources mainly in highly industrialized and urbanized pockets of the world. In other words, the pollutants coming out of natural sources are generally absorbed by the natural environment and no pollutional problem arises but man-made pollutants being concentrated in certain parts of the atmosphere pollute the air.

The nature, dimension and magnitude of air pollution depend on a variety of factors such as residence time of pollutants in the atmosphere (duration of stay of pollutants in the atmosphere), sources of pollutants, nature of pollutants, amount of pollutants etc. "The residence time of pollutants in the atmosphere (also) vary considerably, depending upon the nature of the pollutant itself, upon the way emission has taken place, on meteorological factors (e.g. amount of moisture content in the air, air temperature, nature of air circulation, nature of air pressure, cloudiness etc.) and on sink mechanisms (absorption of pollutants such as nature of vegetation, water bodies etc.)" (J.E. Hobbs, 1980)

2. Sources and Types of Air Pollutants

Major sources of air pollution are **natural sources** (volcanic eruption, deflation of sands and dusts, forest or wild fires of natural vegetation etc.) and **man-made sources** (industries, urban centres, automobiles, aircrafts, agriculture, power plants etc.). A brief summary of the pollutants of natural and anthropogenic sources (man-made sources) is given below:

(1) Pollutants from natural sources : (a) from volcanoes : dust ashes, smoke, carbon dioxide and other gases; (b) from extra-terrestrial bodies : cosmic dusts, dusts produced due to collision of asteroids, meteors, comets etc. with the earth; (c) from green plants : vapour through evapotranspiration, pollen of plant flowers, carbon dioxide from bacteria; (d) from fungi : fungal spores, viruses, (e) from sea and land surfaces : salt spray from seas and oceans, dusts and soil particles from ground surface.

(2) Pollutants from man-made sources : (a) gases from kitchen and domestic heating, industries, incineration of municipal and domestic garbages, automobiles, railways mostly from coal and diesel engines, aircrafts etc.; (b) solid or particulate matter from industries, mines and urban centres; (c) radioactive substances from nuclear plants, nuclear fuel releases, nuclear explosions; (d) heat from industries and domestic kitchnes etc.

Air pollutants are also divided in two categories on the basis of the nature of pollutants e.g. 1. Gaseous pollutants and 2. Particulate matter pollutants.

(1) Gaseous pollutants : (a) carbon dioxide (CO_2), carbon monoxide (CO) from combustion of fossil fuels; transportation, industrial processes and garbage disposal; (b) hydrocarbons (carbon and hydrogen containing compounds in oxygenated hydrocarbons from incomplete combustion of fuels; (c) fluorocarbons from aerosol cans, and refrigeration systems; (d) sulphur compounds such as SO_2 (sulphur dioxide) and SO_3 (sulphur trioxide), H_2S (hydrogen sulphide) and H_2SO_4 (sulphuric acid) from the burning of sulphur containing fossil fuels; (d) nitrogen oxides and other nitrogenous compounds such as N_2O (nitrus oxid), NO (nitric oxide), NO_2 (nitrogen dioxide) and NO_3 (nitrogen trioxide) from high flying air crafts, combustion of fuels and chemical fertilizers; (c) aldehydes from thermal decomposition of fats, oils or glycerol and (f) chlorine from bleaching cotton cloths and flour and many other chemical processes.

(2) Particulate pollutants : (a) Aerosols- are those fine particles which are around one micron to 10 microns in size, these are added to the atmosphere by industry, power generation, automobiles, space heating, agricultural activities; (b) Smokes, soot and fumes are smaller than aerosols in size and are added to the atmosphere through the incineration of municipal and domestic wastes (garbages), power plants and almost all types of manufacturing processes and (c) Dusts include those solid particles which are larger than aerosols in size. These are added to the atmosphere from all types of combustions and agriculture. Particulate air pollutants are also divided into (i) viable or living types (such as bacteria, pollen grain, fungal and other spores, all of which belong to the category of natural air pollutants) and (ii) non- living types (all of the pollutants whether gaseous or particulate from man-made sources as referred to above).

It may be pointed out that burning of fossil fuels (coal, petroleum and natural gas) in the factories, in the automobiles, diesel rail engines, aircrafts, and at homes releases most of the gaseous pollutants such as carbon monoxide (CO), carbon dioxide (CO_2), various oxides of nitrogen (NO, NO_2, NO_3) and particulate matter such as ash, dusts, smoke, soot, water vapour into the atmosphere and thus these pollutants constitute major portion of air pollutants.

3. Types of Air Pollution

Air pollution may be divided on two bases viz. (i) on the basis of types of pollutants, and (ii) on the basis of sources of pollutants. On the basis of types of pollutants air pollution is divided into two major types e.g. (a) **gaseous pollution** and (b) **particulate pollution**. On the basis of sources of air pollutants air pollution is divided into (a) **automobiles pollution,** (b) **industrial pollution** , (c) **thermal pollution** , (d) **urban pollution**, (e) **rural pollution** and (f) **nuclear pollution.** The description of air pollution may be approached in a number of ways such as (i) on the basis of pollutants, (ii) on the basis of sources of pollution etc. Only one approach should be adopted because all the approaches are overlapping. The present author has opted for the topical description of air pollution based on major pollutants. It may be pointed out that the nature of air pollution is so complicated due to a host of pollutants that it becomes difficult to isolate the major pollutants.

3 (i) Carbon Monoxide and Air Pollution

The major source of the production of carbon monoxide (CO) is incomplete burning of fossil fuels like coal and petroleum and wood charcoal. The automobiles using diesel and petroleum are the major sources of carbon monoxide. Besides, carbon monoxides are also produced from oil refineries, metallurgical operations and numerous combustion engines. It is apparent that urban areas and industrial centres are the most significant contributors of carbon monoxide because they account for the largest number of automobiles and industries. According to an estimate about 6 billion tons of carbon monoxide are annually produced and emitted in the atmosphere at global level. Thus carbon monoxide constitutes about 50 per cent of the total air pollutants. The U.S.A. alone produces about 65 million tons of carbon monoxide per year. Other significant contributors of carbon monoxide are the countries located in the northern hemisphere such as Japan, Korea, Russia, U.K., France, Germany, Canada etc. India has also emerged as a major contributor of carbon monoxide to the atmosphere as Kolkata alone discharges 450 tones of carbon monoxide daily into the atmosphere. It may be mentioned that carbon monoxide is not toxic to plants but it causes respiratory problem and suffocation, when inhaled, in the human bodies. Inspite of the presence of oxygen in sufficient amount in a room with burning coal carbon monoxide causes suffocation and if the room is closed, it causes death.

3 (ii) Carbon Dioxide and Air Pollution

Carbon dioxide gas is one of the natural gaseous components of the atmosphere and in itself it is not harmful to human health rather it is a resource because plants manufacture their food through the process of photosynthesis by using carbon dioxide in the presence of sunlight and it is the food manufactured by green plants upon which depend all organisms including man. The content of CO_2 in the atmosphere is increasing at an alarming rate because of two major factors viz. (i) release of CO_2 due to burning of foosil fuels (coal and petroleum) at everincreasing rate, and (ii) gradual decrease in the consumption of CO_2 because of shrinking forest covers due to rapid rate of deforestation.

It is significant to note that pre-industrial level (1750)' of atmospheric content of carbon dioxide (CO_2) was fixed at 0.028 to 0.029 per cent (280 to 290 p.p.m.) by volume but the atmospheric CO_2 has increased from the pre-industrial level of 280-290 p.p.m. to 350-360 p.p.m. by 1988, thus registering an overall increase of 25 per cent from the pre-industrial level. It is believed that the rate of increase of atmospheric carbon dioxide through anthropogenic sources will be accelerated due to relentless march of developing countries towards industrial development and urbanization. Various models have been prepared to estimate the quantum of increase of CO_2 from man-made sources.

According to S.H. Schneider (1975) a doubling of carbon dioxide (pre-industrial atmospheric partial pressure of CO_2 estimate as 293 p.p.m.) to about 600 p.p.m. may increase atmospheric temperature by 1.5^{0}C to 3.0^{0}C. Hoffman and Wells (1987) have remarked that the atmospheric content of carbon dioxide has risen by 25 per cent since industrial revolution and is expected to double (100 per cent rise from the pre-industrial level) by the middle of the 21st century.

The higher concentration of carbon dioxide in the atmosphere increases the **greenhouse effect** (see section 16.5 (1), of this chapter) of the atmosphere and thus increases the temperature of the earth's surface because carbon dioxide is more or less transparent to incoming shortwave solar radiation and thus allows the solar radiation to pass through the atmosphere and reach the earth's surface but stops the outgoing longwave terrestrial radiation from escaping to the space. In other words, atmospheric carbon dioxide together with other greenhouse gases trap the outgoing heat radiation waves of the earth and thus warms up the air which results in gradual increase in the temperature of the earth's surface and the lower atmosphere.

The increasing content of atmospheric carbon dioxide from anthropogenic sources is expected to have far reaching effects on global climate through gradual rise in temperature as given below:

(i) Rise in temperature because of increased greenhouse effect caused by increased content of atmospheric carbon dioxide would cause decrease in precipitation and soil moisture content in the most developed agricultural regions of the world.

(ii) If the concentration of atmospheric carbon dioxide goes on increasing the oceans would be overburdened to absorb the additional carbon dioxide which would result in the gradual increase in the oceanic acidity. Increased oceanic acidity would decrease biological productivity of the marine ecosystems and thus decreased plant covers in the oceanic areas would change the albedo of the ocean surface.

(iii) The increased surface temperature would cause melting of continental and mountain glaciers and thus would cause flooding of coastal areas of lowland countries. The rise in seal level may cause flooding of 15 per cent of the agricultural lands of the U.A.R. bordering the Mediterranean Sea and thus about 8 million people would be displaced. Similarly, a major portion of the lower deltaic region of Bangladesh would be submerged under sea-water and consequently about 8 to 10 million people would lose their agricultural lands and homes.

3 (iii) Chlorofluorocarbons and Ozone Depletion

The chlorofluorocarbons, popularly known as CFCs, belonging to the category of chemicals synthesised by man for use in several kinds of industries including refrigeration, are relatively simple compounds of the elements chlorine, fluorine and carbon and are initially stable compounds which do not have any toxic effect on life processes in the biosphere at the ground level. These synthetic chemicals are widely used as propellants in spray can dispensers, as fluids in airconditioners and refrigerators, as blowing agents in insulation foams (popularly known as stryfoam) and as industrial solvents. It is estimated that about 25 per cent of the total world production of chlorofluorocarbons is used to propel 'personal care products' such as deodorants, hair sprays, shaving creams and numerous other cosmetic products. The most important of the chlorofluorocarbons-hydrocarbons-are the trichlorofluoromethane (trade name freon 11) and dichlorofluoromethane (trade name freon 12).

The emissions of chlorofluorocarbons (CFCs) in aerosol and non-aerosol forms from aerosol spray cans, airconditioners, refrigerators, foam plastics, fire extinguishers (halons), cosmetic goods etc. into the troposphere and their transport to the stratosphere increase the concentration of chloroflurocarbons because they keep on accumulating in the stratosphere as they do not degrade for a long period of time. The chloroflurocarbons (CFCs) after being broken down by the ultra-violet solar radiation destroy the stratospheric ozone which acts as a protective cover for all biotic communities of the biosphere because ozone layer absorbs ultraviolet solar radiation and thus protects the earth from becoming too hot.

It may be pointed out that the air is being increasingly polluted due to release of CFCs in the atmosphere. The atmospheric concentration of CFCs is increasing rapidly at the rate of 13 to 28 per cent (of freon 11) per annum. Thus the depletion of ozone (See section 16.4 of this chapter) due to increasing concentration of chlorofluorocarbons (CFCs) is one of the most dangerous forms of air pollution.

Thus the ozone depletion caused by increased concentration of chlorofluorocarbon would adversely affect the global climate, biotic communities and human beings. It is believed that the depletion of ozone layer would result in 5 to 20 per cent more ultra-violet radiation reaching the populated areas of the world within coming 40 years. The substantial increase in the surface temperature of the earth would cause climatic changes at regional and global levels. The overall warming of the environment would cause melting of continental glaciers and ice caps such as those of Greenland and Antarctica. This would in turn cause rise in sea level and consequent submergence of coastal areas of lowlying countries.

The increased surface temperature and exposure of human bodies to increased ultra-violet solar radiation would cause skin cancer mainly among the white populations. According to an estimate 12 per cent decrease in ozone would cause skin cancer to 120,000 people per year in the USA alone. Secondly, increased exposure of human bodies to ultra-violet solar radiation would decrease immunity of human body against infectious diseases. Thirdly, increased ultra-violet radiation and consequent increased photochemical processes would cause poisonous smogs. Fourthly, human beings will face food shortage because of very severe adverse effects of increased ultra-violet solar radiation on agricultural crops, vegetation communities and fishes in the freshwater and marine aquatic ecosystems.

3 (iv) Methane (CH_4) and Air Pollution

The major sources of the production of methane, which belong to the category of greenhouse gases, are biological processes such as enteric fermentation in cattle, sheep, and other animals, anaerobic situation in wetlands and rice fields and anthropogenic activities, such as burning of biomass and fossil fuels (coal, petroleum and natural gas). Concentration of methane gas in the stratosphere increases water vapour there and thus increased water vapour together with other factors intensifies greenhouse effects of the atmosphere which causes rise in the temperature of the earth's surface. According to an estimate about 400 to 765 $\times 10^{12}$ grams of methane gas are added to the atmosphere every year.

3 (v) Sulphur Dioxide and Air Pollution

Sulphur dioxide gas (SO_2) is produced by both natural and man-made sources. After carbon monoxide (CO) sulphur dioxide is the second most important contributor of air pollutants as it accounts for about 29 per cent of the total weight of all air pollutants. It may be pointed out that sulphur is essential element for both plants and animals only in trace amount but when the concentration of sulphur increases in the atmosphere, it becomes injurious to both plants and animals because increased concentration of sulphur increases the acidity of water and lowers the pH of water significantly. The major man-made sources of sulphur dioxide are thermal power plants (where huge amount of coal is burnt to generate power), crude oil refineries and automobiles which together account for 50 per cent of total SO_2 pollution from man-originated sources.

Sulphur dioxide (SO_2) through the photochemical reactions with atmospheric oxygen (O_2) and with water films on suspended particulates produces sulphuric acids (H_2SO_4) which is highly corrosive and leading culprit to human health and wealth. Sulphuric acids coming down with rainfall cause **acid rain** having very low pH value ranging between 5 and 2.5. Acid rain is very dangerous hazard as it causes irreparable damage to agricultural crops, forests, aquatic life and human bodies. It corrodes buildings, pollutes drinking water storage sources, and degrades soil biological processes. The sulphur content present in coal and petroleum gets converted into sulphur dioxide (SO_2) on burning. This sulphur dioxide after combining with smoke over urban and industrial areas forms poisonous smog which causes respiratory diseases in human body and some times causes deaths.

3 (iv) Oxides of Nitrogen and Air Pollution

A few oxides of nitrogen such as nitric oxide (NO), nitrogen oxide (N_2O), nitrogen dioxide (NO_2) etc. are important air pollutants. Nitrogen oxides are formed through natural process as well as through man-induced processes. The main sources of man-originated nitrogen oxides are thermal power stations, factories, automobiles and aircrafts. In other words, nitrogen oxides are released to the atmosphere through the burning of coal and petroleum. According to an estimate each ton of coal after burning produces between 5 to 10 kilograms of nitrogen dioxide whereas one ton of diesel and petroleum consumed by transport vehicles (such as motor cars, trucks and two-whealers) releases 25 to 30 kilograms of nitrogen dioxide. High concentration of nitric oxide causes several diseases in human bodies such as gum inflamation, internal bleeding, oxygen deficiency, pneumonia, lung cancer etc. Nitrogen oxides released from the exhausts of large fleets of supersonic jet aircrafts (travelling at more than double the speed of sound and at a height more than 15,000 m, where ozone has its maximum concentration) are expected to reduce the concentration of ozone by 30 per cent. The studies have shown that even 5 per cent reduction in ozone in the atmosphere can cause between 20,000 to 60,000 additional cases of skin cancer in the USA alone (A.N. Strahler and A.H. Strahler, 1977).

3 (vii) Thermal air Pollution

Heat energy released from industrial processes, space heating and cooling and power generation stations into the atmosphere is expected to upset the balance between solar energy input and absorption of solar energy at the earth's surface which may lead to some changes in general atmospheric conditions. According to W.W. Kelogg (1977) total world energy production through man made sources in 1977 was about 10^4 GW (G=giga, one giga = 1 billion, W=watt) whereas the absorbed solar energy at the earth's surface was about 8×10^7 GW. According to S.R. Hanna and F.A. Gifford heat emissions from a 4×10^4 MW (M = mega, which means one million = 1,000,000) nuclear power plant may cause and accelerate the formation of convective clouds and precipitation therefrom over the source region and may introduce slight ground fog within 100 km of cooling towers.

3 (iii) Particulate Air Pollution

The particulate matter includes smoke and soot, aerosols and dusts and mists. Aerosols are solid, liquid or solid-liquid particles ranging from 0.0005 to 500 μm in diameter (Ormrod, 1984) but usually aerosols are considered to include the particles upto one micron in diameter. Particles being smaller in diameter than aerosol are called smoke and soot whereas particles larger than aerosols are called dusts when they are solid, and mists when they are liquid. Several solid particulates are emitted from the industrial, urban and agricultural sectors, the fallout of which causes various types of health hazards to living beings on this planet earth.

Solid particulates such as dusts are divided into two categories based on the sources of their production e.g. (i) **metallic dust particulates** coming out of industrial, mining and metallurgical operations include dusts of particles of aluminium, lead, copper, iron, zinc etc. and (ii) **non-metallic dust particulates** including particles or dusts of cement, glass, ceramics, asbestos etc. are produced from industrial operations. Lead particles are generally produced from petrol because lead is added to petrol as an antiknock agent. These particulate matters emitted in the air from man-made sources cause damages to biological communities in a variety of ways (to be discussed in the next subsection on effects of air pollution) and also cause some changes in weather conditions. Dust particles scatter solar radiation and thus affect radiation balance.

3(ix) Domestic Air Pollution

Domestic air pollution includes pollution of air due to pollutants emitted from the houses and offices in both rural and urban areas. The major domestic pollutants are smokes from cigarettes, biri, cigars and other tobacoo smokes, burning of coal, firewood, cow-dung cakes, kerosine oil and liquified gases. Thus there are three major sources of domestic air pollution e.g. (i) several forms of tobacoo smokes, (ii) kitchen smokes, and (ii) coal.

The most widespread and serious domestic air pollutant is kitchen smoke mostly in the rural areas and slums of the urban areas in the developing countries. Most of the population of rural India burn wood, twigs, leaf litters, cowdung cakes, coal and kerosine oil in the kitchens to cook food. The kitchens are generally located in unventilated rooms. These devices release enormous volume of soot and smokes which pollute the air in limited area particularly in and around the village concerned or a particular locality of the city. The 'chulhas' (ovens) in the rural areas are unscientifically designed and hence most of the smokes spread in the kitchen room, nearby rooms and some escape in the air through thatched roofs. Similarly, a sizeable portion of heat goes out unused. Recently, some fuel efficient 'chulhas' have been designed. The common pollutant gases emitted from domestic burning of coal, kerosine oil, firewood, cowdung cakes etc. are carbon monoxide (CO), carbon dioxide (CO_2), sulphur dioxide (SO_2) etc. Incomplete combustion of wood, coal, paddy skins etc. releases carbon monoxide which reaches 50 p.p.m. or even more in unventilated kitchen room. Such polluted air causes eye diseases and suffocation. Several cases of deaths are reported from rural India during winter months due to suffocation caused by carbon monoxide and sulphur dioxide.

About 100 million tonnes of firewood are annually consumed in India for various purposes which produce 31,40,000 tonnes of particulate matter, 1,63,000 tonnes of carbon monoxide, 19,60,000 tonnes of sulphur dioxide, 3,90,000 tonnes of nitric oxides, 23,50,000 tonnes of hydrocarbons and total pollutants emitted from the burning of firewood amount to 8,360,000 tonnes per annum. The burning of 55 million tonnes of cowdung cakes per year in India releases 7,20,000 tonnes of particulate mater, 38,000 tonnes of carbon monoxide, 4,50,000 tonnes of sulphur dioxide, 90,000 tonnes of nitric oxides, 5,40,000 tonnes of hydrocarbons per year whereas total pollutants from cowdung burning amount to 19,10,000 tonnes per annum.

16.8 IMACTS OF ATMOSPHERIC POLLUTION

The changes in the atmospheric chemistry through anthropogenic atmospheric pollution (i.e. air pollution) has far reaching impacts on weather and climate changes and resultant smogs and acid precipitation, on human health, and plants and animals.

1. Impacts on Weather and Climate

(i) Ozone depletion and global warming : Depletion of ozone caused by chlorofluorocarbons (CFCs) emitted from air conditioners, refrigerators, foam plastics, hair driers, spray can dispensers, fire extinguishers and many consmetic goods and nitrogen oxides released by large fleets of supersonic jets travelling at more than double the speed of sound and at a height more than 15,000 m may change the radiation balance at global level. A detailed description of ozone depletion has already been presented in sub-section 16.4 of this chapter. The overall effect of ozone pollution (depletion is also a form of pollution) would be increase in the ultra-violet solar radiation reaching the earth's surface and therefore rise in air temperature. Substantial increase in the surface temperature of the earth would cause global warming of the environment which would cause climatic changes at regional and global levels. Increased temperature would cause melting of continental glaciers and ice such as those of Antarctica and Greenland. This would in turn cause rise in seal level and consequent submergence of coastal lands of lowlying countries.

(ii) Carbon dioxide and global warming : Increased concentration of carbon dioxide and other greenhouse gases in the atmosphere would intensify greenhouse effect of the atmosphere and thus the temperature of the earth's surface would increase which would cause climatic changes and would effect melting of continental and mountain glaciers and continental ice caps resulting into submergence of island nations and coastal lowlands. The detailed description of greenhouse effect and its impacts on weather and climatic changes has been given in the subsection 16.5 (4) of this chapter.

(iii) Smogs : Smoky fog over the cities and industrial areas is generally called as smog or **urban smog.** Smog is generally formed when fog is mixed with smoke. When smog is mixed with air pollutants such as sulphur dioxide (SO_2), oxides of nitrogen (NOx) and ozone (O_3), it becomes poisonous and deadly health hazard to human beings. Sulphur dioxide is the main culprit in the formation of smog. It readily combines with atmospheric oxygen (O_2) and reacts with water films on suspended particulate matter (SPM) to produce sulphuric acid (H_2SO_4). This sulphuric acid after combining with smog makes it poisonous. Nitrous oxide (N_2O) forms nitric acid (HNO_3) which also makes smog poisonous. Ozone after reacting with hydrocarbon compounds forms some toxic compounds such as ethylene which is common pollutant in urban smog. It may be pointed out that these air pollutants (sulphur dioxide, nitrogen oxides, ozone etc.) are trapped in a shallow layer over the cities caused by inversion of temperature (warmer air over cooler air) and thus are mixed with fog over the cities and industrial areas. The resultant fog having poisonous air pollutants is called urban smog and is highly undesirable weather phenomenon for human society.

The incidents of deadly urban smogs of December 1930 in Meuse Valley of Belgium, of October 26, 1948 at Donora in Pennsylvania (USA) and of 1952 in London tell the ordeal of air pollution causing poisonous smogs. The poisonous smog of December 1930 of Meuse Valley of Belgium was caused due to trapping of huge volume of sulphur dioxide emitted from coke ovens, steel mills, blast furnaces, zinc smelters and sulphuric acid plants into a stagnant cold air layer, the result of inversion of temperature. This poisonous fog caused respiratory trouble in human beings, consequently 600 people fell ill and 63 people died. The five-day health disaster of Donora, Pennsylvania (USA) was preceded by the formation of thick fog due to strong inversion of temperature on October 26, 1948. The next day fog thickened and combined with sulphide fumes and soot spewed from mills and became a poisonous urban smog which claimed 20 human lives and 43 per cent of the total population of Donora became ill. A thick polluted fog, urban smog, was formed in December 1952 over London which claimed 4,000 human lives mostly through respiratory diseases.

(iv) Acid rain : The fallout of acids with rains is called acid rain. In other words, 'Rain made acid by pollutants, particularly oxides of sulphur and nitrogen (natural rainwater is slightly acidic due to the effects of carbon dioxide dissolved in the water)' is called acid rain' (D.B. Botkin and E.A. Keller, 1982). Acid rain simply means fall-out of acids caused by sulphur dioxide and nitorogen oxides with rainfall and thus increase in the amount of acidity of rainwater. As pointed out above rainwater is not pure because atmospheric carbon dioxide is dissolved in the rainwater which thus becomes moderately acidic, the pH being generally 5. The water with pH value of 7.0 is called neutral water whereas the pH value below it makes the water acidic and above the neutral point makes the water alkaline. The water becomes more injurious when the pH falls below 4.0.

Sulphur dioxide (SO_2) emitted from man-made sources (combustion of fossil fuels in factories, automobiles etc.) in larger quantities into the atmosphere combines with water to form sulphate and sulphuric acides (H_2SO_4). These acids fall on the earth's surface with rainfall and thus the fall of highly acidic water from above is called acid rain. The pH of rainwater in some localities of the USA mainly in West Virginia has gone down to 1.5, pH of rainwater in Europe is as low as 2.4 whereas the normal range of pH of neutral water must be 7.0.

The main sources of acid rains are oxides of sulphur and nitrogen which are emitted from industrial establishments and different types of vehicles. These pollutants are spread in the atmosphere by wind and form acids (sulphuric acids) after reacting with water in the atmosphere. It may be pointed out that acid rains are not confined to the source areas of the emissions of oxides of sulphur and nitrogen rather they cover much larger areas far away from the source of pollutants that cause acid rains because these pollutants being in gaseous phase are carried away and spread over larger areas through winds and clouds. For example, oxides of sulphur and nitrogen spewed from several mills in Germany and U.K. have caused widespread acid rains in Scandinavian countries (Norway, Sweden) with the result most of the lakes in Scandinavian countries have lost their biological communities and are now biologically termed as '**dead lakes**'.

Acid rains are very often called as **lake killers** in Anglo-American and west European countries because these rains have been identified as main factors of the **deaths of lakes** which mean destruction and death of all aquatic lives including plants and animals in lakes, ponds and rivers. Out of 2,50,000 lakes of the state of Ontario (Canada), 50,000 have been adversely affected by phenomenal increase in the acidity of water and significant lowering of pH due to acid rains. Out of these lakes 140 have been declared as **dead lakes.**

Acid rains also affect human community adversely, though the mode of human diseases and death due to acid rains has not been properly understood as yet. According to American doctor Hamilton about 7500 to 12000 persons die of acidic sulphates coming out of the combustion of fossil fuels all over the globe every year.

The productivity of soils is also significantly lowered because of acid rains as increased acidity destroys mineral elements and other nutrients of the soils. Forests of Canada, the USA, Germany and many countries of middle Europe have been largely damaged due to acid rains. The gradual destruction of vegetation through acid rain is called **dieback of forests.** 'Dieback is the gradual dying of tree or trees, either from the crown downward or from the tips of branches inward toward the trunk', (Oliver and Hidore, 2003). The mountain forests in the Carolina state, Newyork and New England of the USA have been reported to have been severely damaged by dieback. Acid rains also damage several monuments and buildings of historical importance due to corrosion. A siren of possible damage of world famous marble monument of Tajmahal at Agra, India, due to emissions of sulphur dioxide from the oil refinery at Mathura has been raised time and again. Several valuable sculptures and antiques of precious marble and other valuable stones are now being kept in the museums inorder to save them from the danger of acid rains in many of the western countries.

As pointed out earlier, acid rain is not a local problem or a problem of a particular country, rather it is an international problem because air pollutants emitted from a particular country are carried in the atmosphere by the winds and are spread over other countries. Thus the problem of acid rains should be tackled at international level. The acute problem of acid rains in the states of Quebec and Ontario of Canada is not only because of industrialization of these states rather it is more because of industrial growth and urban expansion in the Lake Region, Pittsburgh region and New England region of the USA.

The problem of acid rains in India is no longer alarming atleast at present time as the studies conducted by BARC (Bhabha Atomic Research Centre, India) and WMO (World Meteorological Organization) have revealed no significant level of acidity in the rainwater over most of Indian cities.

2. Effects on Human Health

(i) Carbon monoxide is major pollutant for human community because it combines with haemoglobine molecules of human blood much faster than oxygen (about 200 times faster than oxygen does) and thus causes suffocation inspite of the presence of sufficient amount of oxygen in the air.

(ii) Depletion of ozone due to chlorofluorocarbons (CFCs) is expected to cause skin cancer mainly among white people because of increased exposure of human bodies to more ultra-violet solar radiation. 'Studies of the effect of such ozone reduction on human health have shown that a 5 per cent reduction in the amount of ozone in the atmosphere could cause between 20,000 and 60,000 additional cases of skin cancer in the United States alone' (A.N. Strahler and A.H. Strahler, 1977).

(iii) Sulphur dioxide after combining with water films on suspended particulates forms poisonous fogs known as urban smogs over cities and industrial areas. Thus sulphur dioxide-originated smogs block the respiratory systems of human bodies and cause deaths of human beings. The ordeal of disastrous smogs of Donora (Pennsylvania, U.S.A. 1948), Meuse Valley (Belgium, 1930) and London , (1952) has already been discussed in the preceding subsection.

(iv) SO_2 (sulphur dioxide) pollution also causes diseases of eyes, throat and lungs. SO_2 causes instantaneous irritation of nose and throat when its concentration crosses the permissible limit of 10 p.p.m. in the air for 8 hours of exposure.

(v) SO_2 pollution also causes acid rains which pollute the surface and subsurface water storage sources and thus adversely affects the health of those persons who depend on such polluted water.

(vi) Nitric oxide (NO) in high concentration in the air, when inhaled, combines with haemoglobine thousands of times faster than oxygen combines with haemoglobine and thus causes respiratory problem, gum inflamation, internal bleeding, oxygen deficiency, pneumonia and lung cancer. It may be pointed out that no definite results have been found out in relation to nitric oxide as the causative factor of above diseases in human bodies.

(vii) Numerous suspended particulate matters (SPM) emitted from factories and automobiles during the combustion of fossil fuels (coal, petroleum and natural gas) and from other industrial processes, such as lead, asbestos, zinc, copper, dusts, etc. cause several deadly diseases in human bodies. Lead poisoning and asbestosis are among the deadly diseases caused by particulate air pollution.

(viii) Sudden leakages of harmful and poisonous gases from chemical and gas plants pollute the air to such an extent that hundreds of people die within no time. Besides instantaneous deaths caused by poisonous gases, there are far reaching consequences of poisonous gases on future generations of human beings, micro-organisms such as bacteria, decomposers and fungi and thus environment is so greatly polluted that the ecological balance and ecosystem equilibrium is highly disturbed.

The **Bhopal gas tragedy** (Bhopal, India) of December 1984 is a burning example of one of the deadliest disasters caused by human negligence in the maintenance of deadly gases such as MIC gas (Methyl iso-cynate). The leakage of MIC gas from the Union Carbide Factory at Bhopal on the wintry night of December 2/3, 1984 caused the single biggest air pollution tragedy which, according to official sources, claimed 2500 human lives in the early hours of December 3, 1984, whereas non-governmental sources put the figure beyond 5000. Methyl Isocynate gas was produced at Bhopal based Union Carbide Factory of the USA to manufacture pesticides. The produced MIC gas was stored in underground containers. The poisonous MIC gas leaked from these containers and the leakage continued for 40 minuts. The poisonous gas was quickly spread in nearby densely populated localities of old Bhopal under the impact of morning breeze. According to the report the poisonous gas claimed 3,410 human lives so far. Besides, hundreds of thousands of inhabitants were exposed to poisonous gas and thousands of animals were killed. The Bhopal Gas Tragedy also polluted drinking water, soils, tank and pond water and adversely affected foetus, newly born babies, pregnant women, children, young and old people alike.

A team of doctors of Bombay surveyed Bhopal city after the tragedy and found that the water of the city was highly polluted because of increased concentration of thiocyanate due to leakage of methyl isocynate gas. The amount of thiocyanate was reported to be between 3 and 4 p.p.m. in the water against 0.8 p.p.m. in the water of Bombay. The substantial amount of thiocynate was being transported to human bodies as people used to drink heavily polluted water. This caused high level of thiocyanate in the blood of human bodies. The survey team suggested the affected people to leave Bhopal at least for 3 years.

The foetus in the wombs of women were greatly damaged as 200 women delivered dead babies and 400 babies died within few hours of their birth just after the gas tragedy. About 47 per cent of the pregnant women suffered from instantaneous abortion whereas some pregnant women were convinced to go for self abortion. According to the latest figure released by the government around 10,000 people were rendered permanently disabled, and another 30,000 partially handicapped. Those who suffered minor disability numbered about 1,50,000.

Newly born babies, who could survive, developed blue spots in their livers, suffered from coughs and asthma and most of them lost their eye sight.

3. Effects on Plants

The depletion of ozone caused by chloroflurocarbons and nitrogen oxides, if not checked and corrected, would enormously increase ultraviolet solar radiation reaching the earth's surface. The increased ultra-violet solar radiation would adversely affect plant and animal communities in a variety of ways. Photosynthesis, water use efficiency and yields of plants would be substantially reduced. Soil-moisture would be significantly reduced and thus agricultural crops would weather away resulting into marked decrease in food production.

Photosynthesis by phytoplanktons in the marine ecosystems would be greatly reduced. Many phythoplanktons woud die which in turn would adversely affect zooplanktons and other marine organisms which feed on phytoplanktons. Many of fishes woud die because of want of their food in the form of phytoplanktons. Rise in the temperature of the earth's surface due to ozone depletion and increase in greenhouse effects of the atmosphere due to higher concentration of carbon dioxide and other greenhouse gases would affect the type, density and stability of vegetation which in turn would affect animal community and sediment and chemical element cycles.

The pollution caused by high concentration of sulphur dioxide adversely affects plant community. The studies have shown that lichens are more suceptible to sulphur dioxide and other air pollutants. All lichens die in the zones where the concentration of sulphur dioxide reaches the level of 170 micorgram per cubic metre of air or more in U.K. The studies have further shown that the deciduous forests in the state of Tennessee in the USA and the evergreen forests of Black Forest in Germany are being gradually destroyed owing to sulphur dioxide pollution. Conifers like douglas fir and lodgepole pine in the USA are being adversly affected by sulphur dioxide pollution. In India mango is being badly affected by sulphur dioxide mainly near brick-kilns. Acid rain caused by sulphur dioxide is the main culprit of the destruction of vegetation community. Increased concentration of hydrogen fluoride causes necrosis, and discolouration of plant leaves.

16.7 IMPORTANT DEFINITIONS

Air pollution : In general sense air pollution may be defined as the disequilibrium condition of the air caused due to introduction of foreign elements from natural as well as anthropogenic sources in the atmosphere so that the air becomes injurious to biological and human communities.

Acid rain : The fallout of acids with rains is called acid rain. In other words, the precipitation of more acidic water having average pH 5.0 or less caused by sulphur dioxide pollutants, is called acid rain.

Carbon trading : As per Kyoto Protocal carbon trading or hot air trading simply means that industrial countries have power for mutual transfer of fixed quota of cut in the emission of greenhouse gases.

Coral bleaching : Coral bleaching refers to the loss of algae from the corals resulting into white colour which causes coral deaths due to starvation when the average sea water temperature rises by $2^{0}C$.

Dieback : The gradual dying of vegetation mainly trees due to acid rains is called dieback.

Greenhouse effect : Greenhouse effect means progressive warming up of earth's surface due to blanketing effect of man-made carbon dioxide in the atmosphere (Oxford Dictionary).

Icebergs : The floating gigantic masses of ice independent of ice shelves in the seas are called icebergs.

Isotope : One of a set of chemically identical species of atom which have the same atomic number but different atomic weight is called isotope.

Ozone hole : The patch of the depletion of the concentration of ozone by 100 per cent resulting into total disappearance of ozone over Antarctica is called ozone hole.

Radiative forcing : The radiative forcing refers to 'the effects which greenhouse gases have in altering the energy balance of the earth-atmosphere system' (IPCC).

Urban smog : Smoky poisonous fog over the cities and industrial areas, formed due to mixing of smokes, sulphur dioxide, oxides of nitrogen etc., is generally called smog or urban smog.

17

WEATHER FORECASTING

17.1 MEANING AND IMPORTANCE

The weather forecasting simply means predication of weather conditions comprising air temperture, humidity, nature of sky i.e. cloudiness and precipitation, air pressure and circulation and other atmospheric conditions of a place or a region well in advance at different temporal scales e.g. daily, weekly, monthly etc. based on different sources of information. The prediction of weather conditions is related to atmospheric research and is becoming more and more significant because all sorts of human activities are affected by varying weather elements. In fact, weather forecasts are directly relevant to different segments of society and have become basic needs of the individual (to decide one's daily routine work), general public, administrators (to decide the economic policy, plans and projects for developmental works, budgetary provisions for various economic, social, educational activities etc.), farmers (to decide the nature of crops to be grown in a particular season, crop management etc.), financiers and business establishments, industry and industrialists, architects, transport sectors (operation of airways, railways and roadways), strategic sector (mainly different aspects of military operations) etc.

It may be mentioned that accurate, timely and properly conveyed forewarning (prediction) of the vagaries of weather such as killing frost, dense fogs, droughts, incessant rainfall leading to floods, hailstorms, snowfall etc. may help the people involved in different economic activities to safeguard them to the maximum possible extent for example, if the farmer, who has grown potatoes, peas, tomatoes etc., is given information of likely occurrence of severe frost within a few days, he may irrigate the crops inorder to save them from killing frost. Similarly, if the people living in the riparian tracts of flood plains of the alluvial rivers, are given prior information of prolonged incessant rainfall and likely flood, they may be prepared to evacuate and to move to safer places. It is, thus, apparent that the timely and correct predictions of weather help in human adjustment to the vagaries of weather events mainly extreme events like prolonged incessant rainfall leading to flash floods and water logging, occurrences of hurricanes and tornadoes, occurrences of super cyclones (e.g. 1999 super cyclone of Orissa, India), snowfall, fogs, hailstorms, frosts etc. This is the reason that weather forecasting as part of the atmospheric research has gained currency in each and every country and the scientific and technological development (such as radars, satellites etc.) has given further impetus to the forecasters to improve their abilities to predict the future weather conditions more accurately. It is, thus, imperative to study different aspects of weather forecasting and analysis, namely histogenesis of weather forecasting, sources of weather prediction (tools of weather prediction), types and methods of weather forecasting, problems of weather forecasting mainly its accuracy and reliability, future prospects etc.

17.2 HISTOGENESIS OF WEATHER FORECASTING

The weather forecasting dates back to the emergence of ancient civilization and culture when weather phenomena were considered to be the creation of Gods, and thus religious faiths, though not based on scientific facts and principles, dominated the general beliefs of the public about weather conditions and events. Before the advent of scientific method of weather predictions based on synoptic systems, during the 19th century A.D. contemporary weather lores became popular almost in every country. A few experienced and wise people closely observed the sky covers and its colour, clouds, air movement, rainbows, cyclonic and anticyclonic conditions, positions of the moon and the sun etc. and predicted the likely weather conditions to occur in the form of lores mainly stangza and **weather sayings**. If we look into the bases of weather lores of different regions of the world, it appears that such lores and weather sayings were based on particular aspects and hence **weather lore method** of weather predictions may be grouped in the following categories :

(1) **Lunar lore forecasting**, weather lore forecasting based on the phases of the moon based on the belief that the changing phases of the moon within a lunar month are significant controlling factors of weather conditions; (2) **Colour lore forecasting**, prediction of weather mainly dry or moist conditions on the basis of colour of the sky (besides natural appearance of blue colour when the sky is cloudless), rainbow, nature of halos around the moon, coronas of the sun, colours of the clouds (e.g. red colour indicated dry condition while dark gray colour predicted wet condition-rainfall or drizzle); (3) **Animal (including man) reaction lore method**, based on the belief that some animals react sharply to any immediate weather change to take place; (4) **Atmospheric condition lore method**, was based on the nature of air movement (direction and duration, velocity, day-night rhythm etc.), nature of cloud cover mainly presence or absence of clouds during daylight and night; (5) **Floral lore method**, based on the seasonal plants and their flowering periods etc.

The sayings of weather by Ghagh and Bhaddari in Indian context are very popular among rural folk. It may be mentioned that some weather sayings of Ghagh are still relevant to weather prediction because these are based on close observations of the wind direction, monthly temperature, wind velocity, colours of the sky and clouds, lightning and cloud thunders etc. A few of them are being discussed below :

(A) **Based on wind direction**

(1) 'Vayu chale jo dakhina,
marn kanha se khai.
'वायु चले जो दखिना,
माड़ कहाँ से खाया।'

If the wind blows from south direction, paddy cultivation will be adversely affected (due to shortage of rainfall). Vayu = wind, chale = blows, dakhina = southery, marn = starch of rice, = kanha = how, khai = to eat.

(2) 'Jai din Jeth chale purwai,
tai din Sawan dhool udai.
'जै दिन जेठ चले पुरवाई,
तै दिन सावन धूल उड़ाई।'

If wind blows from easterly direction in the months of May-June (Jeth), the months of July, August (Sawan) will go dry. It means that easterly winds in the months of May and June will weaken low pressure system in north-west India, and hence summer monsoon will be weakened and two rainy months of July and August will go dry. This saying definitely carries scientific base and is very much relevant in weather forecasting.

(3) 'Magh-Poosh jo dakhina chale,
to Sawan main lakshan bhale.'
'माघ-पूष जो दखिना चले,
तो सावन में लक्षण भले।'

If wind blows from southerly direction in the months of December and January, there will be sufficient rainfall in the month of Sawan (July-August).

(4) 'Poorab ke badar pachhiwa jawe,
patali chhani ke moti pakao,
pachhawa badar poorab ko jawe,
moti chnani patali khawe.'
'पूरब के बादर पच्छिव जाये,
पतली छाणि के मोटी पकावो।
पच्छवा बादर पूरब को जावे।
मोटी छाणि के पतली खावे।'

If during summer monsoon season winds blow from east to west, there will be sufficient rainfall and good grain harvest but if the winds blow from west to east, there will be little rainfall and famine will occur.

(5) 'Jo purwa purwai pawe,
jhuri nadia nava chalawe.'
'जो पूर्वा पुरवाई पावे,
झूरी नदिया नाव चलावे।'

If Purwa nakshatra (probably falling in August-September) is dominated by easterly winds, one can sail boat in dry river, meaning thereby, there will be more rainfall.

(B) Based on heating and cooling

(6) 'Rohini varshai Mrig tapai,
kutch kutch Adra jai'
Ghagh kahen sun Ghaghini
swan bhat nahi khai.
'रोहिणी वरषे मृग तपे,
कुछ कुछ अद्रा जाय,
घाघ कहें सुन घाघिनी
श्वान भात नहीं खाय।'

If there is rain in Rohini nakshatra (probably in May) but Mrig nakshatra is exceptionally hot (means if the last fortnight of May and first fortnight of June are hot the low pressure system in north-west India will be intensified and hence summer monsoon will be active) and rain starts after few days in Adra nakshatra (late June or early July) even swan (dogs) will be fed up with rice (means there will be more rainfall and abundant production of rice).

(C) Based on wind and cloudiness

(7) 'Din ko baddar, raat nibaddar,
bahe purwaiya jhabbar jhabbar,
Ghagh kahen kutch anhoni hoi,
kunwa ke pani dhobi dhoi.'
'दिन को बद्दर रात निबद्दर,
बहे पुरवइयां झब्बर झब्बर,
घाघ कहें कुछ होनी होई,
कुंआ के पानी धोबी धोई।'

Ghagh poet tells his wife Ghaghini that if the sky is clouded during daylight but is cloudless during night, the wind blows from easterly direction with high velocity, there will be severe drought, even dhobi (washerman) has to wash cloths with water taken from the wells.

(D) Based on cloud colour

(8) 'Magh main badar lal ghirai,
sachi mano pathar parai'.
'माघ में बादर लाल घिराई,
साची मानो पाथर पराई।'

If the clouds become red in the month of Magh (January-February), it is certain that there will be hailstorm (pathar).

(9) 'Kariya badar jiva darawe,
bhoora badar pani lawe.'
'करिया बादर जिव डरावे,
भूरा बादर पानी लावे।'

Black coloured clouds only show fear of rainfall (but no rainfall) but gray coloured clouds (means, cumulo-nimbus clouds) yield rainfall.

(E) Based on lightning, cloud thunder and sky colour

(10) 'Lal piyar jab hoi akash,
tab nahi varsha ki aash'.
'लाल पियर जब होई आकाश,
तब नाहीं वर्षा की आश।'

If the sky turns red and yellow, there is no hope for rainfall.

(11) 'Shukrawar ki badari,
rahe Shanichar chaay,
Ghagh kahen sun Ghaghini,
bin varshe nahi jay'.
'शुक्रवार की बादरी, रहे शनीचर छाय
घाघ कहें सुन घाघिनी, बिन वरषे नहीं जाय।'

If the cloudiness begins on friday (shukrawar) and continues on saturday (shanichar), Ghagh poet tells his wife Ghaghini that there will be sure rainfall (in fact, this saying predicts the arrival of cyclone which yields precipitation).

(12) 'Sudi Asharh ki panchami
garaj dhamdhama hoi
tau yaa jano Bhaddari,
madhuri megha hoi
'सुदी अषाढ़ की पंचमी
गरज धमधमा होय,
तौ या जानो भड्डरी,
माधुरी मेघा होय।'

Bhaddari poet tells that if there is strong lightning and cloud thunder on the 5th day of Asharh month (July) there will be good rainfall.

(F) Based on planets and satellites

(13) 'Aage ravi pichhe chale,
mangal jo asharh,
tau varshe anmol ho,
prithvi aanand barh.'
'आगे रवि पीछे चले,
मंगल जो अषाढ़,
तौ वर्षा अनमोल हो,
पृथ्वी आनन्द बाढ़।'

The year, when the mars (mangal) is behind the sun (ravi), receives copious rainfall and the people of the earth (prithvi) become happy (aanand).

(14) Asharh authwain andhiari,
jo nikle chanda jaldhari,
chanda nikle badal phor,'.
sadhe teen mahina varsha hoya'.
'आषाढ़ आठवें अंधियारी
जो निकले चंदा जल धारी,
चन्दा निकले बादल फोड़,
साढ़ेतीन महीना वर्षा होय।'

If the moon appears by piercing the cloud on the 8th day (authwain) of the new moon fortninght of Asharh month (July), the rainfall will continue for three and half months.

(G) Based on flora and fauna

(15) 'Koki bole jaya aakash'
tab nahi varsha ki aash'.
'कोकी बोले जाय आकाश,
तब नाही वर्षा की आश।'

If the hen (koki) cries while flying in the sky (aakash) there is no hope (aash) for rainfall (varsha).

(16) 'Mataka main pani garam,
Chiria nahawe dhoor,
Chinti anda chale,
tau howe varsha bharpoor'
'मटका में पानी गरम,
चिड़िया नहावे धूर,
चींटी लै अण्डा चले,
तौ होवे वर्षा भरपूर।'

If the water of a pitcher is hot, the bird (chiriya) baths (nahawe) in the dust (dhoor), the ants (chinti) carry their eggs, then there will be more rains.

(17) 'Utare jeth jo bole dadur,
Kanhe Bhaddari varshe badar.'
'उतरे जेठ जो बोले दादुर,
कहैं भड्डरी वर्षे बादर।'

Bhaddari poet says that if frogs (dadur) start crying in late Jeth month (late June), the clouds (badar) start raining (varshe).

(18) 'Boli lokhari, phooli kash'

ab nahi varsha ki aash.'

'बोली लोखरि फूली काश'

अब नाही वर्षा की आशा।'

If foxes (lokhari) start crying enmass and kash plants start flowering, then the rainy season will end and there will be no hope (aash) for rainfall (varsha).

The weather forecasting switched over from traditional methods of forecasting based on folk lores mainly weather lores, sayings of some experienced persons who gathered knowledge of atmospheric conditions through close observations of weather events to scientific methods with the development of some measuring instruments like thermometer by Galileo in 1593 (to measure temperature) and barometer by Torricelli in 1686 (to measure air pressure), and recording of weather elements. Thus, the later half of the 17th century saw appreciable advancement in elementary weather forecasting with the preparation of wind map by Halley in the year 1686 and further advancement in the preparation of weather map by Buys Ballot in the year 1852. All these denote small beginning in the synoptic analysis of weather conditions. It may be mentioned that the preparation of early synoptic charts before the invention of telephone system by Graham Bell was based on the collection of data of temperature, air pressure, winds, humidity etc. through postal services from various recording places scattered over the globe. Such data were compiled and plotted on maps but there was time lag in the dates of recorded data and plotting of data on maps because of slow process of collection of data, and hence timely prediction of weather conditions could not be possible.

The shortcomings of time lag between the dates of recorded weather data and preparation of weather maps were overcome with the invention of first electric telegraph in the year 1840 which enabled the meteorologists to collect the weather data on time. Thus, quick collection of observation data through the use of electronic telegraph system made the plotting of observed weather data on maps and analysis thereof more realistic. The second breakthrough in the science of weather forecasting took place with the establishment of centers of systematic experiments in weather conditions and forecasting with the application of electric weather telegraphy in the second half of the 19th century, namely by R. Fitzoroy in U.K., by Leverrier in France, by Smithonian Institute in the USA etc. in 1860. This led to the establishment of network of centers of weather forecasting services in different countries. In India such center was established as late as in 1878 (June 15) in Simla where weather data of 51 stations were collected through electric telegraph system and then began the publication of Indian Daily Weather Report but the publication of weather charts in the Indian Daily Weather Report started in the year 1887 (October, 13). It may be mentioned that the 19th century weather forecasting system was based on limited range of observed surface weather data such as air pressure, temperature, wind and generalized prevailing weather conditions recorded at selected land stations. Thus, the weather forecasting was confined to the study of relationships between temperature and pressure patterns, behaviour of winds including direction and speed and weather conditions related to and resulting from such relationships. Initially, such relationships were employed to predict only major atmospheric storms. It may be mentioned that even such limited range of the prediction could not be realistic because still information related to pressure conditions and wind patterns from the oceanic surfaces, which are the source regions of the genesis of most of the atmospheric storms, were not available.

The shortcoming of non-availability of weather data of ocean surfaces was also overcome in the first two decades of the 20th century with the invention of radiotelegraphy as the ships were equipped with radio systems. This device enabled the meteorologists to collect data of weather conditions from both land and ocean surfaces. It may be mentioned that the 19th century weather forecasting was based on only surface data of weather events but the beginning of the 20th century introduced new dimension in the weather forecasting when aeroplanes were used to obtain upper air weather data atleast of the lower tropospheric atmospheric conditions. The postulation of new concept of polar front theory or wave theory of the origin and development of extra-tropical (temperate) cyclones, popularly known as Bjerknes cyclone model, in 1920 and improved scientific communications made weather forecasting more realistic and useful. This empirical method of weather forecasting heavily relied on **subjective approach** and hence depended on the ability of the individual forecaster. It is also true that subjective explanation of weather conditions on the basis of the plotted information of air pressure, air circulation mainly atmospheric storms, humidity, cloudiness etc. on weather charts was more realistic because it was based on closer view and study of local topographic and weather condition but such traditional **empirical method** of weather forecasting also had some inherent limitations and shortcomings such as (i) it was more qualitative because it was based on limited data of weather condition, (ii) it had temporal limitation i.e. the forecast period was very short, say 24 hours, (iii) it was based on the data of small areas and hence it could not be extended for larger areas, (iv) the traditional qualitative technique was unable to cope with the analysis of more and more data etc.

Thus, a need was felt to replace the traditional empirical method of weather forecasting by more scientific numerical methods involving the laws of atmospheric physics and electronic computers. It may also be mentioned that the development of **radiosonde** ('radiosonde is an instrument that is carried aloft by a baloon to send back information on atmospheric temperature, pressure, and humidity by means of a small radiotransmeter'—Webster Dictionary) during 1930's enabled the meteorologists to obtain data of temperature, humidity and air pressure upto the height of 30 kilometers i.e. the troposphere and lower stratosphere. Further development of radiosonde during the decade 1940's provided more accurate data of air circulation besides the above mentioned three weather elements.

The development and use of radars, weather satellites, high-speed computers, statistical methods and techniques, and computer models after 1930 gave further fillip to the science of weather forecasting. It may be pointed out that the use of weather satellites in providing weather data became so important that a new branch of climatology known as **satellite climatology** gained wide recognition. The first meteorological satellite, TIROS-1, was launched by the United States in 1960. The use of radar, mainly doppler radar has become more useful and popular in monitoring and forecasting atmospheric conditions mainly upper air circulation patterns. Basically, two types of weather satellites, namely geosynchronous satellites and polar orbiting satellites, with a variety of sensing instruments (sensors) were developed to collect weather data of various sorts. The visible and infrared radiation is sensed and related data are sent to earth's center by NOAA-15 satellites. The following sensors have been developed for different purposes : (1) Earth Radiation Budget (ERB) sensor to monitor energy budget of the earth and the atmosphere, (2) Total Ozone Mapping Spectometer (TOMS) for obtaining data of ozone, (3) Solar Backscatter Ultraviolet Energy (SBUV) sensor to monitor and evaluate the condition of atmospheric ozone, (4) Stratospheric and Mesospheric Sounder (SAMS) to record temperature, (5) GOES imager to record solar radiation and the solar energy reflected from the earth's surface etc. Recently, **teleconnections** are in use to forecast the weather conditions at local level on the basic tenet that local level weather conditions are controlled by weather events which occur in other parts of the world.

17.3 PROCEDURES OF WEATHER FORECASTING

The weather forecasting has now become a science and it is performed by adopting the following procedures (steps) :

1. Recording of weather data (temperature, pressure, wind speed and direction, cloud forms, humidity and precipitation, visibility, storms etc.).
2. Collection of weather data from weather recording (observations centers) stations

(centers) scattered worldover including both land and ocean surfaces,

3. Transmission of weather data collected from major weather (meteorological) stations (centers) to subcenters.
4. Compillation of weather data,
5. Plotting of weather data on maps and daily weather records, synoptic charts etc,
6. Analysis of weather charts and maps with the help of electronic computers, and
7. Final forecasting of weather and numerical modelling.

Recording of weather data as referred to above involves observations of weather phenomena at numerous weather/meteorological stations located worldover including their locations on land and sea surfaces through various instruments four times a day e.g. at mid-night, 6 A.M., 12 noon and 6 P.M. when readings of air temperature, air pressure, humidity, cloud cover, cloud base, cloud types, different forms of precipitation, wind speed and direction, visibility etc. are taken and properly recorded. The measurement and readings of weather elements mainly atmospheric temperature and pressure, humidity, air circulation etc. of upper atmosphere are taken with the help of certain special kinds of instruments such as radiosonde, instruments attached with high altitude aeroplanes, satellites, radars etc. The National Oceanic and Atmospheric Administration (NOAA), an important polar satellite which moves around the earth having a polar orbital route at relatively low height in the atmosphere, Geostationary Operational Environmental Satellite (GOES), doppler radar etc. are significant meteorological devices to record upper air meteorological information. It may be mentioned that different kinds of satellites are used for getting data of specific weather conditions not only over land surfaces but also over sea surfaces. For example, infrared images are required to forecast areas of probable precipitation from a cyclone. Such images wherein white and dark patches indicate high altitude thick clouds and low altitude white clouds, are obtained through Meteosat satellite, the images from European ERS-I and ERS-II satellites provide data regarding the height of sea waves, wind speed, ocean currents, nature of high latitude ice caps etc., the images received from INSAT Indian satellites of different generations provide information about cloud cover, upper atmospheric air pressure and air circulations, location and movement of atmospheric disturbances (cyclones) being originated over Bay of Bengal and Arabian Sea etc.

The observation and recording of various weather elements at the lower and upper atmosphere over the land and seas at local to global levels is done at various observatories (more than 9500) and meteorological stations located on the land surfaces of the globe, at more than 7400 ship-based observation centers which record weather and sea conditions from the seas, at more than 600 radar stations (radars of different successively improved generations to obtain upper air weather conditions including upper air circulation patterns), at more than 2300 upper air weather stations (to record upper air conditions) etc. The information obtained at various land and ship-based observations and meteorological stations are collected at numerous local and regional (mainly national) centers of the countries from where weather information and data are sent to three major international meteorological centers located at Washington D.C. (USA), Moscow (Russia), and Melbourne (Australia) and a few dozen regional centers. It is evident that there is international sharing of weather data and information through telecommunication systems. The international sharing of weather data is accomplished and monitored by the World Weather Watch (WWW) which is a part of the World Meteorological Organization (WMO). The weather data obtained at local observatories in each country are transmitted to the respective national meteorological centres where the reports and data are transformed into local and regional station summaries and weather maps and charts are prepared (daily weather maps and reports) with the help of computers and mathematical models. Finally, the future weather conditions regarding temperature, humidity, air circulation, cloudiness, precipitation or dry condition, storms position and nature etc. for the next 12 to 24 hours are forecast (predicted) on the basis of analysis of daily weather maps and synoptic charts. This aspect will be elaborated in the succeeding sections. It may be mentioned that various weather elements and conditions are depicted through weather symbols (figs. 17.1, 17.2 and 173.).

17.4 TOOLS IN WEATHER FORECASTINGS

As mentioned above the tools used in various processes and steps of weather forecasting (as referred to above) include different measuring instruments positioned at the ground (to measure air temperature, air pressure, humidity, wind speed and velocity etc.), namely thermometers, barometers, hygrometers, raingauges etc.; radiosondes, satellites, radars, electronic computers etc. to measure upper air weather conditions.

'**Radiosondes,** also called as **rawinsondes,** is an instrument that is carried aloft by a baloon to send back information on atmospheric (upper) temperature, pressure, and humidity by means of a small radio transmitter' (Webster's Dictionary). Aeroplanes are used to obtain aerial photographs which provide information about cloud covers. The most significant device is weather satellite of different kinds attached with different types of sensors for specific purposes and having varying orbital paths around the earth.

The first weather satellite, named TIROS-I (TV Infrared Observing Satellite) was launched in the year 1960. Since then the weather satellites have undergone improvements with modifications in the sensors, which are attached with the satellites, and changes in the orbital paths of the satellites around the earth. It may be mentioned that it is the sensors which send back images of clouds to the earth's centers. On the basis of orbital paths weather satellites are classified into two basic types e.g. (1) geosynchronous satellites, and (2) polar orbiting satellites. Geosynchronous (geostationary) satellites, as the word 'geochronous' implies, have the same rate of movement around the earth as that of the rotational speed of the earth at its equator so that the satellite orbiting around the earth is always positioned over the same location on the earth's surface. The geosynchronous weather satellites are fixed at the altitude of 35,786 kilometers from sea level and this is why such weather satellites are called high-altitude satellites. Such high-altitude satellites provide scanned pictures of larger areas. The ATS series and GOES series of weather satellites belong to this category. Polar orbiting weather satellites, also known as 'low-altitude orbiting satellites' are positioned after their launching by rockets at the altitude ranging between 800 to 1500 kilometers above sea level. The TIROS and NOAA (National Oceanic and Atmospheric Administration) series of weather satellites come under this category.

As mentioned above different types of sensors are attached with the satellites. The sensors are grouped into two broad categories, namely (1) sounding sensors (sensing instruments), and (2) imaging sensors. The sounding sensing instruments like Advanced Very High Resolution Radiometer (**AVHRR**) attached to the low-altitude orbiting satellites like TIROS, NOAA etc. provide useful information about radiation emissions of different radiation wavelengths at different altitudes in the atmosphere. Such radiation information are used to study different aspects of atmospheric thermal conditions and variations, cloud covers, base and heights, water vapour etc. which help in the thermal mapping of the atmosphere. The imaging sensing instruments attached to high altitude satellites provide images of cultural and physical features, thermal variations in the atmosphere, moisture etc. It may be mentioned that images of different aspects are obtained from both types of satellites. i.e. geosynchronous and polar orbiting satellites.

Radars are useful tools to obtain detailed information about clouds and storms mainly the activities taking place inside the clouds of cyclones, hurricanes and tornadoes. Doppler radars, a much improved version of radars, have proved more efficient weather forecasting instrument for locating and predicting tornadoes activities 20 minutes in advance.

The usefulness of the use of weather satellites in tracking and predicting tropical cyclones may be validated by the following two Indian examples.

(1) **1990 Andhra Cyclone :** A depression started to develop in the Bay of Bengal off the south-eastern coast of Tamil Nadu about a week before its final assault on Andhra coast on May 9,

1990. The depression developed into strong cyclone and started moving westward to the Tamil Nadu coast. The movement of the cyclone was being very closely watched and monitored by Indian satellite INSAT-IB. Suddenly the cyclone changed its direction of movement towards Andhra coast. The Indian satellite was tracking and monitoring the cyclone minute by minute. A warning of alertness and preparedness was issued through print and electronic media to the local administration and the people to be adversely affected in the coastal districts of Andhra Pradesh. The advance monitoring, prediction and warning of this disastrous cyclone at least a week before the final count down (on May 9, 1990) and its attack on the coastal districts of Andhra Pradesh saved thousands of people from sure death trap. People had sufficient time to move to safer places and thus warning systems contained human deaths which remained at 1000 marks (official figure being 598). In the absence of prediction of timely warning, and ready response of inhabitants to evacuation programme this killer cyclone being 25 times stronger in intensity than the killer cyclone of 1977 (which claimed 5500 human lives in Andhra Pradesh) might have caused unbelievable human deaths.

(2) **Super cyclone of Orissa** of 29 October 1999 caused a havoc of mass destruction through its notorious acts from October 29 to 31, 1999 in the coastal districts of Orissa inspite of hour to hour monitoring and warning of the movement of this super cyclone from the date of its origin in the Bay of Bengal (October 25, 1999) to its final assault on Orissa coast on October 29, 1999. Indian Meteorological Department (IMD) on the basis of information received from Indian satellite (INST) issued an alarm of warning about the arrival of the super cyclone between Paradeep and Puri by October, 29, 1999. Though the Govt. of Orissa was posted with this warning by 5.30 A.M. but this forewarning could not be conveyed to the general public due to lack of ample radio network. Ultimately, the super cyclone entered Orissa coast on October 29, 1999 and began to play its ugly game of destruction in 10 coastal districts. Moving with a wind speed of 300km/hr the cyclone became stationary for 8 hours over this vast area. The disastrous cyclone generated 9m high tidal surges which transgressed upto 15-20 km inside the coastal region. According to official sources more than 10,000 people were killed and 200 villages were completely washed out but the unofficial sources put the death toll of about 100,000 people. In this case prediction system was 100 per cent accurate and timely but the human failure caused immense loss of human lives and property.

17.5 TYPES OF WEATHER FORECASTS

Weather forecasts are generally classified on the basis of period of time covered by weather prediction or say on the basis of duration of the validity of forecasts into three types as follows :

(1) Short-range weather forecasts,

(2) Medium-range weather forecasts, and

(3) Long-range weather forecasts.

It may be mentioned that besides temporal scales as the basis of weather forecasts, accuracy level of weather prediction is equally important in the above mentioned classification of weather forecasting.

(1) **Short-range weather forecasts are most** useful predictions of weather conditions wherein forecasts are valid from a few hours to 48 hours and sometimes upto 72 hours. Such forecasts are based on the basis of maps, weather charts, satellite imageries and the rate of change of atmospheric weather systems at a specific location or site. It may be mentioned that such forecasts are generally specific weather aspects-based i.e. attempts are made to predict specific weather phenomena such as hurricanes, typhoons, tornadoes, cloud bursts, hailstorms, fogs, cloudiness, duststorms, and visibility. Such forecasts are very useful for transport systems, for example, short range aviation forecasts give advance information about cloud cover, fogs and visibility, wind speed and direction, temperature etc. which help the managers to plan the flights of aeroplanes. It is also significant to point out that the level of accuracy of prediction depends on the time duration of forecasts i.e. the shorter the time duration, the more accurate is the forecasts. For example, the forecasts become accurate upto the level of 80 to 90 per cent if the time duration of forecasts is confined to 12

hours. The short range forecasts are transmitted and relayed through radio and television sets for general public and specific sectors such as for aviation of ships and aeroplanes. In other words, warnings about the likely occurrence of fogs and consequent reduction in visibility, high intensity rainfall, hailstorms, cold or heat waves, atmospheric storms, high velocity winds etc. are issued through print (newspapers) and electronic media (radios and televisions).

Generally two methods are employed for short range weather forecasting viz. (1) persistent method, and (2) continuity method. **Persistent method** is based on the basic tenet that the existing rate of movement of cyclonic front (in the case of temperate cyclone) or non-frontal storms will continue for a couple of hours and the fronts or storms would affect the place which is located ahead of the present position (at the time of forecast) at definite time period. It may be mentioned that such moving fronts and storms may undergo changes and transformations during their onward journey but the possibilities of such changes are not incorporated in this method. It may happen that the fronts or storms may dissipate or may become more vigorous and disastrous than they were predicted. Thus it is evident that the persistent method of short range weather forecasting suffers from the limitation of its inability to predict the enroute changes in the cyclones and the frontogenesis (formation of fronts and cyclones) and dissipation (occlusion) of storms. The **continuity method** is based on the belief that the weather occurring at upwind would continue downwind side and hence would affect the places of its onward journey, for example this method helps in tracking the thunderstorms, tornadoes, dust storms (dust devils) and other short-lived weather phenomena which have temporal and spatial dimensions of a few hours and tens of kilometer-trajectories respectively. The information for the prediction of the severity, rate of movement and likely occurrence times of such short-lived storms are obtained from geostationary and polar orbiting satellites and doppler radars.

2. **Medium range forecast** covers the time span from 3 days to 3 weeks for the prediction of weather conditions likely to occur. Though such forecasts may be very useful for general public mainly farmers but the accuracy level goes down in comparison to the short range forecasts because of inadequacy of the required information of weather conditions, mainly of upper air conditions. In fact, medium range weather forecasts are mean weather conditions for extended period based on the past and present weather conditions.

3. **Long range weather forecasts** have longer temporal range varying from a fortnight to a season or a year. Such forecasts are not, in fact, forecasts or predictions rather these are statements or estimates about temperature and precipitation for the coming couple of weaks or a season. In fact, such forecasts predict departures of temperatures and precipitation from the normal values based on past events and temperature and precipitation data. The forecasts are limited to the prediction of general weather conditions in terms of temperature and precipitation as to whether the conditions would be normal or below normal in the coming season. For example, it is predicted as to whether the south-west monsoons over India would be normal and the rainfall would be normal in relation to long range average rainfall or not or whether it would be normal, above normal or below normal. Some of the atmospheric and sea phenomena such as Southern Oscillation (SO), El Nino (EN) amd (ENSO) effects have immense impacts on global weather. El Nino and Southern Oscillation (see chapter 6 of this book) are significant parameters which are used for the prediction of conditions of S.W. monsoon mainly in terms of rainfall in Indian subcontinent.

Weather forecasts are also classified on the basis of specific purposes for different segments of the society into the following four types :

(1) Aviation forecasts,

(2) Shipping forecasts,

(3) Local forecasts, and

(4) Agriculture-based forecasts.

(1) **Aviation forecasts** involve prediction of weather conditions regarding temperature, winds, visibility, clouds, atmospheric storms (cyclones, hurricanes, tornadoes, thunderstorms), turbulence, jet streams etc. for different aspects of aviation, such as take off, climbing, flying, descent and

landing of aircrafts. (2) **Shipping forecasts** involve issue of warning about sea conditions which include temperature of sea water, nature and ferocity of sea waves (such as tidal surges and tsunami waves, as generated in the Indian Ocean on Dec. 26, 2004 due to occurrence of submarine earth quake, of 8.9 magnitude on Richter scale, off the west coast of Sumatra, which claimed more than 225,000 human lives), storms, visibility due to fogs and dense clouds, floating icebergs, tidal waves and surges etc. (3) **Local forecasts** are area-specific forecasts meant for general public and administrators wherein predictions are made about the weather conditions including temperatures, humidity and rainfall, squalls, hailstorms, snow-falls, cold and heat waves etc. (4) **Agriculture-based forecasts** are meant for farmers and include information and warning about sky conditions (whether cloudy and clear), humidity and precipitation, frosts, fogs, cold and heat spells and other information which may be useful for farming practices and different crops in various stages.

17.6 METHODS OF WEATHER FORECASTING

Weather forecasting is no doubt a significant aspect of meteorology and is directly related to atmospheric research but simultaneously it is also very complex because a host of data are required and numerous variables related to the weather are involved. The weather forecasting also involves mathematical and statistical techniques and models for the analysis of weather data. There are two methods of weather forecasting, namely (1) method adopted by the individuals on the basis of experiences, observation of sky, clouds, winds, local experiences, reactions of flora and fauna to any possible changes in local weather conditions, news from print and electronic media, weather lores and sayings etc., and (2) method adopted by professional weather forecasting services based on accurate data of weather elements collected through scientific instruments and devices. It may be mentioned that people rely more on the second method. Thus, basically there are three major scientific methods of weather forecasting which are followed by professional weather forecasting services as follows:

(1) Synoptic forecasting method,

(2) Statistical forecasting method, and

(3) Numerical forecasting method.

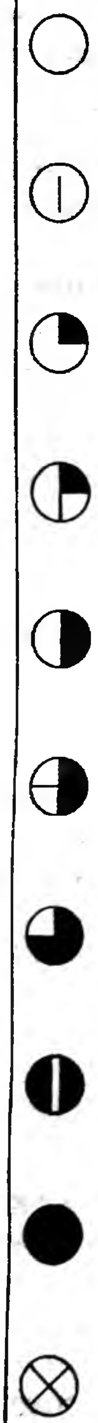
1. Synoptic Forecasting Method

Synoptic literally means 'coincident in time' in general terms but meteorologically it means overall view of weather conditions over larger area at a given moment of time. Thus, **synoptic weather** means an overall generalized picture of weather conditions covering large areas say atleast 2500 square kilometers at given moment of time. The **synoptic weather forecasting** means prediction of future weather conditions for few hours, say 12 hours or a day, on the basis of synoptic weather. The method of weather fore-casting based on synoptic forecasting is called synoptic weather forecasting method. It may be mentioned that this method was the primary method of weather forecasting upto 1950s but began to lose its significance thereafter because of availability of upper air meteorological data and application of statistical and numerical methods in weather forecasting.

The procedures of synoptic weather fore-casting involves the preparation of **synoptic chart** (weather map) of existing or current weather conditions (of the past few hours) on the basis of collected data of surface weather elements (temperature, air pressure, air circulation, wind speed and direction, humidity, precipitation etc.) and **prebartic** or **prognostic chart** and **prontours** on the basis of just prepared synoptic chart for the future projection of weather conditions for the next few hours.

Synoptic chart is defined as a chart showing distribution of meteorological conditions through well defined weather symbols on maps covering a wide region of the earth's surface at a given moment of time. 'The map of current weather is compilled from numerous data gathered from surface observations, from radiosonde determination of winds, temperatures and humidities at various heights from meteorological satellites, radars, ships and aircrafts' (J.E. Hobbs, 1980). It may be mentioned that synoptic charts or weather charts symbolise the atmospheric conditions at a

CLOUD COVER



No clouds (clear sky)
One tenth or less
Two tenths or three tenths
Four tenths
Five tenths
Six tenths
Seven tenths or eight tenths
Nine tenths or eight tenths
Completely overcast (ten tenths)
Sky obscured

WIND SPEED

Knots	Miles (statute) per hour	Kilometer per hour
Calm	Calm	Calm
1-2	1-2	1-3
3-7	3-8	4-13
8-12	9-14	14-19
13-17	15-20	20-32
18-22	21-25	33-40
23-27	26-31	41-50
28-32	32-37	51-60
33-37	38-43	61-69
38-42	44-49	70-79
43-47	50-54	80-87
48-52	55-60	88-96
53-57	61-66	97-106
58-62	67-71	107-114
63-67	72-77	115-124
68-72	78-83	125-134
73-77	84-89	135-143
103-107	119-123	192-198

Fig. 17.

Fig. 17.1 : Representation of selected weather symbols used on weather maps. Source : Compilled from different sources.

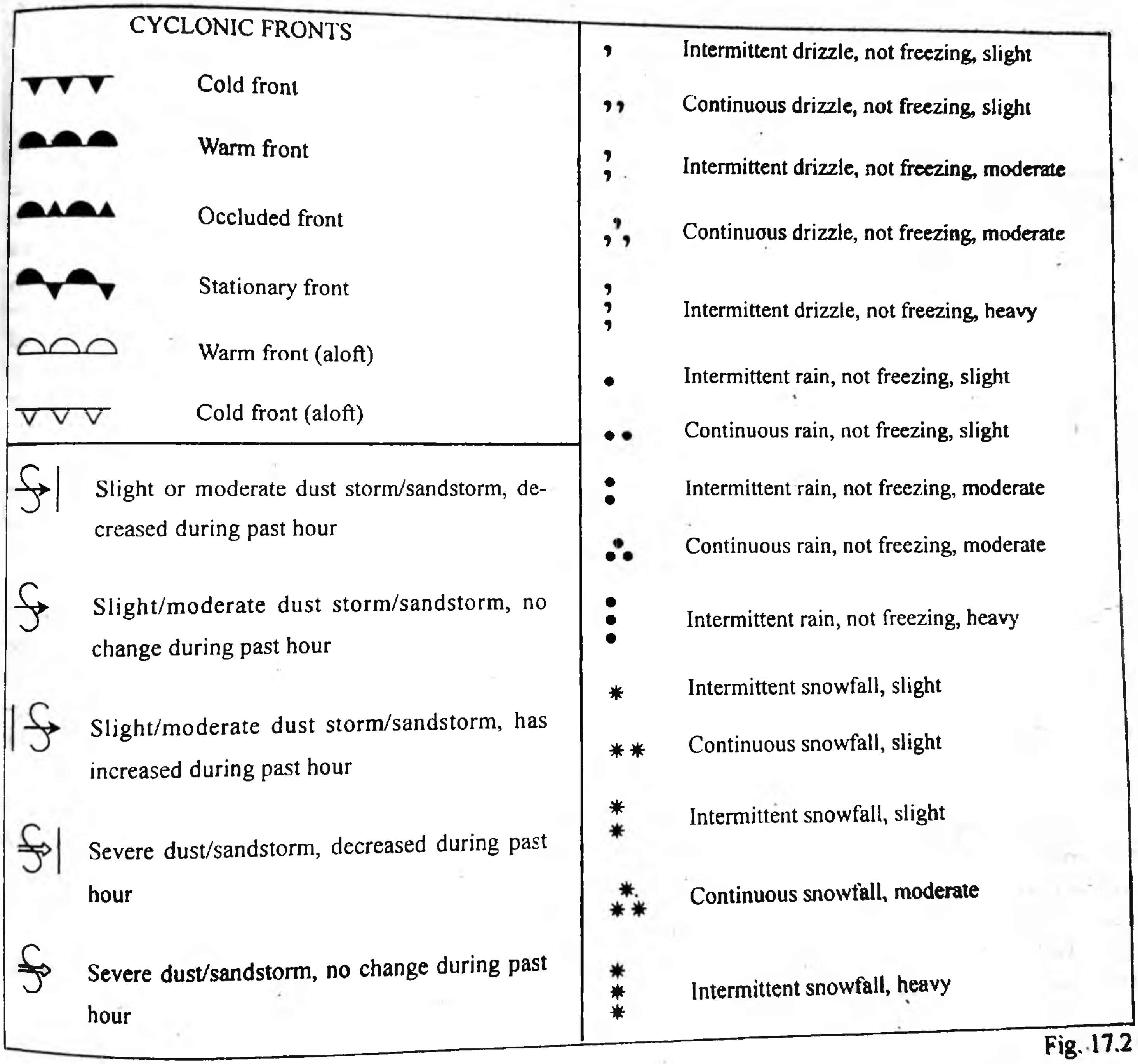


Fig. 17.2

Fig. 17.2 : Representation of selected meather symbols used on weather maps. Source : Compilled from different sources.

particular time and help in future projection (prognosis) of atmospheric conditions for limited time span ranging from a few hours to a day. Different weather elements are plotted on the maps with the help of definite symbols, lines and colours (figs. 17.1, 17.2 and 17.3). For example, the air pressure is represented through drawing of isobars in millibars (mb) having equal class intervals, troughs (V), depressions, Highs (H), Lows (L), ridges, cyclones, anticyclones, cols, cold front, warm front, occluded front, quasi-stationary front, convergence line, cloudiness, drizzle, rain, shower, snow, thunderstorms, dust storms, wind direction and speed, lightning etc. are depicted on weather maps with suitable symbols. Besides, some additional charts, very often called as ancilliary charts, are also prepared with the plotting of 'tropopause, level of maximum wind, jet streams, rainfall, dew point, maximum, minimum and gross minimum temperatures, changes and departures from normal of pressure, temperature etc. Aerological diagrams, weather radar pictures, aircraft reconnaissance reports, weather satellite imagery and other derived data etc. are also used to supplement synoptic chart analysis' (P.A. Menon, 1989). It is evident that preparation of synoptic charts provides a basis for the prognosis (prediction) of future weather conditions. It may be pointed out that a **prognostic chart** is prepared on the basis of synoptic charts for the projection of weather conditions for the next few hours. The prognostic chart projects future atmospheric conditions mainly the surface weather conditions while the charts projecting the future upper atmospheric conditions are called **prontours.**

The **prognostic** and **prontour charts** enable the forecaster to predict the future weather systems for the next few hours on the basis of the nature of past weather systems as represented on the synoptic charts in coded forms. The basis of prognosis (future prediction) is the belief that what happened during the past 24 hours may continue to occur for the next few hours. It may be mentioned that such prediction may not always be true because some changes may take place in the weather systems during next few hours. It appears that simple extrapolation of existing weather conditions for next few hours suffers from the limitation that this method does not accommodate the future changes in weather systems. Besides, the accuracy of synoptic weather forecasts also depends upon the skill and experience of forecaster. In spite of these shortcomings the synoptic weather forecasting may be accurate for the period not exceeding 24 hours. The basis of the likelihood of accuracy of such forecasting is the development of **synoptic model** which is built on the belief that weather conditions do not suddenly and randomly change as far as regular and common weather systems (such as fronts and cyclones) are concerned.

2. Numerical Method of Forecasting

The availability of huge data set about the weather elements and conditions of both surface weather and upper air weather from various sources like existing traditional instrumental sources, observed and recorded information by radiosondes, weather satellites, radars etc. necessitated the development of numerical (mathematical or physical) equations and model to predict weather conditions on the basis of analysis of such data. Such method is also called **numerical** or **quantitative forecasting.** The numerical forecasting is based on the physical principles and laws related to atmospheric gases and motions on the basic tenet that the atmospheric conditions and weather phenomena follow the **'principle of uniformitarianism'** and obey physical laws and principles. The numerical method of forecasting or numerical weather prediction (NWP) involves certain procedures which have been summarized by J.E. Hobbs (1980) as follows :

(1) The mathematical equations as mathematical models should be simplified to the maximum possible extent.

(2) 'The system of equations must be designed to guarantee the conservation of air mass, water vapour, momentum, and total energy for the entire volume for all time.'

(3) 'The spatial resolution must be selected carefully. In principle the finer the grid resolution the better, but computer limitations impose restrictions. In addition the mathematics themselves are complicated and have to deal with four-dimensional fields of data' J.E. Hobbs (1980).

The grid method is used for the collection of weather data and assignment of numerical values to

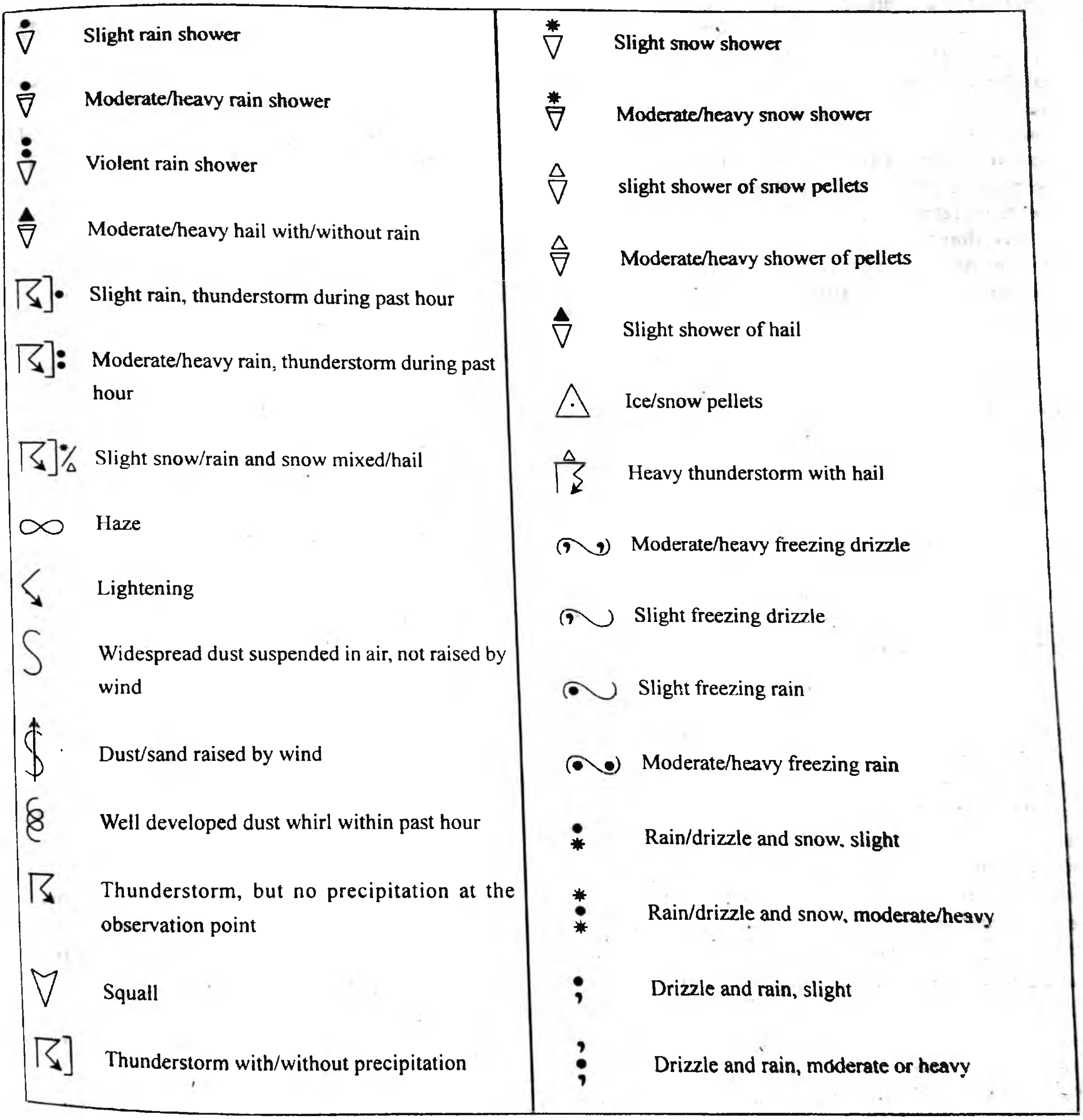


Fig. 17.3 : *Selected weather symbols used on weather maps. Source : Compilled from different sources.*

them. The fastest electronic computers are used to handle mass dataset of weather elements collected from surface and upper atmosphere and to prepare mathematical models using numerous equations related to physical laws which primarily control atmospheric motions at different altitudes or layers of the atmosphere (generally 6 to 11 atmospheric layers at varying altitudes are considered for this purpose), to compute the future state of atmospheric motions and weather conditions and finally to prepare computer-based **prognostic chart.** It is evident that numerical models are designed in such a way that they may generate prognostic charts which help in the prediction of atmospheric motions at different altitudes (layers) and weather conditions.

It may be mentioned that computer generated weather prognostic charts based on computer generated mathematical models incorporating billions of arithmetic and logical operations cannot predict the total future weather conditions alone because these are just one tool of weather forecasting. It is necessary for a weather forecaster to blend the numerical method with the traditional synoptic method for fruitful future prediction. **Secondly,** the numerical weather forecasters are also faced with the problem of availability of numerous alternative numerical methods but the result of same numerical method for the prediction of a specific weather element is not always identical and hence the forecasters have to be careful in selecting numerical methods. **Thirdly,** computer generated numerical models do not include some minor details of weather phenomena such as eddies, surface covers, topographic features etc. but such elements affect weather conditions at local level. **Fourthly,** 'many of the severe weather phenomena most important to human activity occur on space scales smaller than those that are resolved by current operational numerical models, so considerable efforts are being devoted to the development of numerical models capabable of predicting severe storms at mesoscale' (Anthes, 1976, in J.E. Hobbs, 1980). It may be mentioned that severe weather phenomena at meso spatial scale do not include only severe storms like hurricanes, tornadoes, and thunderstorms but also include dust storms, snowfall, cloud bursts, ice storms, flash floods due to continued incessant rainfall etc. **Fifthly,** the computer generated models are hypothetical and represent hypothetical atmosphere which some times deviate from real situation. The prediction of upper air circulation by numerical models is of vital significance because it helps in predicting the probable cites for frontogenesis and probable direction of the movement of cyclones. **Sixth,** the physical assumptions adopted (in numerical models) and the degree of sophistication of each physical process incorporated differ from model to model' (J.E. Hobbs, 1980).

3. Statistical Method of Weather Forecasting

Statistical method of weather forecasting cannot be separated from numerical method because the former supplements the latter but if we consider temporal scale of weather forecasting the statistical method becomes different from the numerical method because it is used for long-range forecasting i.e. more than a month in advance or a season ahead. Basically, there are two statistical approaches to weather forecasting e.g. (i) approach based on **data of past records** of weather elements mainly temperature, humidity, air circulation and precipitation, as basis for the prediction of future conditions, and (ii) **regularity** or **periodicity approach** also known as **analogue method** based on regularity or periodicity of weather conditions in the past and belief of recurrence or repetition of similar weather events in future. For the first approach i.e. **past data approach,** advanced statistical methods such as correlation, regression, factor analysis etc. are used to derive average weather conditions which may recur in future at least for a season or a year ahead. The weather events having periodicity or regularity in the past not necessarily have tendency of continuation in future but the meteorologists have found **quasibiennial oscillation** (QBO) as a significant atmospheric periodic phenomenon between tropical oceanic surface conditions and stratospheric air circulation which provides some degree of accurate forecasting of weather conditions including monsoons mainly in the tropical and subtropical regions on the basis of past periodicity of QBO. The pressure conditions in the eastern and the western Pacific and surface and upper air circulation have periodic recurrence with regularity like Southern Oscillation (SO) and Walker Circulation which combined with El Nino (ENSO) phenomena give almost correct predictivity about weather conditions in both the hemispheres in general and monsoons in particular. In the year of strong El Nino event and weak La Nina, the monsoon in south and south-east Asia becomes weak and dry conditions prevail but the eastern Pacific and the western South American coasts become exceptionally wet (see chapter 6 of this book.).

The aforesaid two statistical approaches of weather forecasting need further elaboration. (1) The **past weather data approach** is based on the inclusion, consideration and statistical analysis of (i) past data of significant weather elements such as temperature, air pressure, humidity and precipitation, surface and upper air circulation etc.; (ii) thermal anomalies over land and sea surfaces; (iii) air pressures over tropical and subtropical sea surfaces and seasonal and annual patterns of surface and upper air circulation over sea surfaces; (iv) periodicity of changes in the photosphere of the sun and sunspots; (v) the long-period records of relationships between temperatures and atmospheric circulation; (vi) seasonal behaviours of polar whirls and stratospheric jet streams; (vii) impacts of volcanic dusts and air pollution on thermal conditions and motions of the atmosphere etc. (2) **Regularity/periodicity or analogue approach** includes the consideration and statistical analysis of (i) selection of repetitive common weather events (i.e. cyclic tendencies of weather events such as floods, droughts, tornado outbreaks, severity of atmospheric disturbances such as cyclones, typhoons, hurricanes, thunderstorms etc.) and frequencies of occurrences of such events in the past; (ii) identification of recurrence intervals of some extreme weather events (such as hailstorms, hurricanes, tornadoes etc.); (iii) establishment of continuity of weather events or periodicities of cyclic patterns of such events which may have sequential tendencies of recurrence; (iv) identification of analogous weather situations which occurred in the past and at the present and future projection of occurrences of similar situations in future, in other words, determination of duplicating weather situations such as duplication of El Nino and La Nina events in the tropical Pacific Ocean bringing copious rainfall in the western coastal areas of Peru of South America (when El Nino is strong but La Nina is weak) but weak monsoon and drought in South and South East Asia.

It may be mentioned that statistical method of weather forecasting provides average picture of temperature and precipitation as to whether these will be normal, above normal or below normal because the prediction is based on statistical measures. It is also significant to point out that accurate prediction of weather and atmospheric conditions is not possible as the atmospheric processes are very complex. It is also questioned, whether the atmosphere is predictable or not? Now **computer based ensemble method** is used for ascertaining the predictability of atmospheric conditions. Thus, **ensemble weather forecasting** analyses all the weather elements together through the advanced electronic computers so that 'each part (weather element) is considered only in relation to the whole' (atmospheric condition). It is, thus, evident that for meaningful and successful weather forecasting to maximum possible extent the forecaster must take a holistic view and should blend all the existing three methods e.g. synoptic method, mathematical method (numerical method), and statistical method together.

17.7 PROBLEMS AND PROSPECTS

As stated earlier weather forecasting is still a very difficult problem because it is related to such atmospheric condition which is not static and is still not properly understood. The problems of weather forecasting are many fold, namely, (i) varying requirements of the users (farmers, general public, administrators, aviation and surface transport sectors, commerce, industrial sectors, medical professionals etc.); (2) lack of proper understanding of the state of the atmosphere and its circulation patterns; (3) scale problem, both spatial and temporal scales; (4) duration of prediction; (5) lack of basic data from many remote and inhospitable areas such as oceans, high mountains in the tropical and subtropical areas, major deserts of the world, both hot and cold deserts; (5) anthropogenic inputs of pollutants in the atmosphere which further complicate the already complex atmospheric system; (6) poor observation and data collecting network mainly from over the oceans and the southern hemisphere; (7) handling of vast weather data; (8) non-observation of some unique weather phenomena such as eddies, turbulence occurrence etc. which are very unpredictable but are significant elements to affect weather conditions at least at local level; (9) varying duration of forecasting for different purposes; (10) complexity of mathematical equations and models etc.

With continuous improvements in the methods of observations and collection of weather data, and proper hanlding and processing of these data may help in better weather forecasting in future but accurate forecasting for different purposes like short range forecasting (12 hours to one day in advance) for general public, aviation and transport sectors; medium and long range forecasting (ranging from few days to weeks, season and even a year in advance) for farmers and policy makers will always remain a teething problem. One has to strike a balance among the requirements of users, required levels of details and prediction by different users, handling and processing of data, proper knowledge of the atmospheric motions, variability of spatial and temporal scales, physical laws and use of mathematical equations.

Besides methodological advancements, the improvements in weather instruments, inventions of new weather instruments and devices, wider use of improved generations of Doppler Radar (for the scanning of the atmosphere from the surface to its upper part and preparing three-dimensional images mainly within the atmospheric storms like thunderstorms, cyclones, tornadoes etc. to detect the changing patterns of air circulation); improved Next Generation Weather Radar (NEXRAD), the Automated Surface Observation System (ASOS), Light Detection and Ranging System (LIDAR), electronic computer, etc. are expected to improve the weather forecasting in both accuracy level and time, space, and duration.

17.8 WEATHER FORECASTING IN INDIA

The weather forecasting is most desirable and significant for agriculture because more than 70 per cent Indian population is engaged in this primary sector and hence Indian economy largely depends on agriculture. The IMD (Indian Meteorological Department) handles all the processes of weather forecasting wherein attentions are paid towards 3 basic types of forecasting e.g. (i) short range forecast for next 48 hours covering mainly maximum and minimum daily temperatures, cloud covers, relative humidity and precipitation; (ii) medium range forecast from 48 hours to 10 days; and (iii) long range forecast for the next season mainly for summer monsoon season.

The IMD utilizes weather data of both ground surface (through numerous observatories located at least in each district) and upper air (through INSAT images and other devices). The short range forecasting is done by Operational Numerical Weather Prediction Method (ONWP) through the processing of collected weather data by advanced electronic computers involving statistical and mathematical equations. The weekly data of mean maximum and minimum daily temperatures, mean daily temperatures, relative humidity, wind direction and speed etc. are averaged and average weather conditions are predicted for the next 48 hours. The images provided by INSAT generations of weather satellites provide daily pictures of cloud covers, and pressure systems at different altitudes which help in predicting weather which may occur during next 48 hours.

The work of weather forecasting in India was initiated by H.F. Blandford, the first Director General of the Indian Meteorological Department (IMD) and some predictions were made about monsoon conditions from 1882 to 1885 but his predictions were based on limited information of the amount of snowfall in the preceding winter season, on the belief that the intensity of surface low pressure system in the north-western parts of the country is the main factor for making the monsoon strong or poor and this lower pressure system is directly related to the Himalayan snowfall i.e. the greater the amount and duration of snowfall in the preceding winter season, the stronger the lower pressure in N.W. India and more active monsoon and vice versa. Later on in 1888 John Elliot correlated the strength of Indian monsoon with weather elements of Australia and the pressure systems in the southern Indian Ocean. The dawn of the 20th century came with more realistic weather forecasting mainly about Indian monsoon when Gilbert Walker (1904) used multiple regression model and mathematical equations including amount of snowfall and its accumulation over the Himalayan mountains at the end of May (i.e. real snow cover, after its melting in the summer, by the end of May), spring season air pressure system in South America, May pressure system in Mauritius and the amount of rainfall in the months of April and May in Zanzibar, amount of rainfall in the month of May in Sri Lanka, Southern Oscillation Index (SOI) etc. to predict the monsoon. The **dynamic stochastic transfer model** was developed by V. Thapliyal in the year 1979 but the predictibility of Indian monsoon was still a gamble. Now the **computer model** developed by Vasant Gowariker known as **'power regression model'** uses 16 weather parameters for the prediction of Indian monsoon as follows :

1. El Nino event of the same year (i.e. the year meant for forecasting),
2. El Nino event of preceding year,
3. Temperature of the month of March over North India,
4. Temperatures of January and February over the northern hemisphere,
5. 500 hpa ridge in the month of April,
6. 50 hpa ridge trough extent in the months of January and February,
7. 10 hpa (30km) westerly wind in January,
8. Pressure systems in the northern hemisphere,
9. Southern Oscillation Index (SOI),
10. Spring season Darwin Pressure System,
11. Pressure in Argentina in April,
12. Pressure systems over equatorial region in Indian Ocean, January-May,
13. Snow covers over the Himalayas, January-March,
14. Temperatures in central India in May,
15. Temperature in the east coast of India in March, and
16. Snow covers of the preceding year in Eurasia in the month of December.

The Gowariker 'power regression model' was modified in 1989 and attempt was made to find out non-linear or curvilinear relationships by using the aforesaid 16 weather variables. It may be mentioned that the weather prediction also includes one very important but non-meteorological parameter, i.e. political parameter or say planning policy parameter. If poor monsoon is predicted by the end of May, the food grain stockists start hoarding essential food grains in their godowns and create artificial scarcity of food grains in the open market resulting into escalation of prices in the general public.

17.9 IMPORTANT DEFINITIONS

Colour lore forecasting : The weather prediction based on the perception of colours of the sky (besides natural blue colour), rainbow, halos around the moon, coronas of the sun, clouds etc. as folk lore or sayings is called colour lore forecasting.

Continuity method : The weather forecasting based on the belief that the weather occurring at upwind would continue downwind side and hence would affect the places ahead is called continuity method of weather forecasting.

Geosynchronous satellites : The satellites positioned over the earth's equator having the same rate of movement around the earth as that of the rotational speed of the earth at its equator so that the satellites orbiting around the earth are always positioned over the same location on the earth's surface, are called geosynchronous or geostationary satellites.

Persistent method : The weather forecasting based on the basic tenet that the existing rate of the movement of cyclonic front will continue for a couple of hours and the fronts or the storms would affect the place which is located ahead of present position is called persistent method of weather forecasting.

Prognostic chart : The weather chart prepared on the basis of synoptic charts for the projection of weather conditions for the next few hours is called prognostic chart.

Prontours : The synoptic charts projecting the future upper air atmospheric conditions are called prontours.

Radiosonde : 'Radiosonde is an instrument that is carried aloft by a baloon to send back information on temperature, pressure, and humidity by means of a small radiotransmitter' (Webster Dictionary).

Synoptic chart : Synoptic chart is defined as a chart showing distribution of meteorological conditions through well defined weather symbols on maps covering a wide region of the earth's surface at a given moment of time.

18

APPLIED CLIMATOLOGY

18.1 INTRODUCTION

The applied climatology may be very crudely defined as the study of impacts of weather and climate on all biota (including plants and animals) in general and human beings in particular on one hand, in turn the influences of human activities on different components of weather and climate whether effected advertently (e.g. weather modification programmes) or inadvertently such as atmospheric pollution through various sources resulting into changes in weather and climate on the other hand (Savindra Singh 2004). The evolution and sustenance of different forms of life in the biospheric ecosystem has always been controlled by environmental systems of different orders. The environmental system consists of three basic components e.g. physical or abiotic components, energy component, and biotic components (plants and animals). The abiotic components consist of three major components such as land, air and water where these three represent lithosphere, atmosphere, and hydrosphere respectively. It is, thus, evident that the weather and climate are significant aspects of atmospheric system. It is also proven fact that weather and climate have always determined and controlled human activities, human health, thoughts and ideologies, culture and civilization and hence it becomes imperative to discuss certain aspects of close relationships between weather and climate and human health and activities and other significant aspects of the biosphere (the life layer, which is a **biological furnace** because it is the biosphere which with the varying combinations of land, air and water, houses different biological species including man in varying ecosystems), such as climate and biosphere, climate and urban planning, climate and weather modifications, climate and transport, climate and industry, climate and culture, climate and recreation and tourism, climate and transport system.

Definition and Scope of Applied Climatology

The field and scope of applied climatology are so vast that it becomes difficult to include all such aspects which relate climate to social and economic spheres of human society on one hand and other organisms on the other hand. In fact, the scope of applied climatology has been unnecessarily broadened and stretched. The scope needs to be strictly defined in narrower terms to make this branch of climatology more impressive and practicable. The following definitions give some insight of applied climatology.

(1) Applied climatology is the scientific analysis of climatic data in the light of useful application for an operational purpose.

— H. Landsberg and W.C. Jacobs, 1951

(2) Applied climatology may be defined as the use of achieved and real-time climatic information to solve a variety of social, economic and environmental problems for clients and managers, in fields such as agriculture, industry and energy.

— K. Smith, 1987

(3) 'Applied climatology is the scientific use of climatic data and theoretical constructs for the solution of particular problems.'

— G.A. Marotz, 1989

(4) 'Applied climatology is one of four major subgroups of climatology together with climatography, physical climatology and dynamic climatology'. — J.E. Oliver, 1981

(5) According to J.E. Hobbs (1997) 'the field of applied climatology can then the considered to encompass four broad groups of problems, as follows :

(a) Design and specification of material or equipment.

(b) Location and use of equipment or structures.

(c) Planning of a particular operation.

(d) Climatic influences on biological activities.'

(6) 'The applied climatology may be very crudely defined as the study of impacts of weather and climate on all biota (including plants and animals) in general and human beings in particular on one hand, in turn the influences of human activities on different components of weather and climate (such as weather modification, global warming and climate change) whether effected advertently or inadvertently such as atmospheric pollution through various anthropogenic sources resulting into changes in weather and climate on the other hand.

— Savindra Singh, 2004

(7) S.A. Changnon (1995) has presented a model to highlight the field of applied climatology. His model consists of inner core, inner ring, and larger outer circle which includes the nature of activities and study as follows.

(A) **'Inner core** : represents the basic component of applied climatology wherein the processes of climatic data collection, processing, assessment and maintenance of such data are considered :

(a) selection of appropriate meteorological instruments,

(b) collection of meteorological data,

(c) transmission of data to various stations and storage centers,

(d) quality assessment of data,

(e) spati..l and temporal representativeness,

(f) archival storage of data, and

(g) accessing of data.

(B) **Inner ring :** mainly related to analysis and interpretation of meteorological data and derivation and generation of useful information related to weather and climate in spatio-temporal context from the climatic data core.

(c) **Outer circle :** The larger outer circle of the field of applied climatology represents the third phase wherein the application of climatic information is given importance. This circle includes different types of users of climatic data and information, such as scientists, engineers, business community, farmers, people involved in recreation and tourism industry etc. in different fields of science such as 'hydrology, agriculture, ecology, geography, energy supply, architecture, transportation, leisure and recreation, tourism and government' (J.E. Hobbs, 1997).

The applied climatology is of recent origin as this term was commonly used in the decade 1941-1950 as claimed by K. Smith (1987). It was soon realized that the use of climatic data and their interpretation in different fields of human activities and other sciences as enumerated above may be more fruitful and hence the importance of this branch of climatology gained currency and received more scientific attention resulting into widening and strengthening its scope in the decade 1951-1960. Now, applied climatology has become more popular and useful due to 'the development of specific skills and techniques using modern methods of data handling linked with improved understanding of statistical theory, particularly as related to extreme (weather) events and probability analysis' (J.E. Hobbs, 1997).

18.2 CLIMATE AND BIOSPHERE

The biosphere is a life supporting layer which surrounds the earth and makes plant and animal life possible without any protective device. The biosphere consists of all the living organisms (the biotic component), energy (the energy component) and abiotic or physical environment (abiotic component) and there are continuous interactions between living organisms and physical environment and among the living organisms themselves. Thus, these three components are mutually interdependent and are interrelated through a series of large-scale cyclic mechanisms which make the input-output mechanism efficient and effective in the biosphere. The atmospheric processes mainly precipitation and resulting water, solar energy, and atmospheric gases (significant weather and climatic elements) are responsible for this large-scale input-output mechanisms through biogeochemical cycles which make the circulation of matter effective in the biospheric ecosystem. Thus, climate affects and controls major and minor components of the biosphere and various physical, biological, and chemical processes which make the biospheric ecosystem as functional system. A few relationships between climate and biospheric components and processes need elaboration such as climate and soils, climate and soil erosion, climate and energy flow and biogeochemical cycles, climate and physical processes, climate and biological processes, climate and ecological productivity etc. as follows :

1. Climate and Soil

The soil is, infact, the very heart of the life layer, known as biosphere, because it represents a zone wherein plant nutrients are produced, held, maintained and are made available to plants through their roots and to the micro-organisms which live in the soils. The soil zone is considered to be a great **biological factory** because (i) the soil layer functions as a medium for the transfer paths of energy and matter and helps in the biological cycling of nutrients; (ii) a great varieties of organic compounds are generated in the soil layers; (iii) the soil layer provides habitat and ideal environmental conditions for living organisms of several varieties and numerous species in its different horizons; (iv) this is the soil layer where organic materials derived from plants and minerals derived from the parent rocks are disintegrated and decomposed and are changed into elements; (v) necessary nutrients are made available to plants from the soil layer; (vi) soil layer holds water in storage which is used by plant and animals etc. It may be mentioned that the formation of soils is the functions of climate because the breakdown of rocks by decomposition and disintegration leading to the formation of soils is triggered by different combinations of temperature, humidity, atmospheric oxygen (oxidation) and carbon dioxide (carbonation), frost (congelifraction) etc.

The composition of soils is generally studied through its vertical sections which are termed as **soil profiles** and these extend from the ground surface down to the unweathered parent rocks. The entire vertical section of soil layer from the uppermost stratum of plant community down to the basal weathering surface consists of two major zones e.g. (1) vegetation zone, and (2) soil zone. The soil zone consists of two layers or sub-zones, namely (1) the **solum** which contains loose unconsolidated weathered materials, organic matter and living organisms, and (2) **sub-soil zone** which contains inorganic matter and uninhabited weathered rocks known as **regoliths**. There are four major components of soil system, such as (i) flora and fauna and organic matter, (ii) inorganic minerals, (iii) soil solution, and (iv) soil atmosphere.

It is the soil solution which makes the process of **root osmosis** functional because plants take nutrients in solution form through their roots from the soils and it is the presence of water in the soils which makes the nutrients in solution form. The water reaches the soil zone through infiltration of rainwater or meltwater. The amount of water held by the soils is determined by the rate of infiltration of rainwater and meltwater and the water retention capacity of soils. The clay soils, loam soils and sandy soils account for low, moderate and high rate of infiltration respectively. On the basis of amount of water retained in the soils with respect to soil volume three stages of the proportion of soil matter, soil water and soil air can be identified e.g. (1) **saturated stage,** when all the voids and pores within the soils are filled with water, the saturated soils cannot hold further addition of water and thus there is **through flow** of water; (2) **field capacity stage,** when fifty percent of the total voids and pore spaces are filled with water and the remaining 50 per cent are occupied by air; and (3) **wilting stage,** when soil water is lost through continued evaporation, evapotranspiration, uptake of water by plant roots etc. and thus no further water is available to soil organisms including plants.

The **soil atmosphere** component of the soil system includes the consideration of the presence of different gases and air, the movement of air within the soils and temperature distribution. It is important to note that there is variation in the proportion of oxygen and carbon dioxide of the aboveground atmosphere and the soil atmosphere as is evident from table 18.1

Table 18.1 : Composition of soil and aboveground atmosphere (in percent by volume)

	Oxygen	Carbon dioxide	Nitrogen	Water Vapour
1. Above-ground Atmosphere	20.97	0.03	79.00	<100
2. Grassland Soil	18.40	1.60	79.2	
3. Arable soil	20.70	0.10	79.2	Frequently 100

The concentration of CO_2 in the soil atmosphere is several times higher than the natural concentration of CO_2 in the above-ground atmosphere. This difference of carbon dioxide between the soil atmosphere and above-ground atmosphere is because of the fact that there is a continuous production of carbon dioxide due to decomposition of organic matter by the microscopic organisms in the plants through respiration and thus there is gradual depletion of soil oxygen (O_2) with the increase of soil organisms. The ratio between CO_2 production and O_2 consumption depends on a variety of factors e.g. the amount of moisture in the soil, soil temperature, the rate of decomposition of organic matter by the decomposers, the activities of organisms and plant roots in the rhizosphere or rootsphere etc. There is inverse relationship between the amount of soil water and soil air. If there is minimum amount of water in the soils (wilting stage), there is maximum air in the soil (the stage of well aerated soil or aerobic stage of soil). Contrary to this, if there is maximum amount of water in the soil (saturated stage) there is minimum air in the soil (the stage of poorly aerated soil or **anaerobic** stage of soil environment). Thus the $CO_2 : O_2$ ratio in the aerobic soils is around 1 because plants consume maximum amount of oxygen but the $CO_2 : O_2$ ratio becomes more than 1 in the anaerobic soil because due to excess water plants are unable to consume required amount of oxygen as their respiration is retarded.

Besides oxygen, a few more gases are evolved due to decomposition of organic matter by the decomposers e.g. methane, ethylene, sulphides etc. It is evident that the water-air ratio in the soils is very crucial factor for the survival and growth of soil organisms particularly plants because abundant oxygen is required by the plant roots for the proper growth of vegetation. If the soils continue to be wet and over-saturated for longer period the amount of air present in the soil becomes minimum and therefore the respiration by plants is retarded, with the result several plants die.

The soil temperature is very important factor for the growth of soil organisms. It is affected by a host of factors e.g. horizontal distribution of insolation and ground temperature from equator towards the poles, shades of vegetation, flux of heat energy into the soil, exchange of heat between the soil and air, retention power of heat by a given soil type, diffusion of heat by the soils, presence of organic matter in the soils etc. Soil temperature largely controls the activities of micro-organisms, enzyme activity and the biological processes that regulate plant growth e.g. seed germination, root osmosis etc. The decomposition of organic matter by the decomposers (microbes) and mineralization of the soils are directly related to temperature i.e. decomposition and mineralisation increase with the increase of soil temperature. The decomposition of organic matter is considerably slowed down when the soil temperature falls below 10^{0}C. Thus the organic matter is least decomposed in the colder regions and consequently there is greater accumulation of organic matter. Contrary to this, there is maximum decomposition of organic matter in the humid tropical areas and more and more nutrients, resulting from the decomposition of organic matter.

Soil forming processes, which include (1) soil enrichment, (2) losses from the soils, (3) translocation of materials, and (4) transformation of materials, are largely controlled by climatic conditions of area concerned. Out of these four soil forming processes 2nd and 3rd processes (i.e. losses from the soils, and translocation of materials) are directly determined and controlled by climatic elements.

The loss of materials of the soil body includes (i) loss of surface materials through lateral movement of water (the resultant of precipitation—rainwater and snow-meltwater) and hence lateral displacement of materials by surface runoff, (ii) loss of radiation energy (heat) through evaporation and loss of water from plant leaves through transpiration, (iii) loss of gases (loss of nitrogen through the process of denitrification), (iv) removal of soil materials through lateral drainage of water within the soil profile, (v) loss of surface materials both organic and inorganic (minerals) from the soil surface to the lower horizons through the process of **leaching** or **eluviation** (downward movement of water, dissolved and suspended organic and inorganic materials).

Translocation of soil materials, triggered by water which is a significant climatic component, involves two types of vertical movements in the soil profile e.g. (1) upward movement (capillary action), and (2) downward movement (**leaching or eluviation**). These vertical movements of soil materials take place through water when ground surface is level but when the ground surface is sloping, lateral movement is more dominant. The process of eluviation involves the downward movement of fine particles (both mineral and organic from the upper soil horizon mainly A_2 horizon) with percolating water. Thus, due to transfer of fine particles downward coarse particles are left in the upper soil horizon. These skeletal mineral grains left behind in the A_2 horizon include quartz and silica. The increase in the content and proportion of silica in A_2 horizon is called **silication.** The process of illuviation involves accumulation of materials (removed from the upper soil horizons and moved downward) in the lower soil horizons mainly B horizon. Such materials include clay particles, organic matter (humus) or sesquioxides of iron and aluminium. The process of **decalsification** removes calcium carbonate due to reactions of carbonic acids with carbonate mineral matter in the upper horizon under the broader process of eluviation (removal of materials). The accumulation of carbonate minerals in the B horizon of **illuviation zone** is called **calcification.** The **desalinization** removes salts whereas **salinization** causes precipitation of soluble salts.

Climate plays an important role in the **formation of soils.** The major soil forming factors include (1) climate, (2) biotic factors or organisms, (3) relief or topographic factors, (4) parent materials, and (5) time. The soil forming factors have been expressed in the form of the following equation by H. Jenny (1941) ·

Soil is the function of climate, organisms, reliefs, parent materials and time as follows :

$$S = f(cl, o, r, p, t \ldots)$$

Where S = soil
f = function of
cl = climate
o = organisms
r = relief or topography
p = parent material
t = time

Dots in the equation are meant for the inclusion of other factors which may be of the local importance.

Climate affects the moisture content of the soils and temperature which in turn affect the soil forming processes. In fact, the properties of soils are largely determined, affected and controlled by the amount of soil water and the movement of water in different horizons of soil profile. The downward movement of water helps in the formation of soil horizons through the process of **eluviation, illuviation, humification** and **mineralization** of organic matter, as elaborated earlier. In the areas of heavy rainfall (e.g. humid tropics) the amount of soil water increases enormously which leads to greater amount of dissolution of soluble elements, transfer of these dissolved materials from the surface horizon, increase in eluviation (leaching), decrease in pH level and therefore increase in the **acidification** of soils. In fact, **leaching** is a process of removal of soluble materials, both organic and inorganic in solution form, whereas the **eluviation** is a process of downward movement of leached materials, and both the processes make the upper horizon of soils poor in soil nutrients.

The temperature largely affects the rates of chemical, physical and biological reactions within different horizons of soil profile. The rise in soil temperature accelerates the speed of chemical reactions and biological decomposition in warm and humid climates. The combination of temperature and moisture of soil affects the rate of chemical weathering and bacterial activity. For example, clay proportion and decomposition of organic matter by bacteria greatly increase in the regions characterized by high temperature and high humidity(warm and humid tropical climate). Climate affects surface materials through weathering and erosion and parent rocks through weathering mainly chemical weathering. It may be mentioned that it is the weathering of parent rocks which leads to the formation of soils.

Climate also determines soil types and their distributional patterns in the world because the soil forming processes regionally vary with spatial variations in climatic conditions. This is why the Russian geologist, V.V. Dokuchaiev, related the formation and development of soils to climate and vegetation (both are mutually inter- dependent and interactive) of a given region. Thus, the Russian pedologists based their classification of soils on the association of soil types with the climatic and vegetation zones in early 20th century. The classification of world soils into 3 broad categories of (i) zonal soils, (ii) intrazonal soils, and (iii) azonal soils is primarily based on climate and vegetation characteristics. E. Bridges also presented classification of world soils into soil types zones at global level on the basis of bioclimatic zones. It may be highlighted that the spatial patterns of soil forming processes, physical (structure, texture, colour etc.) and chemical and organic matter etc. are determined by different weathering mechanisms of parent rocks (it may be mentioned that it is the weathering of parent rocks which forms soils) which in turn are determined by spatial patterns of climatic conditions. For example, soil formation is exceedingly slow in cold climate of tundra region due to very low temperature (most part of the year is characterized by subzero temperature, snow covered ground surface and poor vertical drainage (of water) with the result the soils are very thin and very low in pH level (acidic soils). Cold forest soils of light colour are formed in taiga climatic region because of relatively better vertical drainage, longer period of sunshine (than tundra region) and moisture surplus(due to least evaporation as the temperature is not so high). In the regions of warm temperate regions having deciduous and mixed forests and continental climate less acidic soils are formed due to less effective leaching process. With rise in temperature and moisture contents equatorward leaching becomes active and acidic soils are formed. The humid subtropical climate allows effective decomposition of organic matter and leaching of soluble materials resulting in the formation of more acidic soils (with lower pH value). The bacterial activity, chemical actions and leaching processes are most activated due to high temperature and high humidity throughout the year in humid tropical climates resulting into the formation of soils having low humus content, rich in iron and aluminium contents while the soils formed in drier regions are alkaline (high pH level) and less acidic. Light coloured soils with high concentration of alkaline compounds, and low organic matter are formed in the steppe (grass land) climate.

Climate in association with relief and topography also affects soil forming processes and soil properties because topography determines through its slope the nature of drainage. and erosion by surface runoff, the resultant of rainfall, which in turn affects the soil forming processes and therefore the properties of the soils of a given locality. The flat upland surface is characterized by ideal drainage and least erosion and therefore well leached thick soils are formed whereas flat but lowland surfaces are characterized by poor drainage (rather waterlogging) and hence thick gleyed soils are formed. The topography with moderate to steep slope allows more erosion and hence the soil never becomes mature and soil profile is not developed.

2. CLIMATE AND SOIL EROSION

Erosion is a comprehensive natural process of detachment and removal of loosened rock materials and soils by exogenetic processes such as running water, ground water, sea waves, winds etc. Erosion caused by natural processes without being interfered by human activities is also called **geological erosion** while **accelerated erosion** refers to the increased rate of erosion caused by human activities like land use changes. The **soil erosion** normally means accelerated erosion or **man-induced erosion** because of greater impact of human activities than natural factors on soil erosion.

Soil erosion involves mainly two processes e.g. (1) loosening and detachment of soil particles from soil mass, and (2) removal and transport of detached soil particles downslope (if the soil erosion is being effected by raindrops and overland flow on the soils developed over hillslopes), downstream (when the soil erosion is effected by rills and gullies), or downwind (in the case of soil erosion through deflation by wind).

Two types of soil erosion have been identified by L.D. Mayer and W.H. Wischmeier (1969) on the basis of the impact of raindrops on soil surface and the action of runoff on a hillslope having thin to thick veneer of soil, namely, (1) **transport limited soil erosion**, and (2) **detachment limited soil erosion.** The transport limited soil erosion refers to such soil erosion when the soil erosion equals the rate of transporting capacity of the agents of transport e.g. rainfall and runoff while 'detachment limited soil erosion' refers to such soil erosion when the rate of soil erosion (detachment of soil mass) is less than the transporting capacity of the transporting agents. The soil eroding mechanisms include splash erosion, surface wash, sheet erosion, rill and gully erosion etc.

Different forms of soil erosion are related to raindrops, surface runoff, overland flow and surface water (all are the ingredients of precipitation) under varying climatic conditions. Climate and geology play most significant role in affecting soil erosion. Intensity, amount and duration of rainfall are determined by climate and these in turn determine the nature and characteristics of natural vegetation of the region concerned. Vegetation, in turn, also affects different parameters of rainfall. It may be mentioned that the vegetation is dependent on climate and soil characteristics (both physical and chemical) are dependent on climate, vegetation and regional geology.

The soil erosion is the function of erosivity and erodibility of soils as follows :

$$SE = f(\text{Eros. Erod.})$$

Where SE = soil erosion

Eros = soil erosivity

Erod = soil erodibility

Soil erosivity is defined as the potential ability of processes (such as raindrop, running water in the form of runoff and overland flow) to cause erosion of soils in certain set of climatic conditions. **Soil erodibility** refers to the resistance of soil erosion or its vulnerability to soil erosion. The factors which affect soil erosion include climate, topography, rock type, vegetation, soil character and human activities. The following equation may be developed including all the factors of soil erosion and previous soil erosion equations such as (i) universal soil loss equation, (ii) the equation of soil erosion developed by FAO (Food and Agriculture Organization) etc.

$$E = f(C, T, R, V, S, H)$$

where E = soil erosion

f = function of

C = climate (rainfall factors, quantity, intensity, energy and distribution of rainfall)

T = topography including steepness and slope length factors

R = rock type

V = vegetation

S = soil character (physical and chemical properties), soil erosivity and soil erodibility.

H = human activities (land use changes, farming and building activities, cropping and management factor, conservation practice factor etc.)

Climatic factors influencing soil erosion include variants of rainfall (raindrops, amount and intensity of rainfall, runoff, rainfall duration etc.), humidity, temperature and wind (speed and direction). In fact, the intensity, amount (quantity), duration and distribution of rainfall are the most important components of rainfall factor which determine the nature and magnitude of soil erosion most. Large amount of rainfall (due to persistence of rainfall for relatively longer duration) with high intensity causes maximum soil erosion if other factors also favour soil erosion but high intensity of rainfall for short duration (and hence low amount of total rainfall and poor runoff) causes little erosion of soils. The magnitude of soil erosion caused by rainfall erosivity parameters is dependent on surface covers, whether vegetated or open. Vegetation determines infiltration-runoff ratio which ultimately determines the nature and magnitude of soil erosion. Overland flow is generated when rainfall intensity (rainfall intensity means total amount of rainfall received per unit time mainly per hour) exceeds infiltration rate (amount of rainwater percolating into soil horizons or ground surface per unit time). According to N. Hudson (1971) and M.A. Morgan (1969) rainfall intensities may go upto 225 mm per hour whereas infiltration rates range between very low value of 2mm to very high value of 250 mm per hour in different regions having varying climatic and environmental conditions. Densely vegetated, mainly forested, areas allow maximum infiltration of rainwater because it reaches the ground surface very slowly in the form of **aerial streamlets** through the branches and stems of trees and thus the resultant runoff and overland flow is either absent or is insignificant and hence soil erosion is negligible. On the other hand, bare arable soils generate maximum overland flow and allows least infiltration of rainwater because of less compaction of soils caused by the use of agricultural equipments. This results in maximum erosion of soils which are exposed to falling raindrops in the absence of any vegetation.

The **terminal velocity of rain drops** (the constant velocity of falling raindrops, known as terminal velocity, is the result of equilibrium between the gravitational force and frictional resistance of the air) depending upon size, density and shape of raindrops affects the nature and magnitude of soil erosion. On an average, the terminal velocity of raindrops increases as the size of raindrops increases. The standard large natural raindrops with diameter of about 5 mm have terminal velocity of about 9 meters per second. The momentum of falling rain, known as **kinetic energy** or **rainfall energy** is closely related to the intensity of rainfall. The kinetic energy of rain determines the power of raindrops to break down soil aggregates, to splash these split aggregates, to cause turbulence in surface runoff to carry away soil particles etc. The raindrops having high kinetic energy resulting from high intensity rainfall detach soil particles from the aggregated mass at faster rate. Such type of soil erosion is called **raindrop erosion** which is the most significant process of soil erosion on exposed soil surface. The surface runoff, having far less kinetic energy than falling raindrops, transports the detached soil particles occasioned by raindrop erosion or **splash erosion.** Raindrop erosion or splash erosion also helps in compacting the soil surface and plugging or sealing the pore spaces within the soil with finer particles such as clay. This compaction of soil surface reduces the infiltration capacity and increases surface runoff.

The kinetic energy or simply rainfall energy resulting from rainfall intensity also determines the rate of detachment of soil particles. High-intensity rainfall has high erosive power because of high resultant kinetic energy whereas low-intensity rainfall has low or little erosive power. Temperature also affects, though indirectly, the nature and rate of soil erosion mainly by wind. Alternate wetting and drying of soils causes hydration and dehydration of thin soil layer having montmorillonites. This process causes expansion (due to wetting and hence hydration) of soil particles which weaken the soils and develop myriads of tiny cracks in the outer surface of the soils. These are filled with water during the next rains and thin layer of the soils becomes as soft as curd and slump down to be removed by surface runoff. Such mechanism of soil erosion becomes more effective and operative in those tropical and subtropical areas which are characterized by wet and dry seasons. Wind becomes more effective agent of soil erosion in the arid and semi-arid regions during dry season of temperate climate. Wind also deflects raindrops and reduces (in the case of high speed wind) kinetic energy of raindrops.

'Rainfall erosivity involves energy expenditure for breaking down soil cohesiveness, splashing the particles as well as entraining them in overland flow. The most critical property of rainfall erosivity is kinetic energy' (Jeje, 1986). Several investigators have related rainfall parameters to soil erosion in different parts of the world having varying climatic conditions and land uses but the results do not reveal any relationship between regional patterns of soil erosion and climatic types.

The study of correlation (table 18.2) between soil erosion (1991-1994) and rainfall erosivity parameters e.g. total amount of rainfall, rainfall duration, rainfall intensity (mm/hr), runoff, discharge etc. in the riverine cultivated gullies located in Deoghat area of Allahabad district, Uttar Padesh (India) representing intervening zone between the Ganga plains and Rewa plateau (Madhya Pradesh) having subtropical monsoon climate by Savindra Singh et al (2002) revealed the fact that runoff is the most significant predictor of soil erosion in both cultivated and non-cultivated (covered with thin vegetation cover) gullies as it explains 70.39 to 87.79 per cent variance except for the year 1991 and has the highest values of correlation coefficients (r = 0.839 to 0.937) in relation to soil loss. Runoff parameter is followed by discharge factor in relation to soil erosion predictor as the coefficients of correlation ranged between 0.713 and 0.929 during 1992-94 except the year 1991 (r= 0.219). Rainfall amount emerged as the third significant rainfall erosivity parameter of soil erosion in the hierarchical order. Rainfall intensity and rainfall energy (kinetic energy) indices (e.g. EI 30', EI 15', KE>25 etc.) have proved to be insignificant erosivity parameters as these, when correlated with soil erosion, yielded very poor correlation coefficients and in some cases negative correlations were obtained.

Table 18.2 : Hierarchical orders of correlation (r) between soil loss and soil erosivity parameters

Parameters	Coefficients of correlation (r)			
	1991	1992	1993	1994
Runoff	0.425	0.839	0.883	0.937
Discharge	0.219	0.713	0.808	0.929
Rainfall amount	0.485	0.508	0.878	0.502
Rainfall intensity (mm/hour)	–0.185	–0.064	0.304	0.356

Source : Savindra Singh and Alok Dubey, 2002.

On the other hand L.K. Jeji (1986) found peak intensity, AI 15', EI 30', EI15' and KE>25 rainfall energy (kinetic energy) indices as good predictor of soil loss as he obtained correlation coefficients between 0.56 and 0.87 for soil loss from bare, cultivated and forested erosion plots in southern Nigeria.

Climate and regional patterns of soil erosion : It may be mentioned that the rate of soil erosion (both natural and man-induced) varies considerably from one climatic region to the other climatic region. Even in single climatic region there is considerable variation in the rates of soil erosion because of the complexity of the climatic and non-climatic factors which control soil erosion. For example, it has been estimated that the average rate of soil erosion on agricultural land in the USA is about 30 tonnes per hectare per year but strip mining often gives rise to tremendous increase in erosion activity in the region having almost uniform climatic conditions. For example, in a mining district of southern Kentucky (USA) an annual sediment yield of more than 10,000 tonnes per square kilometer was recorded but undisturbed watersheds in the same area yielded only about 10 tonnes per square kilometer per year (Nature and Resources, Vol. 19, No. 2 1983) while the climatic conditions are the same. It has been reported that soil erosion during the constructional stages in the urban areas increases 20,000 to 40,000 times more than the normal rate of soil erosion in the undisturbed natural areas. The rate of soil erosion of 34,0000 tonnes per square kilometre per year has been reported from Central China. A study by Savindra Singh and S.P. Agnihotri (1987) has shown that the rate of soil loss by rill and gully erosion in the intervening zones between the Ganga plain and the foreland of Peninsular India is 2.35 million cubic metres per year in Jawa Block of Madhya Pradesh (India).

Soil erosion caused by agricultural practices and extensive deforestation, clearance of grassland covers and overgrazing has assumed alarming proportion in tropical, subtropical and semiarid (savanna) regions undermining climatic variations. Extensive deforestation in the tropical evergreen rainforests has immensely damaged the physical and chemical properties of soils and has accelerated soil erosion by many folds. According to the report of the study of runoff and erosion under various covers of vegetation (viz. forest or ungrazed thicket, crop and barren soil) in five locations of Upper Volta (Ouagadougou), Senegal (Sefa), Ivory Coast (Bouake and Abidjan) and Tanzania (Mpwapwa) in tropical region of Africa (as reported by A. Goudie, 1984) the mean annual runoff is 0.9 per cent, 17.4 per cent and 40.1 per cent of the total mean annual rainfall for forest or ungrazed thicket cover, agricultural fields and barren soil respectively. It is apparent from the above recorded data that mean annual runoff increases considerably from forest cover to barren soil. The rate of soil erosion also increases in the same direction but at much faster rate. The study shows that the average rate of soil erosion in the forest or ungrazed thicket cover, agricultural fields and barren soils in the aforesaid five locations of four tropical African countries is 0.09,28.8 and 69.1 tonnes per hectare per year respectively. Thus it is apparent that the rates of soil erosion ircrease from minimum rate of 0.09 tonne per hectare per year in the forested cover to 320 times under crop covers and 768 times under bare soil conditions. These figures clearly demonstrate the dominant role of man in accelerating the rate of soil erosion through his various activities mainly deforestation and agricultural practices and making rainfall erosivity parameters more effective.

The areas of deforested mountain slopes with steep gradients and semi-arid savanna lands of East Africa having seasonal regime of rainfall (during summer months) are the regions of most severe soil erosion caused by varied land use practices such as (i) extensive deforestation, (ii) overgrazing, (iii) over cultivation, (iv) excessive collection of firewood and (v) excessive burning of grass land, woodland and forest. The temperate grasslands have also been converted into extensive agricultural regions and thus are prone to excessive soil loss. The problems of accelerated soil erosion have been reported from different grassland biomes of the temperate grasslands of the world viz., steppes of Russia, prairies of Canada and the U.S.A. pampas of South America, Veld of South Africa and Downs of Australia. The studies of soil erosion and sediment yields under various land uses in the northern Mississippi, the U.S.A. (as reported by A.N. Strahler and A.H. Strathler, 1976) denote the fact that the surface runoff decreases considerably from cultivated crop fields (40 cm per year) through grazed pastures (38 cm per year), abandoned fields (18 cm per year), depleted hardwood (13 cm per year) to pine plantation (only 2.5 cm per year). It is evident from the above information that increasing vegetation cover from shrubs to forests increases infiltration of rainwater considerably and thus surface runoff is reduced markedly. This trend of increasing surface runoff from forest cover to cultivated crop fields is also closely reflected in the increasing rate of soil loss and sediment yield in the same direction as average annual soil loss and sediment yield increases from the minimum value of 0.05 metric ton per hectare for pine plantations through depleted hardwoods (0.2 metric ton per hectare per year), abandoned fields (0.3 metric ton per hectare per year), grazed pastures (36 metric tons per hectare per year) to very high value of 500 metric tons per hectare per year from the cultivated crop fields. It appears from the above statements that the rate of soil loss and sediment yield from cultivated crop fields is 1000 times greater than the rate from forested areas. This clearly demonstrates the dimension of impact of human activities on rainfall erosivity factors (accelerated) and hence on soil loss and sediment yield.

The studies of soil erosion under various land uses in eastern England (R.P.C. Morgan, 1973-75) also indicate much difference in the rates of soil erosion under different land use categories having similar climatic conditions. For example, the rates of soil loss over top slope, midslope and lower slope segments of bare soil cover are 7.10, 17.69 and 15.02 tons per hectare per year respectively. On the other hand, annual rate of soil loss is almost negligible in the areas of grassland covers (ranging between 0.17 to 0.68 ton per hectare per year) and forest covers (annual erosion rate ranging between 0.008 to 0.012 ton per hectare per year).

Extensive deforestation and overgrazing have led to serve soil loss in the monsoon lands of Asia in general and India in particular. The rill and gully erosion is most severe form of soil erosion in India. It is estimated that more than 37,00,000 hectares of agricultural lands have been rendered wastelands in India due to intense rill and gully erosion. Though deforestation (the percentage of forest cover to that of the total geographical area has decreased from 30 per cent to about 12 per cent) and consequent soil erosion has become a serious problem all over the country right from the nude and denuded hills of the North-Eastern Hill region in the east to bare Aravallis in the west and from extensively devegetated and sick Himalayas in the north to Nilgiris and Tamil Nadu plains in the south and from the Western Ghats in the west to the Eastern Ghats and coastal plains in the east, but soil erosion through rill and gully erosion has assumed alarming dimension in the states of Uttar Pradesh (12,30,000 hectares), Madhya Pradesh (6,83,000 hectares), Rajasthan (4,52,000 hectares), Gujarat (4,00,000 hectares), Maharashtra (20,000 hectares), Punjab (1,20,000 hectares), Bihar (6,00,000 hectares), Tamil Nadu (60,000 hectares) and West Bengal (1,04,000 hectares) where large areas have been engulfed by rill and gully erosion.

Extensive deforestation and terraced cultivation over Garhwal and Kumaun Himalayas have accelerated the rate of soil erosion. The studies show that 24.99 million tonnes of top soils are eroded every year from the middle and Siwalik ranges of the Himalayas. Thus the mean annual rate of soil loss from the Uttaranchal Himalayas is 8.34 hectare metres per 100 square kilometres (8.34 ha m/100 km^2/year). It means that 0.834 mm thick soil cover is eroded every year from the catchment area of about 21,400 km^2 of the Ganga in the Uttaranchal Himalayas. In all 179.72 million tonnes of top soils are eroded every year from Uttar Pradesh and are disposed off by the Ganga river at Varanasi. Total amount of average annual silt carried away from Uttar Pradesh to Bihar by the Ganga System is about 23,456 hectare metres or 328.384 million tonnes and average annual runoff of the Ganga System between Uttar Pradesh and Bihar is about 21,328 thousand hectare metres or 213.28 thousand million cubic metres. The average annual silt-load factor of the Ganga's catchment area in Uttar Pradesh (674,535 km^2) is about 3.476 ha m/100 km^2/year or 0.3476 mm per year. It means that every year about 0.3476 mm of top soil of Uttar Pradesh is eroded and carried away to the state of Bihar by the Ganga river system.

It may be concluded that since soil erosion is mainly controlled by climatic parameters (rainfall, humidity, temperature, winds etc.) in association with non-climatic parameters, it is accelerated in the climatic regions having seasonal regime of rainfall and its uneven distribution. Wherever the land use changes by man make the vegetated land cover open and bare the surface runoff generated by high intensity and continued rainfall for longer duration causes intense soil erosion in the tropical rainforest, savanna, hot arid, monsoon, mediterranean and temperate climatic regions.

3. CLIMATE AND VEGETATION

Plants play very import role in the biosphere because these are primary producers in the biospheric ecosystem and provide directly or indirectly food to all terrestrial and aquatic animals including man. The social groupings of plants are called **plant community** which directly depends on climatic parameters (insolation, heat, humidity, evaporation etc.) besides non-climatic parameters. Green plants directly receive and trap solar energy (light energy) and prepare their own food with the help of sunlight, atmospheric carbon dioxide and water through the process of photosynthesis. The solar energy converted into food or chemical energy is transferred to animals (including man) and micro-organisms through different **trophic levels** of food chain. The association or group of plant communities of any region is called **vegetation.** Different species of plants are evolved in a habitat having favourable climatic and other environmental conditions through the processes of **adaptation, competition** and **natural selection.** This results in the development of various vertical strata or layers of vegetation between the soil surface or ground surface and tree canopy. This vertical stratification of plants is the result of competition among various species of plants community to get sunlight because it is the primary source of energy for photosynthesis. It is thus evident that the availability of sunlight is mainly responsible for the development of vertical stratification of plants wherein the height and physiological characteristics of different plant species vary significantly.

It is commonly agreed that climate and vegetation are interdependent because if the vegetation is the result of climate, vegetation in turn also affects and modifies climate. In the beginning the classification of world climates was based on relationship between vegetation, and temperature-humidity because it was conceived that the vegetations of a given area/region were the function of temperature and humidity (which are important climatic elements) conditions of that area/region. The climate types, thus, were based on vegetation types and were named after plant associations such as equatorial rainforest climate (evergreen trees), savanna climate (the region having coarse grasses and scattered dwarf trees), taiga climate (having coniferous evergreen forests or subarctic regions of North America and Eurasia), tundra climate (having vast treeless almost ice covered surfaces of arctic regions) etc.

It may be mentioned that the basis of influences of climate on vegetation types and their distribution is still used for classification of world climates into major climatic types.

Temperature, sunlight, soil moisture, humidity etc. are the major climatic factors which affect the successional development of vegetation community. It may be pointed out that macro-climatic conditions of a given region are not as much effective in the successional (seral) development of vegetation of that region as are the effects of micro-climatic conditions of the neighbourhood of the plants covering a few square meters of area. The variants of climate (water, wind) also affect the spatial propagation of plants through seed dispersals. The main agents of seed transportation are wind, rivers, ocean currents (directly or indirectly related to climate), animals and man. Wind transports seeds mainly in suspension from one place to another place. Smaller and lighter seeds are efficiently transported by winds but such seeds are succeptible to high rate of mortality. Water transports seeds and disperses them through its various types of movements e.g. running water (river), sea waves, tidal currents, ocean currents etc.

There is wide range of variations in the distributions of vegetation on the globe. There is zonal pattern of vegetation from equator towards the poles (horizontal zonation) and from sea level to vegetation level on the high mountains (vertical zonation). The world distribution of plants, both horizontal (latitudinal) and vertical (altitudinal), is affected and controlled by a variety of factors e.g.

(1) **climatic factors** (sunlight, temperature, moisture and humidity, precipitation, soil moisture, wind etc.), (2) **edaphic factors** (soil nutrients, soil texture, soil structure, acidity and alkalinity, nature and properties of soil profiles etc., (3) **biotic factors** (effects of living organisms mainly animals and man of a given habitat on plants, interactions between different plant species and animals like natural selection, competition, mutualism, parasitism etc.), (4) **physical factors** (reliefs and topography, slope angle, gradient and slope aspect etc.), (5) **tectonic factors** (continental displacements and drift, plate movements, endogenetic forces and movements, vulcanicity and seismic events etc.), (6) **fire factor** (natural forest fires through lightning, man-induced forest fire, both intentional and accidental, (7) **dispersion** of plants, (8) **human interferences** etc.

The regional variations in plant species and vegetation types are mainly because of spatial variations in the combinations of major climatic parameters such as sunlight and heat, atmospheric and soil moisture and temperature, precipitation, and wind because plants develop adaptation to varying climatic conditions as referred to above through varying morphological and physiological characteristics such as leaves, barks, shape and length of roots so that they can withstand excessive heat, moisture, water, aridity, evapotranspiration, frosts, seasonal extremes of climatic conditions, short to long growing periods etc. This is why there is close relationship between world distributional patterns of plants (and also animals) and the present climatic types of the world. Thus, based on the relationships between the distributional patterns of vegetation and world climates the world has been divided into different biome types (table 18.3) Since the vegetation is the most dominant component of the biomes and vegetation-climates are very closely and intimately related and hence the world is divided into various biome types on the basis of major world climates and climatic zones. Each biome is further divided into subtypes on the basis of vegetation (table. 18.3).

Table 18.3 : World biome types

Biomes of the First Order (based on climatic zones)	Biomes of the Second Order (based on vegetation)	Biomes of the Third Order
1. **Tundra Biome**	(i) Arctic Tundra Biome	
	(ii) Alpine Tundra Biome	
2. **Temperate Biome**	(i) Boreal Forest Biome (Taiga Forest Biome)	(a) North American Biome
		(c) Asiatic Biome
	(ii) Temperate Deciduous Forest Biome	(a) North American Biome
		(b) European Biome
	(iii) Temperate Grassland Biome	(a) Soviet Steppe Biome
		(b) North American Prairie Biome
		(c) Pampa Biome
		(d) Australian Grassland Biome
	(iv) Mediterranean Biome	(a) Northern Hemispheric Biome
		(b) Southern Hemispheric Biome
	(v) Warm Temperate Biome	
3. **Tropical Biome**	(i) Tropical Forest Biome	**(a) Evergreen Rainforest Biome**
		(b) Semi-evergreen Forest Biome
		(c) Deciduous Forest Biome

		(d) Semi-deciduous Forest Biome
		(e) Montane Forest Biome
		(f) Swamp Forest Biome
	(ii) Savanna Biome	(a) Savanna Forest Biome
		(b) Savanna Grassland Biome
	(iii) Desert Biome	(a) Dry or Arid Desert Biome
		(b) Semi-arid Biome

(1) **Tropical evergreen rainforest biome** is characterized by largest number of plant species and luxuriant growth of vegetation due to high temperature and high humidity (both atmospheric and soil moisture) and precipitation throughout the year *i.e.* no seasonal contrasts. The vegetation is characterized by broad-leaf evergreen dense forests having drip leaves in accordance with the equatorial climatic conditions. The combination of sunlight, temperature, humidity and precipitation elements of equatorial climate has been responsible for the development of evergreen dense forest. The number of plant (mainly trees) species is so large and their diversity is so great that one hectare of land in equatorial region accounts for 40 to 100 species. The trend of progressively decreasing sunlight from the uppermost stratum (canopy) to the ground stratum sets in keen competition among various members of vegetation community for getting sunlight for photosynthesis. The underlying areas of tree canopy receives only 3 per cent of total sunlight reaching the tree canopy. Wind speed also decreases downward from the upper most canopy and it becomes almost zero at the ground surface but the moisture content in the air increases from the uppermost canopy to the ground surface because evaporation also decreases downward. This vertical trend of climatic parameters and stiff competition for getting sunlight for photosynthesis has been responsible for the development of well organized vegetation stratification having maximum number of strata (5). In fact, 'stratification (of vegetation) results from competition between species for favourable locations which in turn exert control over micro-climate and other factors affecting the habitats of plants and animals' (P.A. Furely and W.W. Newey, 1983).

(2) **The monsoon deciduous forest biome,** characterized by seasonal variations in temperature, humidity and precipitation (more than 80 per cent of mean annual rainfall is received during four wet monsoon months-June to September) of monsoon climate consists of four vertical strata of vegetation having lesser number of plant species than tropical evergreen rainforest biome. The seasonal regime of rainfall and dry summer season have given deciduous characteristics to trees which are characterized by thick girth of stems; thick, rough and coarse dark and large hydromorphic leaves or small and hard xeromorphic leaves. The large hydromorphic leaves enable the trees to trap more and more rainfall during wet seasons but these large leaves are shed in dry period to conserve moisture whereas small and hard xeromorphic leaves enable the trees to withstand dry weather and water deficiencies.

(3) **The Savana biome :** Though general characteristics of typical Savanna vegetation are trees and grasses but the Savanna biome is, no doubt, dominated by grasses. The Savanna vegetation community has developed layered structure wherein three distinct layers have clearly developed. (1) **The ground layer** is dominated by various types of grasses and herbaceous plants. The grasses are generally coarse, stiff and hard having the height ranging between 80 cm to 350cm. The African elephant grass attains enormous height of 500cm. The grasses bear deserted look during dry summer season but they become lush green again during humid summer season. (2) **The middle layer** consists of shrubs and stunted woody plants. (3) **The canopy layer** is formed by trees of various types. The general characteristics of trees depend on the availability of water and moisture and therefore there is great taxonomic variety of

Savanna trees which are usually 6-12m in height. The Savanna trees have developed various unique characteristics to withstand dry conditions. For example, there are a few species of trees which have developed such mechanisms which help them to reduce evapotranspiration from their leaves during warm dry season and enable them to remain green even during dry season of deficient water supply. On the other hand, there are such tree species which cannot withstand dry conditions and therefore they shed their leaves and bear the characteristics of deciduous trees. The roots of Savanna trees have also developed according to the environmental conditions as they are very large which can penetrate into the soils and ground upto the depths from 5m to 20m so that they can obtain water from groundwater even during dry season when the groundwater table falls considerably. The small plants and many herbaceous plants have special kinds of root systems characterized by root tubers and swellings so that they may preserve water which may be used by plants during dry season.

(4) **Hot desert types of climate** is not conducive for vegetation growth because of acute scarcity of water. This is why most of the regions under this climate are either devoid of any vegetation such as Lybian and Arabian deserts or if there is any vegetation at all, that is very little, sparse and bushy in character. The vegetation of hot desert climate is of xerophytic type which has special characteristics to withstand harsh climate characterized by extreme aridity, high temperature and very high rate of evaporation. They have their own moisture conserving devices such as long roots, thick barks, waxy leaves, thorns and little leaves so that they may avoid evapotranspiration and consequent loss of moisture form them. Most of the vegetation are found in the from of bushes. Cactus, acacia, date palm, a few flowering plants etc. form the composition of natural vegetation of hot desert climate.

(5)Though the Mediterranean regions having **Mediterranean climate** are widely scattered over different continents, there is more or less broad generalization in the overall structure and composition of vegetation community of all the regions of Mediterranean biome. The structure of Mediterranean vegetations is such that they can withstand the aridity of summer season. Consequently, the leaves have developed sclerophyllous characteristics in that they are stiff and hard and the stems have thick barks. The Mediterranean vegetation community consists of a variety of sclerophyll plant formation classes which range from Mediterranean mixed evergreen forests (in the coastal lands immediately bordering the aseas and the oceans) to woodland, dwarf forest and scrubs.

The **xeromorphic structure** such as thickened suiticles, grandular hairs, sunken stomata etc. enables the plants to withstand dry conditions. The sclerophyllous structure of plant leaves enables them to regulate the gaseous exchange according to the availability or scarcity of water during different seasons of the year. The plants have also developed special types of root systems in accordance with the regional environmental conditions mainly the availability of moisture. The European Mediterranean regions are characterized by multi-layered structural pattern of vegetation community consisting of (i) topmost layer of evergreen and deciduous oak trees, (ii) middle layer of shrubs locally called as **maquis** or **garigue**, and (iii) the ground layer of numerous herbaceous plants. The Californian Mediterranean lands are characterized by the (i) topmost layer of oak trees, (ii) the middle layer of **chaparrals**, equivalent to European **maquis**, and (iii) the ground layer of herbaceous plants and grasses. The South African Mediterranean Biome is characterized by attractive flowering plants of numerous varieties *e.g.* Erica, Ereesia, Lobellia, Kniphofia species etc. The shrubs are locally called as **fymbos**. The Australian Mediterranean Biome is characterized by numerous species of eucalyptus.

(6) The **China type of climate** (20^0-40^0 latitudes in both the hemispheres) characterized by abundant rainfall, high temperature and long growing season of 7 to 12 months favours luxuriant growth of natural vegetation. Dense forests of evergreen nature are found in more humid areas but areas of moderate rainfall are characterized by deciduous sparse forests and grasslands. Normally, mixed forests of coniferous trees and broad leaf trees are found. The broad-leaved forests are both evergreen and deciduous depending on the spatial

variation of distribution of annual rainfall.

(7) In the **Steppe climate** of **temperate grassland biome** the grasses are the most dominant members of different regions of the temperate grasslands of both the hemispheres. The perennial grasses, mostly belonging to the family of Gramineae, of this biome are considered to be the **climax community.** Besides, some herbaceous plants are also found in this biome but trees and shrubs are conspicuous by their general absence. There are two concepts of the evolution of temperate grasslands biome viz. (i) The temperate grasslands are the result of climatic conditions and pedogeneic properties of these areas. The extreme continental climate and limited supply of water to the plants because of low rainfall are the main factors for the dominance of grasses and general absence of trees and bushes. (ii) The climatic origin of the temperate grasslands is not always acceptable because many scientists believe that these grasslands are the result of human activities mainly burning of vegetation.

This biome exhibits close relationships among vegetation types, soil types and climatic conditions and between plant and animal communities. The temperate grassland biome is unique in the sense that it has single-layered structure of vegetation community where the upper canopy of the grasses is formed by their leaves but for a short period the flowering stalks also join the canopy and add grandeur to the top-layer. The flowers do not have petals. The pollination of flowers and the dispersal of seeds are facilitated by wind. It may be pointed out that most of the areas of the temperate grasslands have been now cleared and are used for cereal crops. Thus the temperate grasslands have become now the grainaries of the world and the heartland of the world dairy industry. There are spatial variations in the general characteristics of the vegetations of different parts of the temperate grasslands of the northern and the southern hemispheres.

(8) **The temperate taiga climate of boreal forest biome** or temperate coniferous forest biome is characterized by the dominance of coniferous trees (different species of pine, fir, spruce, larch etc.) which are well adopted to the extreme climatic conditions of the Siberian type of climate. These trees form dense cover of forests of mostly evergreen nature. The trees assume conical shape with tapering top-end so that snow may not accumulate on the branches and leaves of these trees rather this shape facilitates the snow to slide down the trees. Leaves are small, thick, leathery and needle shaped so that they may control excessive transpiration during winter season. Coniferous forests are also characterized by very little undergrowth because the poor and leached podzolized soils having higher acid content do not favour much vegetative growth at the ground surface.

(9) In **tundra climate** there is perfect relationship between vegetation and the condition of moisture in the soils. The characteristic lithosols of tundra biome support only lichens and mosses. Only 3 per cent species of the total world species of plant could develop in tundra climate because of the severity of cold and the absence of minimum amount of insolation and sunlight. The vegetations of tundra climate are cryophytes *i.e.* such vegetations are well adapted to severe cold conditions as they have developed such unique features which enable them to withstand extreme cold conditions. Most of the plants are tufted in form and range in height between 5 cm and 8 cm. These plants have the tendency of sticking to the ground surface because the temperature of the ground surface is relatively higher than the temperature of the overlying air. The herbs have developed only in those areas where heaps of ice and snow protect the plants from gusty icy winds. Such herbaceous plants include willow, the stems of which are very close to the ground surface (hardly a few centimetres above the ground). Though the growth rate of these herbaceous plants is exceedingly slow but their survival period is unbelievably very long (between 150 to 300 years). The evergreen flowering plants develop on the ground like cushions mostly during short cool summers.

Climate and forests : The forest climate is highly moderated and modified in terms of temperature and humidity by vegetation communities of varying strata and thus forest climate represents average weather so long as the forests are not adversely affected by human activities. It may be mentioned that the average forest weather represents mature forest ecosystem when the forest area does not have any open space and the vegetation communities attain final **sere** of successional development resulting into **climax vegetation.** The successional seral development of forests represents their dynamic nature. There are two schools of thoughts about the successional or seral/non-successional development of forests of varying vegetation communities, namely (1) school of 'climax or equilibrium concepts', and (2) 'mosaic cycle or dynamical concepts'. The **climax theory** envisages sequential and successional slow development of vegetations according to climatic and other physical conditions resulting into final equilibrium stage of the development of **climax vegetation** or **climax community** which is indicative of mature forest ecosystem. There are two theories of climax vegetation *e.g.* (i) **monoclimax theory,** and (ii) **polyclimax theory.** The monoclimax theory put forth by F.E. Clements (1916, 1936) states that regional climate is the dominant control factor of climax vegetation. In other words, the form of vegetation of any region during each stage of the successional development of vegetation community is determined by the climate of that region. This is called uniform climax condition and the vegetation developed during such uniform climax condition is **climatic climax vegetation** wherein the ecosystem becomes mature, micro-level changes in the environment including climate do not occur, species become competent enough to reproduce their offsprings in their own place of living, the intrusion of any external aggressive colonists becomes impossible, there is progressive increase in the complexity and diversity of communities, the ecosystem reaches the state of stability and no significant changes occur in the ecosystem (but in the absence of human interference only).

Poly-climax theory states that plant community of each ecosystem or habitat is not in equilibrium with climate of that habitat. In some habitats or regions plant communities do not always undergo the process of successional changes. In such cases the climax vegetation is not determined by climate of the region concerned but is determined by soil types or topographic characteristics, or natural forest fires, or destructive and constructive activities of man etc. The theory further states that many climax vegetation communities may develop in a single climatic region. A.G. Tansely has defined climax on the basis of main dominant factor which controls the maximum growth of vegetation of any habitat such as climatic climax, edaphic climax (when soil is most dominant), relief climax, anthropogneic climax, biotic climax etc.

The **mosaic cycle theory** is based on the basic concept that 'ecosystems consist of patches of 'mosaic stones' which cycle continuously through a set of states with adjacent patches cycling asynochronously (out of step)' (Alexander Robertson, 1997). This theory was put forth by Aubreville (1936). It means it is not necessary that the entire forest ecosystem of a region having distinct climatic conditions attains equilibrium stage of climax vegetation at the same time rather different patches of forest ecosystem passes through different cycles of their development and attain equilibrium stage at different times (asynchronous). 'Most studies of climate-forest interactions, including those by mosaic-cycle theorists (and also climax theorists) are based on conventional climatological, statistical and physical models that are necessary to provide a basic understanding of 'average' relationships, between climate and forests and weather and forest' (Alexander Robertson, 1997).

4. Climate and Ecological Productivity and Energy Flow

The solar energy or the sunlight is received and trapped by the green plants in the biosphere. The green plants contain pigment chlorophyll through which they convert solar energy into organic molecules (molecules having carbon). In fact, green plants use light energy to convert carbon dioxide and water into carbohydrates and other biochemical molecules. This process of conversion of light energy into food or chemical energy is called **photosynthesis.** The organisms which produce their own food are called **primary producers.** They are also known as **autotrophs.**

Primary producers fall in two categories *e.g.* (i) phototrophs, and (ii) chemotrophs. Phototrophs are those primary producers (green plants) which trap solar energy (light energy) and produce their own food through the process of photosynthesis. The chemotrophic primary producers are primarily bacteria which produce their food energy through chemical processes wherein simple organic compounds are oxidised to obtain food energy. In other words, chemotrophs use already photosynthesised organic matter which is already present in the biosphere to produce their own food. The primary producers include chlorophyll containing green plants, green purple bacteria, blue green algae and phytoplanktons.

The total accumulated amount of energy stored by the autotrophic primary producers per unit area per unit time is called **productivity.** In fact, the productivity of ecosystem refers to the rate of growth of energy or organic matter per unit time by autotrophic primary producers through the process of photosynthesis with the help of solar energy (light energy). The production of organic matter of energy by autotrophic primary producers is called **production** and the green plants involved in the production activity are called **primary producers.**

The productivity of the ecosystem depends on two factors *e.g.* (1) the availability of the amount of solar radiation to the autorophic primary producers, and (ii) the efficiency of the plants to convert solar energy (light energy) into chemical energy (food energy) which is used by green plants to build up their tissues. *Primary production/ productivity* is measured in two ways e.g. (i) **grass primary production** (GPP), and (ii) **net primary production** (NPP). Gross primary production is the total amount of energy produced by the autotrophic primary producers at trophic level one. In other words, gross primary productions refer to total amount of energy assimilated by autotrophic primary producer green plants. Net primary production (NPP) represents the amount of energy or organic matter fixed or stored at tropic level one. Thus, net primary production excludes the amount of energy which is lost through respiration by autotrophic primary producer plants. Net primary production is, thus, gross primary production minus the energy lost through respiration. Net primary production represents the usable amount of energy at trophic level one, which is made available to higher trophic levels. The ecosystem productivity whether, gross or net, is generally measured in dry gram/m^2/day or year.

Biomass refers to the quantity or weight of living matter per unit area per unit time and is represented in terms of dry weight. Biomass is comprised of plants and animals and therefore it is referred to as *plant biomass or animal biomass. Total plant biomass* including both, the above ground and subsurface plants is called standing crop.

It is necessary to draw a distinction between productivity and production. Productivity refers to the rate of increase of biomass whereas production is an amount of biomass of a given unit area at a given time.

Since the primary productivity of natural ecosystem largely depends on the amount of available solar radiation, there is positive correlation between primary productivity and solar radiation. Since there is marked decrease in solar radiation received at the earth's surface from equator towards the poles, primary productivity also, on an average (besides a few intermediate zones of exception), decreases markedly towards the poles. This results in spatial variations in primary productivity at global, regional and local scales. E.P. Odum (1959) has identified three levels of primary productivity of terrestrial ecosystems at world scale viz. (i) the regions of high ecological productivity represented by shallow water areas, moist forests (tropical and temperate), alluvial plains and regions of intensive farming: (ii) the regions of low ecological productivity represented by arctic snowcovered wastelands, and (iii) intermediate ecological productivity *e.g.* grasslands, shallow lakes and farmlands except intensively cultivated areas.

Though the productivity of ecosystem largely depends on the availability of required amount of solar radiation (sunlight) and the efficiency of plants to use this energy, there are also other factors which affect and control the ecosystem productivity e.g. abiotic-factors (temperature, water quantity and depth of water, and above all climate and chemical factors-nutrient supply) and biological factors (mode of interactions between various populations such as mutualism, parasitism, predation etc. and internal instinctive control mechanisms within the populations such as social organization, territoriality and social hierarchies). When the aforesaid factors are favourable, there is quite high relative level of productivity. When one or more factors are in short supply or are not favourable to ideal ecosystem productivity, ecological productivity becomes low. Such factor, which inhibits ecosystem productivity and therefore ecological production, is called **limiting factor.** For example, water is limiting factor in the hot desert areas because sufficient vegetation cannot develop due to scarcity of water though sunlight, temperature and nutrients are plentiful. Similarly, sunlight and temperature are limiting factors in polar areas.

Energy flow : Solar radiation is the basic input of energy which enters the ecosystem. This solar energy passes through the hierarchy of trophic levels in a food chain and food web and ultimately becomes output from the ecosystem as energy is lost through respiration from each trophic level. *Biosynthesis* is the process of the formation of organic tissue which represents the transformation of solar or light energy into chemical or food energy. *Biodegradation* is the process of breakdown and decomposition of organic matter and thus this process refers to the release of nutrients and food (chemical) energy in the form of heat. The energy flow (transfer of organic molecules) in the ecosystem is unidirectional and is noncyclic (is not available again for reuse).

The radiant solar energy or light (of the sun) energy is trapped by green plants (primary producers or autotrophs) and is used to prepare food (chemical organic matter) through the process or photosynthesis. Thus, autotrophic (or phototrophic) green plants transform a part of solar energy into food or chemical energy which is used by the green plants (primary producers at trophic level 1) to develop their tissues and thus it is stored in the primary producers or autotrophs at the bottom of trophic levels (i.e. trophic level 1).

The chemical energy stored at trophic level 1 becomes the source of energy either directly or indirectly to all of the animals at different trophic levels in a food chain in a natural ecosystem. Some portion of energy is lost through respiration from trophic level 1 and some portion of chemical energy is transferred to plant-eating animals (herbivores) at trophic level 2. Some portion of plants falls down without being consumed by herbivores of trophic level 2 on the ground surface and is ultimately consumed by detrivores or decomposers and thus some energy is also transferred from trophic level 1 to the decomposers living in the soils. It may be pointed out that the transfer of energy from trophic level 1 (green plants, primary producers or autotrophs) is performed through the intake of organic tissues (which contain potential chemical energy) of green plants by the herbivorous animals (when a cow grazes grasses, chemical energy stored in grasses is transferred to the cow).

Thus, the chemical energy consumed by herbivorous animals (derived from trophic level 1 through food intake) helps in the building of their own tissues at trophic level 2 and thus the energy is stored in them. This stored energy in the bodies of herbivores now becomes the source of energy for carnivorous animals (secondary consumers) at trophic level 3. A substantial portion of chemical energy is lost through respiration from herbivores at trophic level 2 because the animals have to consume energy for their movement for getting food from green plants. In other words, energy is required for the work to be done and when work is done energy is dissipated and the work is done when one form of energy is transformed into another form (second law of thermodynamics). Some portion of potential chemical energy is transferred to carnivorous animals at trophic level 3 through intake of food from herbivores. Some portion of energy is released by herbivores as wastes (e.g. dung, urine etc.) which are decomposed by detrivores or decomposers. Still some portions of herbivores, when dead, are broken down and decomposed by the decomposers (fig. 18.1).

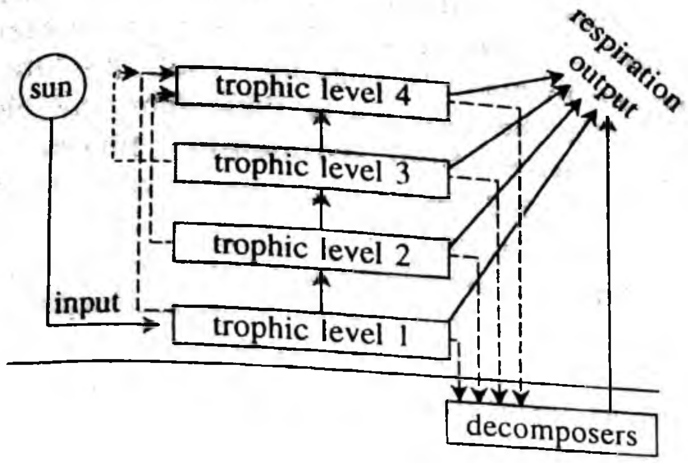


Fig. 18.1 : Generalized pattern of energy flow in an ecosystem. Solid lines indicate major pathways and dashed lines indicate minor pathways of energy flow.

A substantial portion of potential chemical energy stored in the bodies of carnivores is lost through respiration from trophic level 3 because the carnivorous animals have to run for greater distances to catch their preys. A portion of chemical energy is transferred to trophic level 4 or trophic level represented by omnivores (those animals which eat both plants and animals, man is the most important example of omnivores). The animals at trophic level 4 mainly man, also take energy from trophic levels 1 and 2 (fig. 18.1). Again some portion of energy is released through respiration from trophic level 4 by omnivores. The omnivores, after their death, are decomposed by the decomposers.

Thus, it is obvious from the above discussion and fig. 18.1 that there are three-way pathways of flow of energy in the natural ecosystem e.g. (i) transfer of chemical energy from each trophic level to the next higher trophic level (i.e. from trophic level 1 to 2, from 2 to 3 and 3 to 4) and direct transfer of chemical energy from trophic levels 1 and 2 to trophic level 4 (top trophic level); (ii) transfer of chemical energy from dead organisms of each trophic level to decomposers, and (iii) loss of energy in the form of heat through respiration from each trophic level and from decomposers (fig. 18.1). The whole amount of heat energy released from different organisms through respiration is lost to the atmosphere and thus is not again available to the organisms for reuse. It is thus evident that the energy flow in the ecosystem is unidirectional and non-cyclic.

The first law of thermodynamics, "that in any system of constant mass, energy is neither created nor destroyed but it can be transformed from one type to another type, energy inflow or input in a system is balanced by energy outflow or output", holds good in the mechanism of energy flow in the ecosystem as elaborated above. Light energy (solar radiation) is transformed into chemical energy (food energy) by autotrophic green plants through the process of photosynthesis. The chemical energy is released as heat energy through respiration by the organisms at different trophic levels. It is evident that climatic elements (mainly water—resulting from precipitation, air moisture and sunlight-solar radiation) play major role in the energy flow in the biospheric ecosystem.

5. Climate and Circulation of Matter in the Biosphere

The circulation of elements or matter collectively called as nutrients (both organic and inorganic) in the biospheric ecosystem is effected by water and energy (chemical) flow. The organic and inorganic substances are moved reversibly in the biosphere, atmosphere, hydrosphere and lithosphere through various closed systems of cycles (hydrological cycle, sediment cycle, oxygen cycle, carbon cycle, nitrogen cycle, phosphorous cycle etc.) in such a way that total mass of these substances are always available for use by biotic components. It is evident that climate plays direct and indirect roles in the circulation of matter in the biosphere.

Circulation of matter (nutrients) in the biospheric ecosystem is accomplished in a series of cyclic pathways which are collectively known as geobiochemical (biogeochemical) cycles. 'A biogeochemical/geobiochemical cycle is the cycling of chemical elements through the earth's atmosphere, oceans and sediments as it is affected by the geological and biological cycles. It can be described as a series of compartments or storage reservoirs, and pathways between these reservoirs' (D.B. Botkin and E.A. Keller, 1982). P.A. Furely and W.W. Newey (1983) have defined biogeochemical cycles as 'large scale cycles, involving inorganic substances which pass through a biotic phase and then return to an inorganic state'.

The elements derived from the atmospheric and sedimentary reservoirs are pooled into soils. The chemical or inorganic elements stored in sedimentary phase are made available to soil pool or reservoir due to weathering and erosion of rocks. The inorganic elements of the atmospheric phase are brought to the soils under the impact of precipitation. The inorganic elements or nutrients pooled in the soil reservoir are taken up by plants in solution form through the process of root osmosis. The plants then convert these inorganic elements into such forms which are easily used in the development of plant tissues and plant growth by biochemical processes (generally photosynthesis). Thus, the nutrients driven by energy flow pass into various components of biotic communities through the processes known as **biogeochemical cycles.**

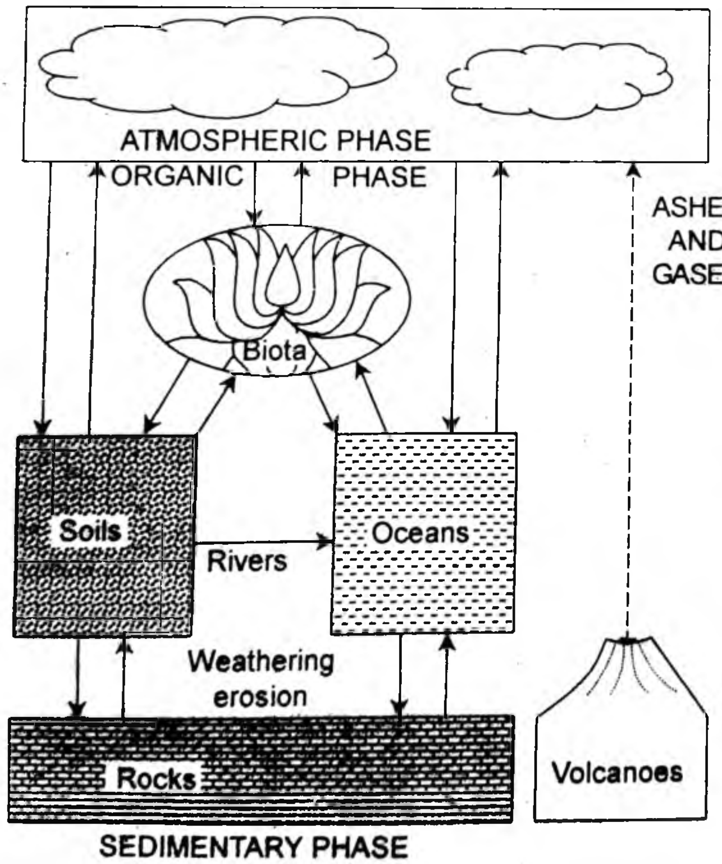


Fig. 18.2 : Generalized and simplified biogeochemical cycles (based on B.D. Botkin and E.A. Keller, 1982).

In a generalized form the biogeochemical cycles include the uptake of nutrients or inorganic elements by plants through their roots in solution form from the soils where these inorganic elements, derived from **sedimentary phase,** are stored (fig. 18.2). Some nutrients are leached from the soil pool and are brought back to the sedimentary phase while some nutrients (chemical or inorganic matter) are washed out and brought to the ocean by rivers. The inorganic elements or nutrients taken up by plants are transported to various trophic levels along the food chain through energy flow.

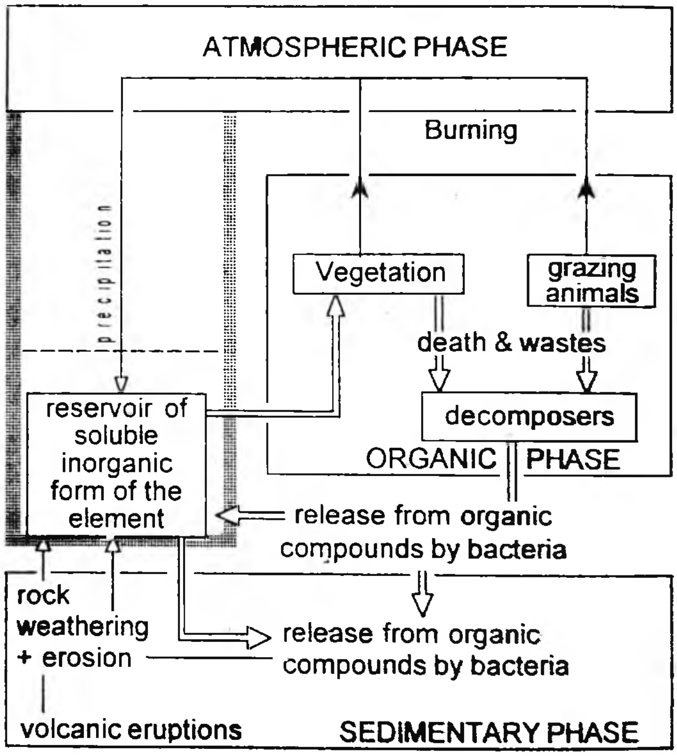


Fig. 18.3 : Pattern of terrestrial biogeochemical cycles. Solid arrows indicate major pathways of nutrients (after W.B. Clapham, 1973).

When nutrients are used and assimilated in the building of plant tissues and their bodies and when these are circulated and assimilated among different organisms of different trophic levels, these materials become **organic matter** and are stored in **biotic reservoirs or pools of organic phase.** Organic elements of plants and animals are released in a variety of ways as given below:

(i) Through the decomposition of leaf falls from plants, dead plants, parts of plants and dead animals by microbes or decomposers mainly bacteria. The gradual degradation of *dead organic matter (DOM)* in the litter layer is accomplished by saprophytes (those organisms which feed on organic compounds of dead plants and animals). These organic materials after decomposition are again converted into inorganic materials which again join the soil pool.

(ii) Through *burning* of vegetation by lightning, accidental forest fires or deliberate forest fires kindled by man. The portions of organic matter on burning are released to the atmosphere and again fall down on the ground surface under the impact of precipitation and again become soluble inorganic form of element to join **soil pool or soil storage** while some portions in the form of ashes after their fall on the ground surface are decomposed by bacterial activity and these again join **soil storage.**

(iii) The waste materials excreted or released by animals (dung, stool etc.) are decomposed by microbes or decomposers (mainly bacteria) and are again converted into inorganic elements which again find their way in soluble form to **soil storage.**

Thus, it is obvious that biogeochemical cycles involve the movement and circulation of soluble inorganic substances (nutrients) derived from **sedimentary** and **atmospheric phases** of inorganic substances (sedimentary and atmospheric phases are two important basic components of inorganic phase of elements) through **organic phase** of various biotic components and finally their return to inorganic state. The study of biogeochemical cycles may be approached on to scales e.g. (i) cycling of all the elements together or (ii) cycling of individual elements e.g. water or hydrogen cycle, carbon cycle, oxygen cycle, nitrogen cycle, phosphorous cycle, sulphur cycle etc. Beside, hydrological cycle, sediment cycle, and mineral cycle are also included in the broader biogeochemical cycles.

18.3 CLIMATE AND HYDROLOGICAL PROCESSES

Climate is directly responsible for driving hydrological processes such as surface runoff and overland flow, surface retention of rainwater, infiltration of rainwater, soil water, through flow, baseflow, channel storage and channel flow etc. and hydrological cycles through a sets of climatic parameters such as temperature, evaporation, transpiration, condensation and precipitation. The hydrological processes and cycles are largely affected and modified by human activities e.g. urbanization and industrialization, land use changes mainly deforestation, building activities etc. by making changes in the different components of hydrological processes and cycles. These aspects have been dealt with in much detail in chapter 8 of this book (see section 8.4, hydrological cycle).

18.4 CLIMATE AND GEOMORPHOLOGICAL PROCESSES AND LANDFORMS

Geomorphological processes, known as exogenetic processes originating from the atmospheric components of the biosphere or say simply from the atmosphere, include all the **denudational processes** (weathering and erosional processes). The geomorphological processes are the direct result of, and are controlled by climate. The spatial variations in geomorphological processes (different types of weathering processes such as physical, chemical, biotic and physico-bio-chemical weathering, and erosional processes such as, fluvial, aeolian, marine, groundwater, glacial and periglacial processes) are caused due to varying conditions and combinations of temperature, humidity (precipitation) and air circulation (wind). The spatial variations in geomorphological processes with other environmental factors produce spatial variations in landform characteristics. The control of climate on geomorphological processes and resultant landforms is so great that a distinct school of geomorphology, **school of climatic geomorphology,** emerged in France and Germany in the 20th century, and **climatic geomorphology** was developed as a distinct branch of geomorphology on the concept that each climatic type produces its own characteristic **assemblages of landforms and set of** geomorphic processes which shape them on the basis of the following major themes (D.R. Stoddart, 1969) :

1. Landforms differ significantly in different climatic regions.
2. Spatial variations of landforms in different climatic regions are because of spatial

variations in climatic parameters (e.g. temperature, humidity, precipitation etc.) and their influences on weathering, erosion and runoff.

3. Quaternary climatic changes could not obscure relationships between landforms and climates. In other words, there are certain diagnostic landforms which clearly demonstrate climate-landforms relationships.
4. Besides, 'not only do different levels of magnitude and frequency of processes have different environments, but within a single environment different attributes of morphometry (e.g. hydraulic geomorphometry, slope forms and divide configuration) may themselves be formed by processes of different magnitude and frequency' (R.J. Chorley, et. al, 1985). The above mentioned themes of climatic geomorphology need explanation separately.

The advocates of climatic geomorphology have attempted to collect information about the characteristics of such landforms which may be regarded as diagnostic landforms to determine climate-landforms relationships. Such typical diagnostic landforms are regarded as representatives of a particular climate. Climatogenetic or climatically controlled landforms are identified and differentiated in two ways e.g. (i) general observation and acquaintance of whole landscape of each climatic region, and (ii) identification of typical or distinctive landforms which represent the control of a particular climate. The typical landforms are, in fact, main tools of climatic geomorphologists which help them in determining-climate landforms relationships in different climatic regions. Such distinctive landforms are designated as **diagnostic landforms.** The diagnostic landforms identified by the climatic geomorphologists so far include inselbergs, duricrusts, pediments, tors etc.

Geomorphological Processes and Climatic Controls

It is an established fact that different processes work in different climatic regions and with climatic variations there is also variability in the nature and mode of influences of climatic parameters which affect denudational (weathering and erosion) processes. Temperature and humidity have emerged as the most significant climatic parameters of the control of geomorphological processes in different climatic regions. High mean annual temperature and rainfall (and hence perennial humid condition with high temperature throughout the year) favour deep chemical weathering in humid tropics, but the presence of gullies on steep slopes and canyons in the same humid tropics presents a geomorphic riddle. Besides, vegetation also plays important role in controlling geomorphic

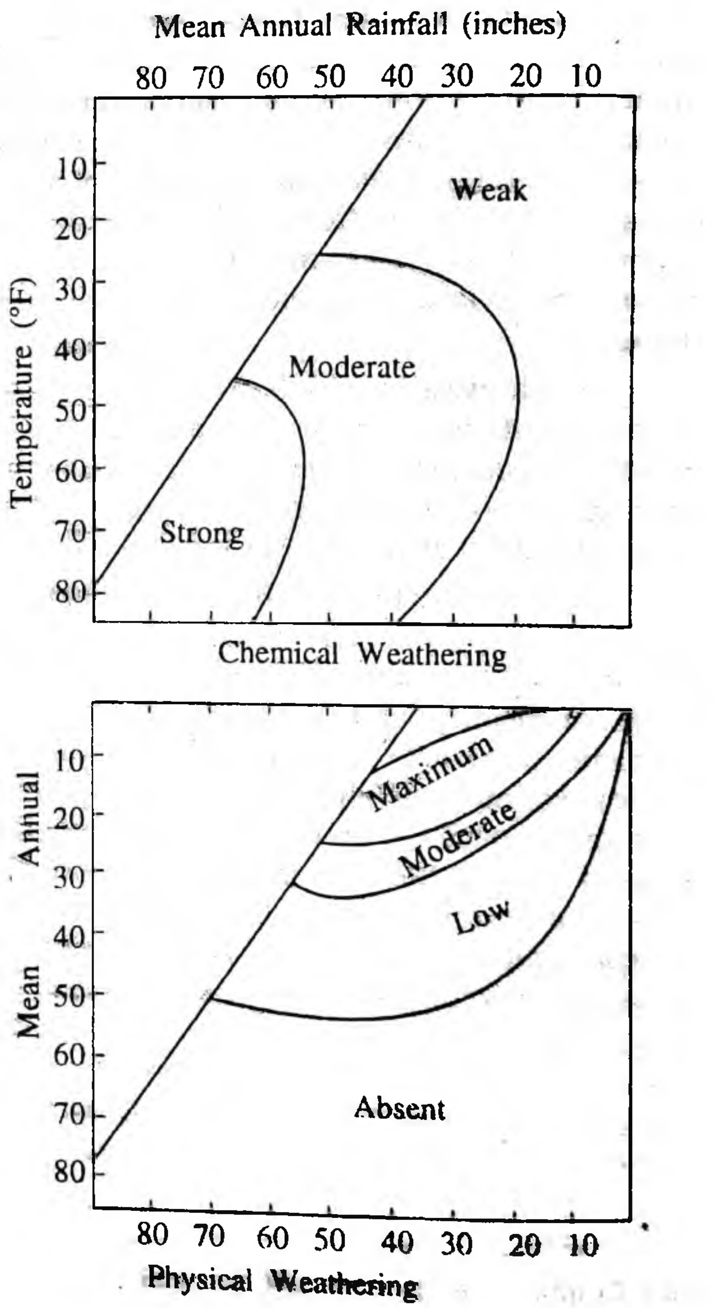


Fig. 18.4 : A : Chemical weathering. B : physical weathering in relation to mean annual temperature and rainfall (After L.C. Peltier, 1950).

processes in tropical humid areas, because the combination of high mean annual temperature and rainfall favour dense vegetation even on steeper slopes with the result the processes of soil erosion, sheetwash and physical weathering are considerably slowed down. Dense vegetation covering the valley sides and even reaching the valley floors discourages lateral erosion by streams and thus the processes of valley widening becomes sluggish. Dense vegetation of humid tropics also reduces surface runoff because a sizeable portion of rainfall is intercepted by forest canopy and thus rainwater reaches the ground surface in the form of **aerial streamlets** through the leaves, twigs, branches and stems of trees and thus allows more infiltration.

The areas, cleared of natural vegetation through human activities in the humid tropics, are subjected to active vertical erosion. Sapper (1935), Friece (1935) and Wentworth (1928) have identified active deep chemical weathering and vertical erosion in hot and humid climates due to high mean annual temperature and rainfall. Excessive humidity accelerates the process of landslides, soil creep and slumping. Different combinations of temperature and precipitation generate different types of weathering mechanisms (figs. 18.4), weathering regions (fig. 18.6) and effectiveness of massmovement, wind action and pluvial erosion (fig. 18.5) in different climatic regions.

T.C. Chamberlin and R.T. Chamberlin (1910) differentiated landforms of humid tropics from those of the mid-latitude temperate landforms. Different rock types respond differently to the combinations of water and temperature in different climates. For example, limestones become chemically weak to weathering and erosion in hot and humid climate because chemical weathering becomes more active but these become resistant to chemical weathering in hot and arid climate because of scarcity of water and humidity. Soil creep is also more or less absent in arid regions because of scarcity of water (and hence under-saturation of soils).

Even there is such spatial variation in the climatic parameters within a single climatic region that geomorphic processes are also influenced spatially by such variation. Altitude, slope aspect, direction, insolation, and precipitation are significant variables which influence processes and landforms resulting therefrom. For example,

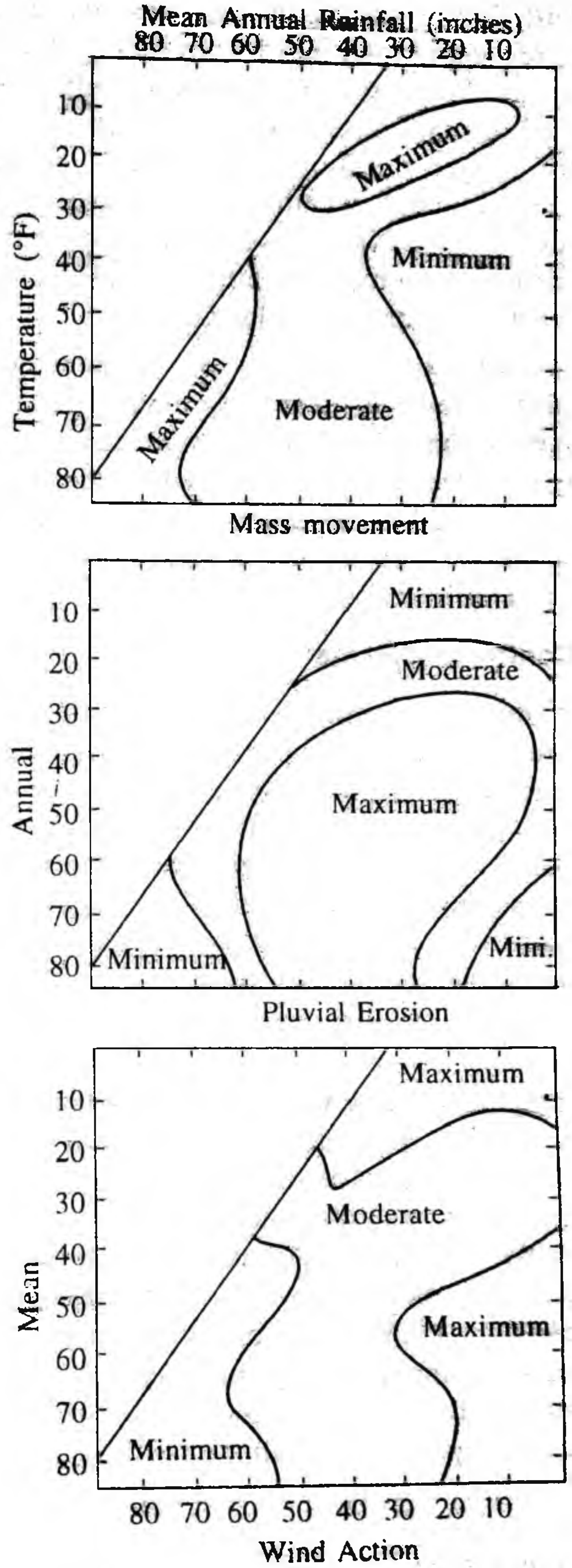


Fig. 18.5 : A : Nature of massmovement, B : pluvial erosion and C : wind action in different climatic conditions (after L.C. Peltier, 1950).

southward facing slopes of east-west trending valleys are steeper than northward facing slopes because the latter receive comparatively less amount of insolation and thus are covered with snow for longer duration, freeze-thaw is less effective and hence weathering and erosional processes are also less active while southward slopes are more affected by weathering and erosion due to greater amount of insolation.

Several examples may be cited which demonstrate strong influence of climatic parameters on geomorphological processes and landforms resulting therefrom. This aspect will be detailed out in the succeeding sections. Climate controls morphogenetic processes and landforms both directly and indirectly.

Direct Control of Climate

It may be pointed out that different morphogenetic processes operate in different climatic regions and with climatic variation the mode and rate of operation of geomorphic processes also differ from one climatic region to the other. Besides weathering, climate also influences the mechanisms of transportation and deposition. A few geomorphologists have studied in detail the morphoclimatic mechanisms in some climatic regions.

Temperature is a very significant climatic parameter which not only influences but also controls the mechanisms of different morphogenetic processes. It is known to all that temperature varies considerably in different climatic regions. If temperature (mean) of a region is below freezing point (less than 1^{0}C), then there is frequent and widespread frosting. If there is such fluctuation in daily temperature that it goes down below freezing point during night but rises above freezing point during day time, then there occurs **diurnal freeze** (during night) **and thaw** (during day) cycle which leads to alternate processes of contraction (due to freezing during night) and expansion (due to thaw during day time). The repetition of this mechanism causes frost weathering in periglacial climate (**congelifraction**) during transitional periods of summer and winter seasons in temperate climate. Jointed rocks are shattered under the impact of frost weathering which is responsible for the origin of distinctive landforms like tors where the rocks are widely jointed. The impact of freeze-thaw mechanism on unconsolidated geo-materials becomes very interesting in active layers of periglacial areas where if this mechanism becomes active in clay materials, **solifluction (congelifluction)** becomes operative as clay deposits resting on slopes are softened and loosened due to frost action and slump downslope when lubricated by meltwater (when frost thaws due to rise in temperature).

Frost action also influences surface runoff and underground drainage. For example, there is more or less regularity in stream discharge in hot and humid climate but there is much variation and fluctuation in the climates having frost actions as discharge becomes minimum during winter due to freezing of a sizeable portion of water but there is maximum discharge of water during summer due to thaw of frozen water. The whole of **active layer** lying above **permafrost** in periglacial climate freezes but the upper part of it thaws during summer but the thawed water does not reach greater depth in active layer and hence water flows rapidly as active surface runoff (though for very short duration) and the streams become able to transport loads of large size even on gentle slopes hut the streams soon become overloaded and are called **stone streams.**

Aeolian process is influenced by frost action in a variety of ways. Generally, frost discourages transportation of materials in cold climates as the loose fine materials are consolidated due to frosting but some times strong winds like-blizzards remove these consolidated materials but the mechanism of abrasion is not effective and hence topographic features produced by deflation, abrasion, sandblasting, and pitting in hot desert areas are not found in frost susceptible climates. The resultant deposits are called **niveo-aeolian deposits** in cold climates.

Coastal processes are also affected by frost action. The coastal rocks are hardened due to frost action during winter in cold climates, with the result they protect the coasts from active erosion by sea waves but the sea cliffs suffer from rock disintegration due to frost weathering caused by freeze-thaw action.