Chapter Three

Climatology

Chapter Concepts

- **Atmosphere**
- **Atmosphere Pressure**
- **Atmospheric Circulation**
- **Horizontal Distribution of Air Pressure**
- **Meridional Circulation**
- **Moisture in the Atmosphere**

Atmosphere

The atmosphere is a thin envelop of gases surrounding the Earth that forms a protective boundary between the outer space and the biosphere generally considered to be below 480 km (300 mi). Earth's atmosphere is formed by gases from the crust and interior and the exhalations of all life over the time. Atmosphere is a mixture of gases that is odorless, colourless, tasteless, and formless, blended so thoroughly that it behaves like a single gas. Earth's atmosphere is unique because, it supports life.

The stabilisation of atmosphere in its present form took place in the *Cambrian Period* (about 600 million years ago). The gases of the present atmosphere are not direct residue of the earliest form of the planet rather they are evolutionary products of the volcanic eruptions, hot springs, chemical breakdown of solid matter and distribution from the biosphere including photosynthesis and human activity.

Composition of Atmosphere

The main gases and their proportions have been shown in **Fig. 3.1**. A unit mass of dry air is made up of 78.084 per cent nitrogen (N_2), 20.946 per cent oxygen (O_2), 0.934 per cent argon (A), 0.036 per cent carbon dioxide (CO_2), and smaller proportions of rare gases such as neon, helium, methane and hydrogen.

1. On the basis of composition of gases, the atmosphere may be divided into (i) Heterosphere, and (ii) Homosphere **(Fig. 3.2)**.

Homosphere

It extends from the Earth's surface up to an altitude of 80 km (50 miles). Even though the atmosphere rapidly decrease in density with increasing altitude, the blend of gases is nearly uniform throughout the homosphere. The only exceptions are the concentration of ozone (O_3) in the stratosphere (ozone layer) from 19 to 50 km, and the variation in water vapour and pollutants in the lowest portion of the atmosphere near the Earth's surface. The stable

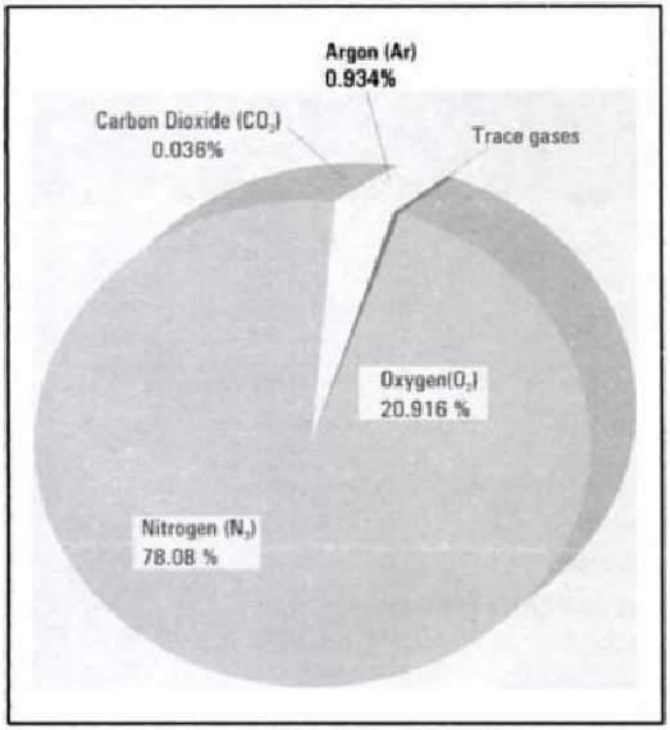


Fig. 3.1 – Stable components of modern atmosphere (Percentage concentration by volume)

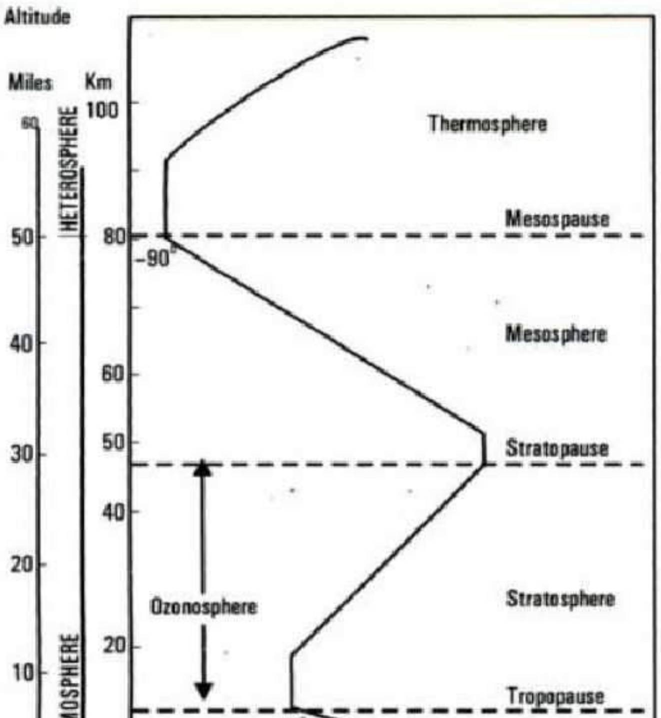


Fig. 3.2 – Vertical structure of atmosphere

mixture of gases throughout the homosphere has evolved slowly. The present proportion, which includes oxygen, was attained approximately 600 million years ago (*Cambrian Period*).

The homosphere may be divided into:
(1) Troposphere, (2) Stratosphere, and
(3) Mesosphere.

Troposphere

Troposphere extends up to the tropopause, defined by a temperature of -57°C, occurring at an altitude of 19 km at the equator, 13 km in the middle latitudes, and about 8 km near the poles. It contains approximately 90 per cent of the total mass of the atmosphere and the bulk of all water vapour, clouds, weather, and air pollution. The height of the tropopause varies with season, latitude, surface temperatures and pressures. The normal decrease in temperature in the troposphere has been shown in **Fig. 3.3.** The temperature in the troposphere decreases at the rate of 6.4°C per 1000 meters. This decrease in temperature is known as the *normal lapse rate*.

Stratosphere

Above the troposphere lies the stratosphere. The troposphere ranges from about 19 to 50 km above the Earth's surface on equator. The temperature in the troposphere varies from -57°C at the tropopause to 0°C at the stratopause (50 km). This sphere is characterised by the presence of ozonosphere, or ozone layer. Ozone is highly reactive oxygen molecule made up of three oxygen atoms (O_3). That make up most of the oxygen gas. Ozone absorbs wavelengths of ultraviolet light. Through this process, the most harmful ultraviolet radiation is effectively 'filtered' from the incoming solar radiation, safeguarding the Earth's surface.

Mesosphere

The Mesosphere is the area from 50 to 80 km. Its upper boundary, the mesopause, is the coldest portion of the atmosphere, averaging -90°C, although that temperature may vary by ± 25° to 30° C **(Fig. 3.4).**

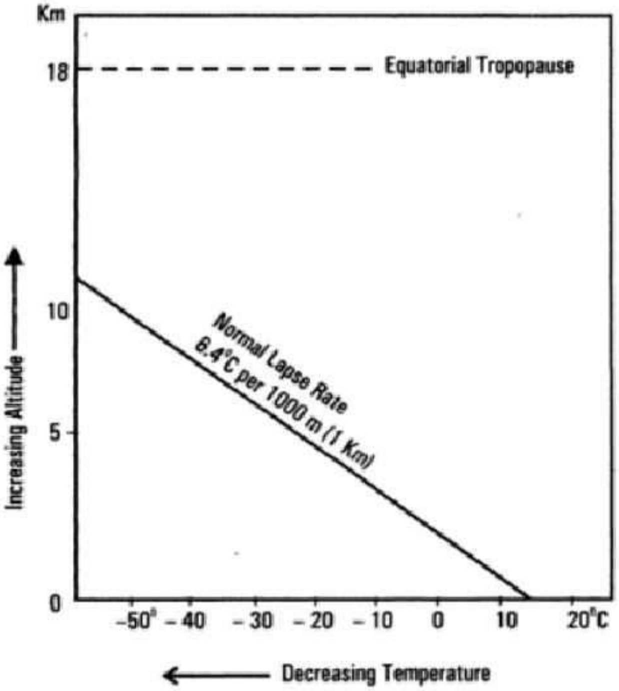


Fig. 3.3 – Normal lapse rate

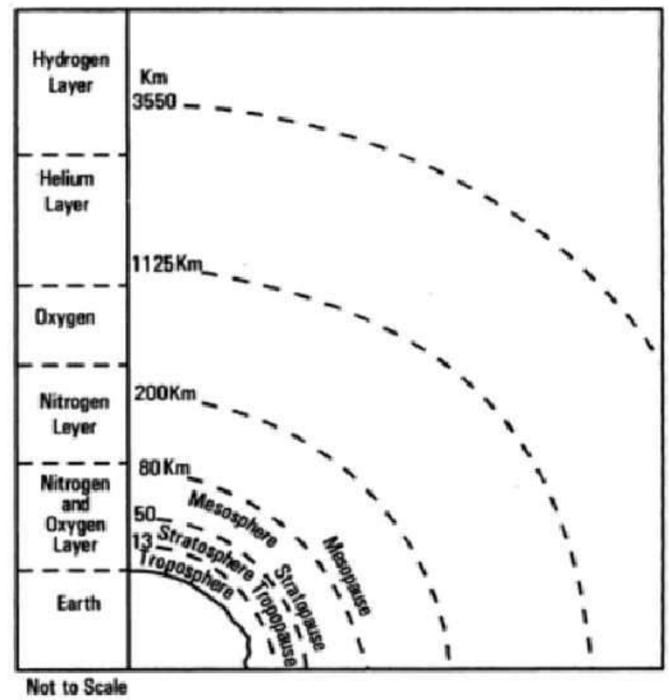


Fig. 3.4 – Chemical zones in the atmosphere

Heterosphere

The gases in this part are not evenly mixed. The heterosphere begins at around 80 km (50 mi) altitude and extend outward some 10,000 km. The solar constant is, however, measured at the altitude of 480 km. Above that point, the atmosphere is rarified (nearly a vacuum) and is called exosphere, which means *'outer space'*. It contains individual atoms of the light gases hydrogen and helium, weakly bound by gravity. The heterosphere has thermal region (called the thermosphere) and within it functional layers (called the ionosphere).

Thermosphere (the 'Heatosphere')

This is a region extending from 80 km to 480 km in altitude. It contains the functional ionosphere layer. High temperatures are generated into the thermosphere because the gas molecules in this sphere absorb shortwave solar radiation. The temperatures rise sharply in the thermosphere, up to 1200°C (2200°F) and higher. Despite such high temperatures, the thermosphere is not *'hot'* in the way you might expect. Temperature and heat are two different things. The intense solar radiation in this portion of the atmosphere excites individual molecules and atoms (principally nitrogen and oxygen) to high levels of vibration. The density of molecules is so low that little actual heat is produced (heat is the quantity of thermal energy). Heating in the lower atmosphere near the Earth's surface is different because the greater number of molecules in the denser atmosphere transmit kinetic energy as sensible heat, meaning that we can sense it **(Fig. 3.4)**.

Ionosphere

This is a zone of the upper atmosphere (Heterosphere) characterised by gases that have been ionized by solar radiation. The ionosphere is composed of atoms that acquired electrical charges when they absorbed cosmic rays, gamma rays, x-rays, and shorter wavelengths of ultraviolet radiations. These charged atoms are called ions, giving the ionosphere constantly, producing a constant flux (flow) of electrons and charged atoms.

The incoming solar radiation begins to interact with the atmosphere at altitudes beyond 480 km (300 miles). This outer region is also where gaseous particles escape the Earth's gravity. Particles are far apart that some of them have a high enough velocity in a direction away from the Earth to escape to space. The atmosphere is very thin at this altitude, but it is here that incoming space vehicles and meteorites begin to heat due to friction.

Above this, to perhaps 1125 kilometres (675 miles) atomic oxygen is prevalent. Beyond this layer of atomic oxygen, helium is most common out to 3540 km. Still farther out, hydrogen atoms predominate. The boundaries among the ozone is not clearly defined **(Fig. 3.4)**.

Solar Constant

The solar constant is the average value of insolation received at the *thermopause* (480 km or 300 miles) above the Earth's surface, when the Earth is at its average distance from the Sun. Solar constant is measured at a height of 480 km above the sea-level. The average value of solar constant is 1.968 calories per cm^2 per minute.

Heating of the atmosphere: The energy emitted by the Sun passes through space until it strikes some object. The quantity of radiation is about 1.968 calories per square centimeter per minute (*approximately 2 calories per cm^2 per minute*) which is known as solar constant. A calorie is the amount of energy required to raise the temperature of one gram of water (at 15°C) one degree Celsius. Thus, the solar constant is the basic amount of energy available at the outer limits of the Earth's atmosphere (480 km or 300 miles above the Earth's surface). Several processes deplete the solar radiation as it passes into the atmosphere. The processes include reflection, scattering, absorption, long wave-radiation, and transmission.

Reflection

The Earth and its atmosphere reflect part of the solar radiation back to space. There is considerable variation in reflection of natural surfaces. Reflectivity or *albedo* is expressed as a percentage of incident reaching the Earth's surface. Clouds are by far the most important reflectors in the earth environment. Cloud's reflectivity ranges from 40 to 90 per cent depending on the type and thickness. The most obvious effect of scattering in the atmosphere is sky colour. The only reason our sky appears blue is the of scattering of radiation in the shorter wave-lengths of visible light. Scattering also explains the orange and red colours seen at dawn and sunset. At these times, the radiation passes through the atmosphere at a very low angle. Thus, it passes a long distance through air close to the ground. The lower atmosphere contains not only the dry gases, but water vapour, solid particles, organic material, and salt. These larger particles scatter the long- wavelength radiation. In fact, the atmosphere absorbs most of the radiation in the shorter wave-lengths (violet to green). Only the longest wavelengths–orange and red – pass through.

Absorption

Sound or light energy gets converted into heat. Most often it changes to sensible heat, which raises the temperature of the absorbing object. For example, sunlight striking the side of a house is absorbed and heats the wall.

Transmission

Reflection, scattering, and absorption deplete the solar beam as it passes through the atmosphere.

Scattering

Scattering is a process by which small particles and molecules of gases diffuse part of radiation in different directions. The process changes the direction of radiation in a relatively random fashion.

Dawn and Twilight Concepts

The diffused light that occurs before sunrise and after sunset represents useful work time for humans. Light is scattered by the molecules of atmospheric gases and reflected by dust and moisture so that the atmosphere is illuminated. Such effects may be enhanced by the presence of pollution and other suspended particles, such as those from volcanic eruptions or forest fires. The duration of dawn and twilight is a function of latitude because the angle of the Sun's path above the horizon determines the thickness of atmosphere through which the Sun's rays must pass. Lower Sun angles produce longer dawn and twilight periods.

At the equator, where the Sun's rays are nearly perpendicular to the horizon throughout the year, dawn and twilight are limited to 30-45 minutes each. These times increase to 1-2 hours at 40° latitude, and at 60° latitude they range upward about 2.5 hours, with little true night in summer. The poles experience about *7 weeks* of dawn and *7 weeks* of twilight, leaving only 2.5 months of near darkness during the six months when the Sun is completely below the horizon.

Determinants of Temperature

The average temperature of the earth is about 15°C. Its disfribution is, however, not even. The spatial distribution of temperature is determined by the following factors:

1. **Latitude** : The insolation and temperature of a place largely depend on latitude. The intensity of insolation decreases from the equator towards the pole. In addition, day-length and sun angle change throughout the year which affect the rate of insolation. Consequently, the lower latitudes record high temperature as compared to the higher latitudes.

2. Altitude : Within the troposphere, temperatures decrease with increasing altitude above the Earth's surface (the normal lapse rate is 6.4°C per 1000 m). Thus, world-wide mountainous areas experience lower temperatures than do regions near sea level, even at similar latitudes. For example, Libreville (Gabon) 15 m above the sea level, and Quito (Ecuador) about 2500 m above the sea level both are located almost on the equator. The mean annual temperature of Libreville is 28°C while that of Quito only 13°C. The great variation in temperature of the two places is simply because variation in altitude.

3. Cloud Cover: There is a direct effect of cloud cover on the amount of insolation. The cloudiness affects the local, daily, seasonal and annual temperatures and the ranges of temperatures. According to the meteorologists, over 50 per cent of the sky is overcast every day. Cloudy days are generally cooler and cloudy nights are warmer. The maximum clouds are recorded in the equatorial region. Consequently, the highest temperatures are not found along the equator. Conversely, the hot deserts have the minimum cloud cover as a result of which the highest temperatures are recorded along the Tropic of Cancer (places, like Al-Azizia (Libya), Death Valley (California), and Ganganagar and Jodhpur (India).

4. Distance from the Sea/Ocean: The location of a place in relation to sea and or oceans also affects the distribution of temperature. In fact, there is differential heating of land and sea at the same latitude. The sea water can pass its heat downward, or evaporation and ocean currents can reduce the surface temperature, but the land is opaque, and the Sun's rays on land can penetrate only up to a depth of only one meter, while they penetrate much deeper in water (seas/oceans). The two places situated at the same latitude – one along the sea coast and the other in the interior away from the coast – will record different temperatures. For example, Mumbai and Adilabad (Andhra Pradesh) are situated almost at the same latitude, but because of differential heating of sea-coast and interior land, there is a marked difference in their mean annual and diurnal range of temperature. The annual range of temperature at Mumbai is only about 6°C, while that of Adilabad is about 20°C. A typical example of extreme temperatures in summer and winters may be provided by the city of Tashkent. At Tashkent the mean maximum temperature of July is 40°C, while the mean minimum temperature of January reads -40°C. These extremes in temperature are the results high degree of continentality of Tashkent. In fact, Tashkent is quite far away from the ocean bodies and it is surrounded by the lofty mountains which create a strong barrier in the path of oceanic winds.

5. Winds: The role of prevailing winds is also quite significant in the distribution of temperature. The winds help in the redistribution of temperature and in carrying moderating effects of the oceans to the adjacent coastal areas. For example, the wind blowing from low latitudes to high latitudes raise the temperature of the region, while winds blowing from high latitudes to low latitudes lower the temperature. The winds coming from the Siberia, significantly reduce the temperatures in the northern plains of China even along the coastal areas. Some of the local winds like *Gibli* (Libya), *Chinook* (USA-Canada), *Mistral* (France), and *Berg* (Germany) change the temperature dramatically. Similarly, '*Loo*' a local wind, raises the temperature in the Satluj-Ganga Plains of north India significantly.

6. Topography and Slope: The distribution of temperature is also affected by the physiographic features. The ground slope facing the Sun receives more insolation (temperature) than the leeward slopes. For example, the southern slopes of Himalayas record more temperature than that of the northern slopes. A north facing slope may have snow on it, whereas a south-facing slope is bare at the same altitude. The north slope gets less intense radiation and as the sun gets lower in the sky, will be in shadow long before the south facing slope. It is just the reverse in the case of Southern Hemisphere. The coastal windward slope of the mountains and hills have relatively low temperatures because of oceanic influence and ascending air than the leeward slope. This is why there is much difference in the temperature of Mumbai and Pune. Slope aspect influences many natural phenomena. For example, the height of permanent snow and ice on mountain varies from one slope to another as does the tree line. Similarly, the depths of snow and frost differ on north and south-facing slopes. These phenomena also affect the temperature.

Topography also plays an important role in climates of some lowlands. On a continental scale, mountain ranges that run north and south have very different effect from those run east west. The presence of the Himalayas obstructs the Siberian cold air to enter into the sub-continent of India. The heavy rainfall along the southern slopes of Himalayas is the result of obstruction it creates in the path of the Indian summer monsoon winds.

7. Ocean Currents: The ocean currents also affect the distribution of temperature on the land and oceans. The warm ocean currents flowing from the lower latitudes to the higher latitudes carry the warm water towards the polar areas, while the cold water currents bring the cold water towards the equatorial regions. For example, the Gulf Stream raises the average temperature of Norway coast by about 5°C, while the Labrador current reduces the temperature of the Canadian coast by about 8°C. Because of the warm water of the Gulf-Stream, the ports of the northern Europe (60°N) remain open throughout the year, while the ports of Canada even at 50°N remain frozen during the winter season.

Horizontal Distribution of Temperature

The horizontal distribution of temperature is also known as regional distribution of temperature. The horizontal distribution of temperature on the earth surface is not uniform. The horizontal/regional distribution of temperature is controlled by several physical factors, e.g. (i) latitude, (ii) altitude, (iii) cloud cover, (iv) distance from the sea, (v) winds, (vi) slope of land, and (vii) ocean currents.

In general, the temperature decreases from equator towards poles. The rate of decrease in temperature from equator towards pole is known as *temperature gradient*. Since the tropical zone receives the highest insolation, the average temperature in this zone are high throughout the year. The presence of clouds in the equatorial belt, however, obstructs the rate of insolation. Consequently, the highest temperatures are not recorded along the equator, instead, the regions of Tropic of Cancer and the Tropic of Capricorn. In the western parts along the Tropic of Cancer and Tropic of

Capricorn, the skies remain clear over the greater parts of the year. Consequently, the highest temperatures in the world are recorded along the tropics, especially in the hot deserts.

Normally, isotherms run east-west and are almost parallel to the latitudes. This trend shows strong control of latitudes on the horizontal distribution of temperature. Isotherms are, however, more irregular in the Northern Hemisphere because of large extent of land-mass. Moreover, isotherms are more closely spaced in the Northern Hemisphere which shows a rapid change in temperature. The isotherms of January and July are the representatives for the horizontal distribution of temperature.

Thus, the horizontal distribution of temperature over the Earth's surface is a function of both location (latitude, altitude and slope), and dynamic movement (energy transfer by atmosphere and ocean currents).

January Temperature

The distributional pattern of temperature in the month of January has been shown in **Fig. 3.5.** In January the Sun's rays are vertical in the Southern Hemisphere. Consequently, higher temperatures are recorded in the Southern Hemisphere. The thermal equator (a line joining all points of highest mean temperature) tends southward into the interior of South America, Africa and Australia indicating higher temperatures over landmasses. The isotherms generally run parallel to the equator. The coldest area in the month of January lies in the Siberia. Verkhoyansk and Oyamakon (Russia), each has recorded a minimum temperature of -68°C, and a daily average of -50.5°C for January **(Fig. 3.5).**

July Temperature

The mean July temperatures have been shown in **Fig. 3.6**. In July, the longer days of summer and vertical rays of the Sun are in the Northern Hemisphere. The thermal equator shifts northward with the high summer Sun and reaches the Libya, Egypt, Saudi Arabia, Persian Gulf, Iran, Pakistan and Central India. The highest temperature was recorded at *Al-Azizia 58°C on 13th September, 1922* **(Fig.3.6).** On water, the Persian Gulf is the site of the highest recorded sea-surface temperature of 36°C, difficult to imagine for a sea or ocean body **(Fig.3.6).**

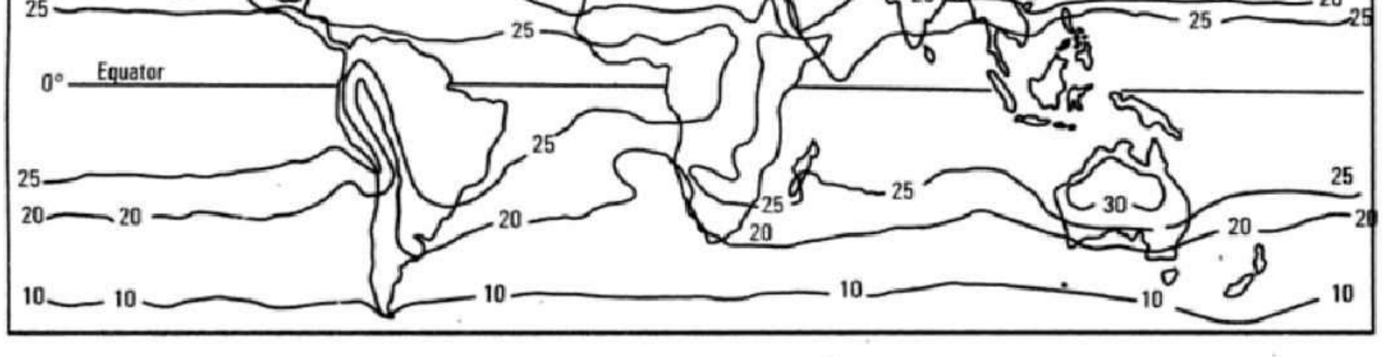


Fig. 3.5 – Mean January temperature

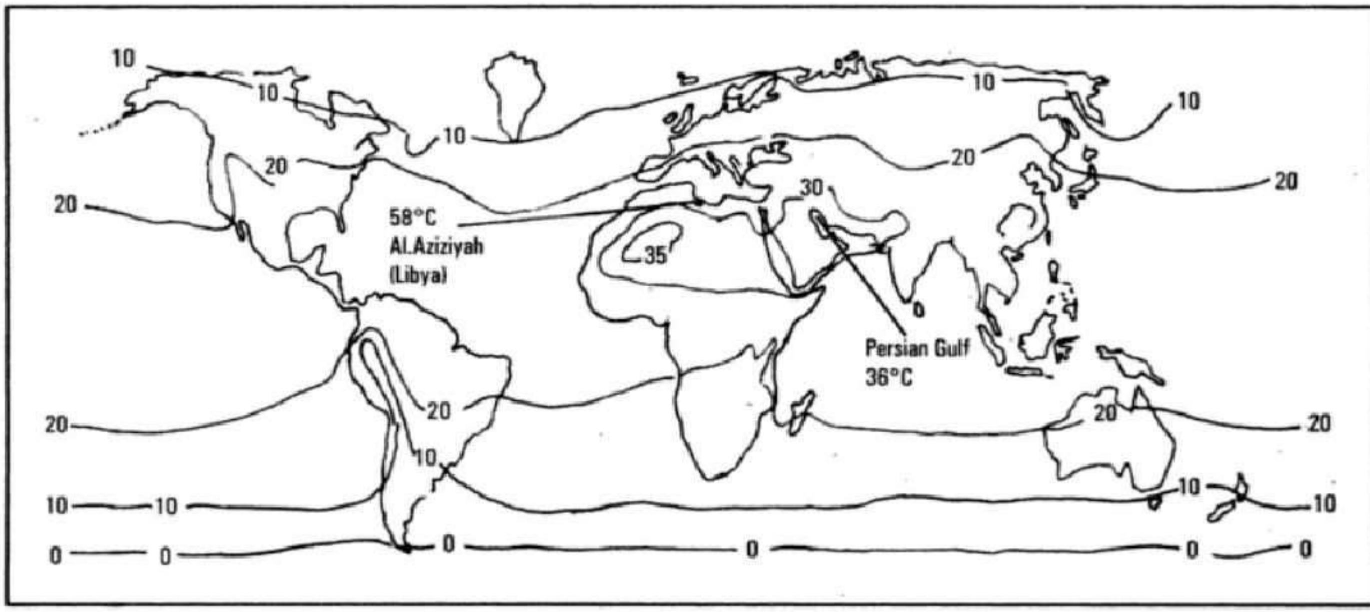


Fig. 3.6 – Mean July temperature (°C)

Annual Range of Temperature

The difference of the mean monthly temperature of January and July is known as the annual range of temperature. The highest annual range of temperature is generally recorded in the sub-polar region in Siberia where the average annual ranges of temperature is about 64°C **(Fig.3.7).** The annual range of temperature to the west of Bay of Hudson is also around 60°C. The Southern Hemsiphere, on the other hand, produces relatively little annual range in mean temperature. In general, the Northern Hemisphere, with greater land area overall, registers a slightly higher average surface temperature (15°C) than does the Southern Hemisphere (12.7°C).

Diurnal Range of Temperature

The difference of the highest and the lowest temperature in a day at a given point is known as the diurnal or daily range of temperature. The highest diurnal range of temperature is recorded in the hot deserts of the world.The magnitude of the daily change in temperature varies a great deal. Near the equator, the daily range exceeds the annual range. Near the two poles, the daily range is reduced to almost zero since there is generally only one daylight and one nighttime period each year.

The daily range of temperature over the oceans is also small. There are several reasons for the low range. First is the high specific heat of water. The oceans heat slowly and cool slowly. Second, there is mixing of the surface water with the water below that modifies heating and cooling. Third, solar radiation penetrates deeper into the ocean than into the land. Fourthly, the ocean currents mitigate the temperature.

The daily range of temperature in the Sahara Desert (*Al-Aziziyah*) and the Desert of Arizona, is more than 22°C. The greatest known recorded daily range in temperature occurred in Libya (North Africa), where the temperature dropped from a high of 56°C in the afternoon to 0° the following morning (September, 1922). The difference is an amazing 56°C.

Inversion of Temperature

Generally the temperature decreases in the troposphere with height at the rate of 6.4°C per 1000 m. If there is an increase of air temperature with increase in height, it is known as inversion of temperature. This is also called as the *negative lapse rate*. The inversion of temperature may occur, near the Earth's surface, or at greater height in the troposphere. Different types of inversion of temperature are:

1. Low Level or Ground Surface Inversion: Atmospheric condition in which temperature near the ground increases, rather than decreases, with elevation. Out of the different types of inversion, the ground inversion of temperature is the most important as it directly affects the society. Ground inversion occurs generally, in the tropical and subtropical areas during long winter nights only **(Fig.3.8)**. The inversion of temperature in the tropical zone, however, disappears with the rise of sunrise. The duration and height of the surface inversion increase poleward. The ground surface inversion occurs under the following geographical conditions:

(i) long winter nights
(ii) cloudless clear sky
(iii) dry air-low-relative humidity
(iv) calm atmosphere or slow movement of air
(v) snow covered surface

2. Upper Air Inversion: It occurs when the warm air is transported upward into the cold air due to eddies. It may be caused due to compression of the descending air as it happens in the case of subtropical high pressure belts (anticyclones).

3. Frontal Inversion: It is caused either the horizontal or vertical movement of air. The temperate cyclones are formed due to the convergence of warm westerlies and cold polar air and thus the warm air overlies the cold air. The presence of warm air above and cold air below reverses the normal lapse rate and inversion of temperature occurs.

Social Relevance of Inversion of Temperature

The inversion of temperature and its duration affects adversely the society and the economy of the region of its occurrence. Some of the important consequences of inversion are given below:

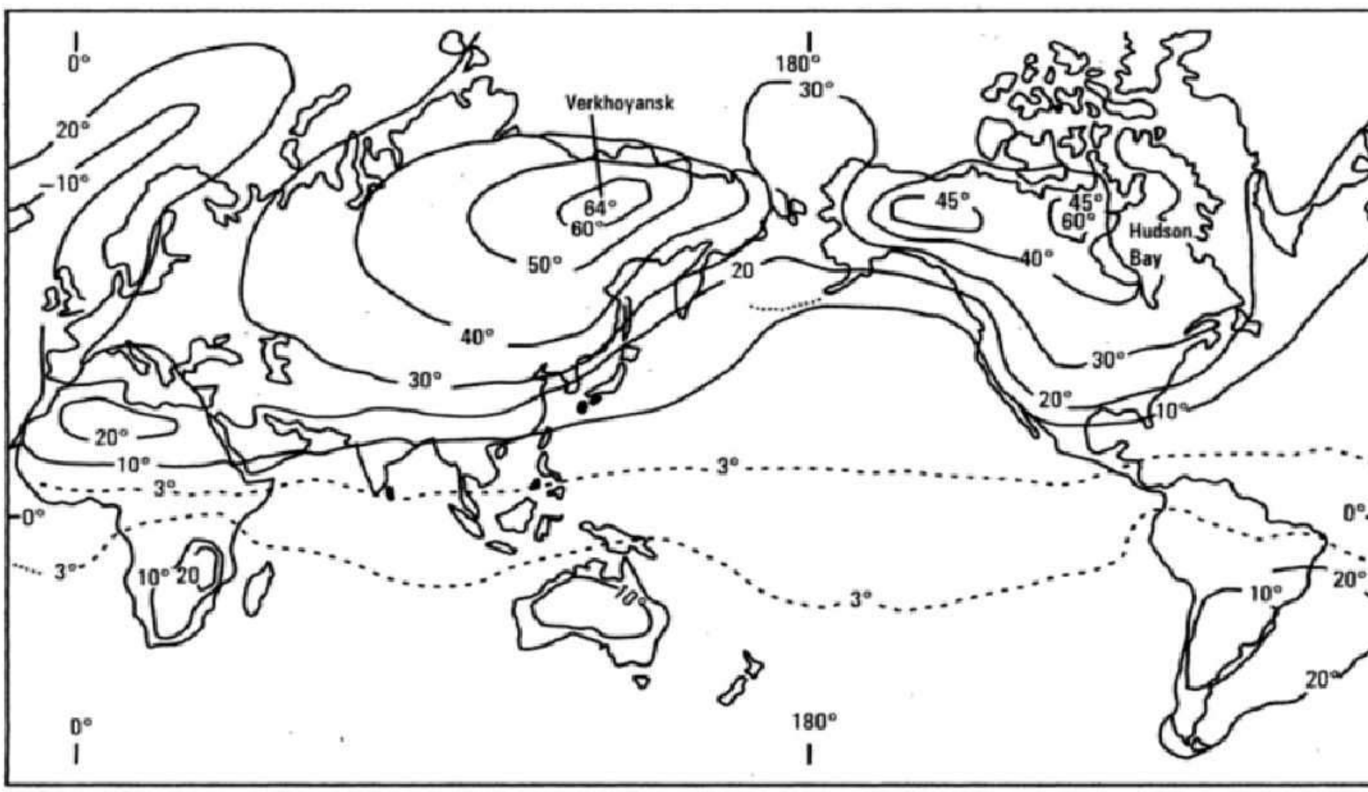


Fig. 3.7 – Annual range of air temperature

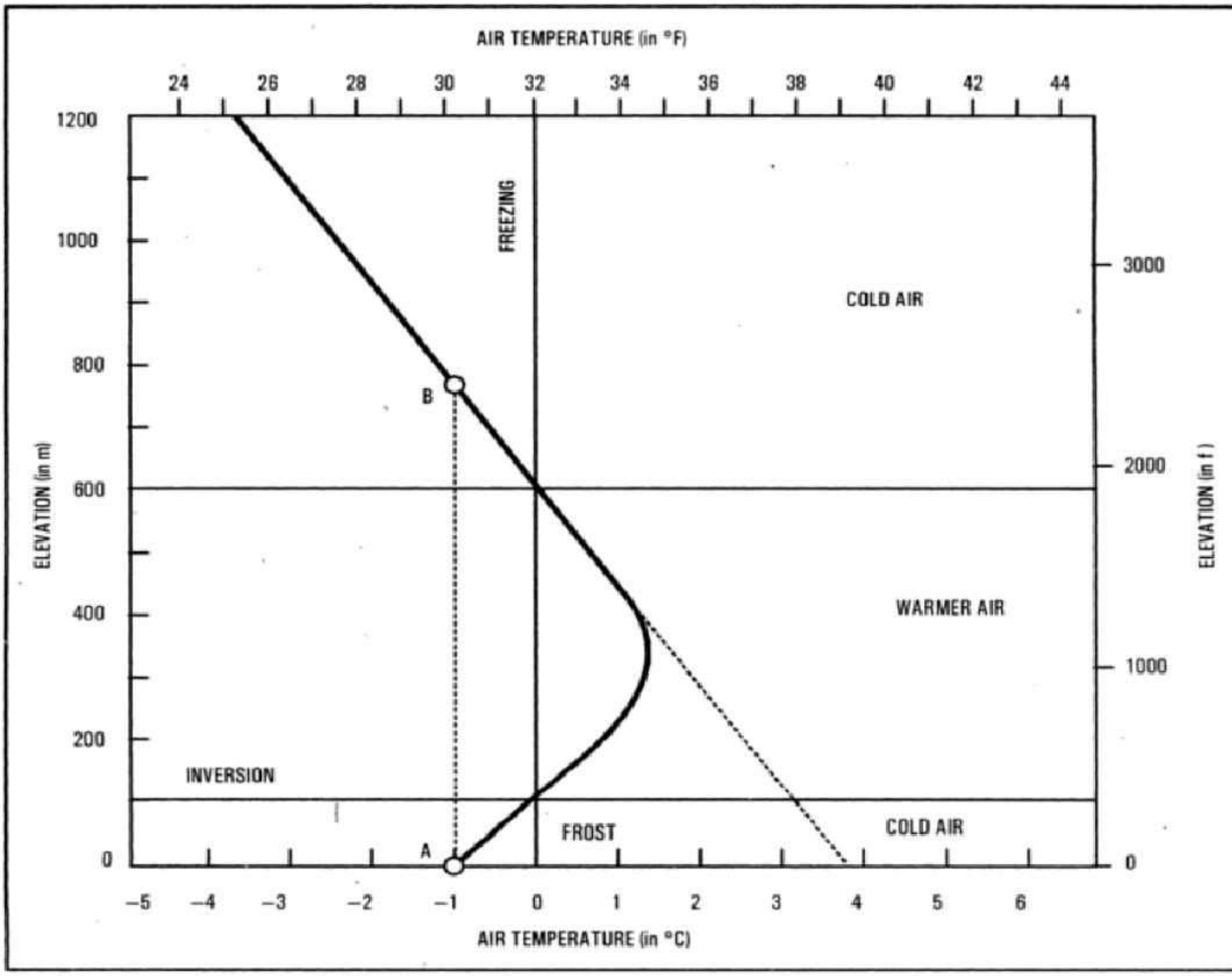


Fig. 3.8 – Low level – Inversion of temperature with frost

1. Occurrence of Fog

There develops clouds in contact with the ground (fog) with visibility usually restricted to less than 1 km. In the urban areas, the fog mixed with the smoke takes the shape of *smog*. While fog is injurious to crops, the smog is a health hazard. In 1952, in London about four thousand people died because of the urban smog. Breathing problem, asthma, and bronchitis, etc. diseases are common in Delhi especially during the winter season.

2. Accidents

At the occurrence of inversion, fog is a common phenomenon. Due to poor visibility under the foggy conditions, the frequency of road, railway, air sea-routes accidents increases. Near New Foundland, where the warm water of Gulf Stream mixes with the cold water of Labrador, there develops intense fog which is a great barrier in the movement of ships and navigation.

3. Damage to Crops

The winter crops, e.g. wheat, barley, gram, lentil (*Massoo-pulse*), mustard, peas, vegetables, chilly, potatoes, and fruit orchards are seriously damaged. The sugarcane crop of the great plains of India, especially in Western Uttar Pradesh, Uttarakhand, Punjab and Haryana develops the disease of red-rod which reduces the sugarcane content. In Brazil, and Yemen, the occurrence of fog is, however, considered favourable for the growth and yields of coffee. Orchards in the valley of California, Switzerland, France, Italy and Spain often get damaged due to severe fog and frost.

4. Impact on Human Settlements

In the Mediterranean region, the human settlements and location of orchards is closely influenced by the inversion of temperature. The lower parts of valleys of the Alps Mountains are almost without settlements, while the upper parts are inhabited. The upper slopes of the valleys are characterised by fruit orchards, hotels, while the lower slopes are almost deserted.

5. Inversion of Temperature and Atmospheric Stability

Inversion of temperature causes atmospheric stability which stops upward (ascent) and downward (descent) movements of air. The atmospheric stability is less conducive to rainfall.

Atmospheric Pressure

Our atmosphere is surrounded by gases. All gases have weight. The force per unit horizontal area exerted at any given level in the atmosphere by the weight of the air above that level. The atmospheric pressure is maximum at the sea level which is equivalent to about 1 kilogram per sq centimeter or 14.7 pounds per square inch. The standard air pressure at the sea level is 1013.25 millibars. The air pressure decreases most rapidly with height near sea level where the air is most dense. It decreases by about 50 per cent for every 5 km of ascent. We, however, do not feel such enormous weight on our 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 height and, therefore, the balance between the outward pressure exerted by air of human body and inward pressure exerted by atmosphere is disturbed, with the result man suffers from nose and ear bleed at higher altitudes on the mountains.

The atmospheric pressure decreases with altitude. Moving upward from the Earth's surface, the decrease of pressure with altitude is initially quite rapid. At higher altitudes, the decrease is much slower. Because atmospheric pressure decreases rapidly with altitude near the surface, a small change in elevation will often produce a significant change in air pressure **(Fig. 3.9)**.

As atmospheric pressure decreases, the boiling point of water becomes lower. For example, the boiling point, which is 100° C at sea level, is reduced to 90°C at 3000 m. At 5000 m, the boiling point is 84°C. As the boiling point decreases, the time required to cook foods by boiling increases. At places like Leh and Kargil, boiling potatoes and pulses is a very slow process.

Pressure Gradient: The distribution of air-pressure is not uniform. Generally, pressure gradient is defined as the 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 isobars **(Fig. 3.10)**. 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.

Atmospheric Circulation

The movement of air in the air is known as atmospheric circulation. When the average of the entire globe is considered, the motion is referred to as the general circulation of the atmosphere. Earth's atmospheric circulation is

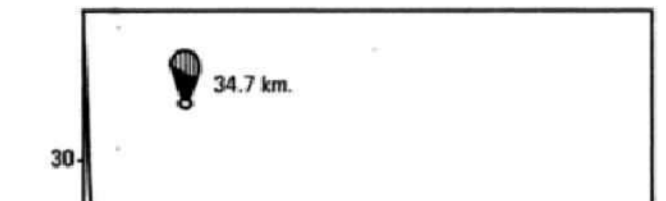


Fig. 3.9 – Atmospheric pressure decreases with increasing altitude above the Earth's surface

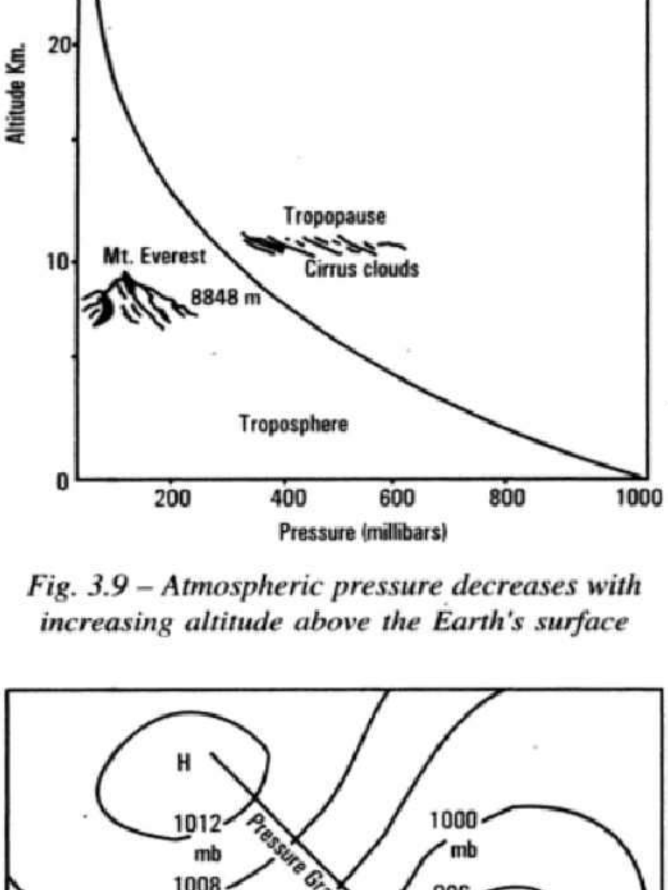


Fig. 3.10 – Pressure gradient and wind direction

an important transfer mechanism for both energy and mass. In the process, the imbalance between equatorial energy surplus and polar energy deficit is partly resolved; Earth's weather patterns are generated and ocean currents are produced.

The atmospheric circulation, speed and direction of winds are controlled by several forces. A brief description of these forces have been given in the following:

1. Gravitational Force of the Earth. The gravitational force of the Earth is practically uniform, equally compressing the atmosphere near the ground world-wide. Density of air pressure decreases as altitude increases.

2. The Pressure Gradient Force: This force drives air from areas of higher pressure to areas of lower pressure, causing wind **(Fig. 3.10)**.

3. The Cariolis Force: It is a deflective force. A deflective force appears to deflect wind from a straight path in relation to Earth's rotating surface – to the right in the Northern Hemisphere and to the left in the Southern Hemisphere **(Fig. 3.11)**.

4. The Friction Force: The friction force drags on the wind as it moves across surfaces; it decreases with height above the surface. The effect of surface friction extends to a height of about 500 m and varies with surface texture, wind speed, time of day and year, and atmospheric conditions. Rougher surfaces produce more friction. All four of these forces operate on moving air and water and affect the circulation pattern of global winds **(Fig. 3.12)**.

Direction of Winds

Winds are named for the direction from which they come. A wind blowing from east to west is an *east wind*, while a wind blowing from west to east is a *west wind* **(Fig. 3.13)**.

Geostrophic Winds (Rossby Waves)

Geostrophic winds are the winds moving between pressure areas along the paths that are parallel to the *isobars*. In the upper troposphere the pressure gradient force equals the Coriolis force so that the amount of deflection is proportional to air movement **(Fig. 3.14)**. Geostrophic winds are characteristics of upper tropospheric circulation (usually above

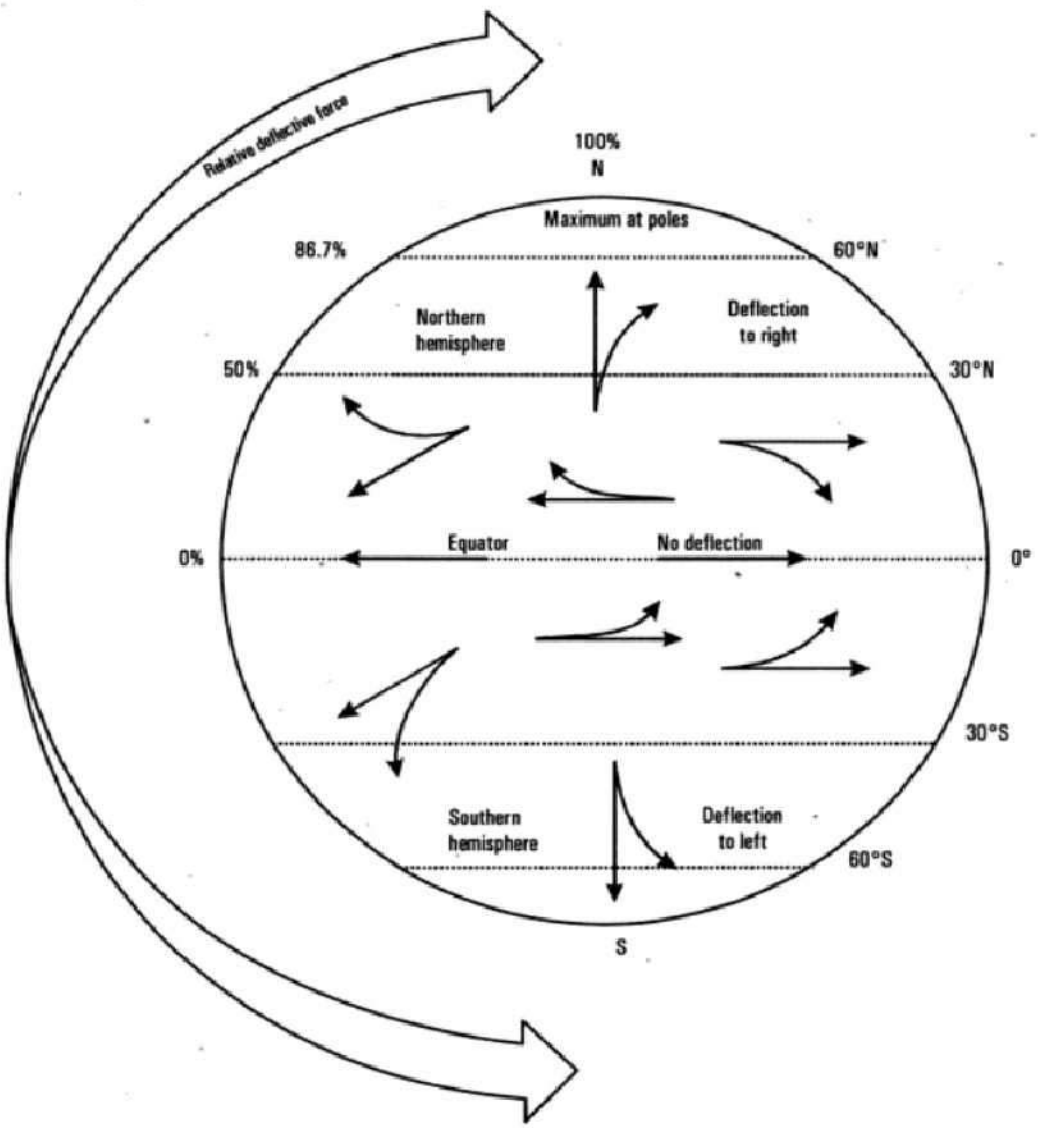


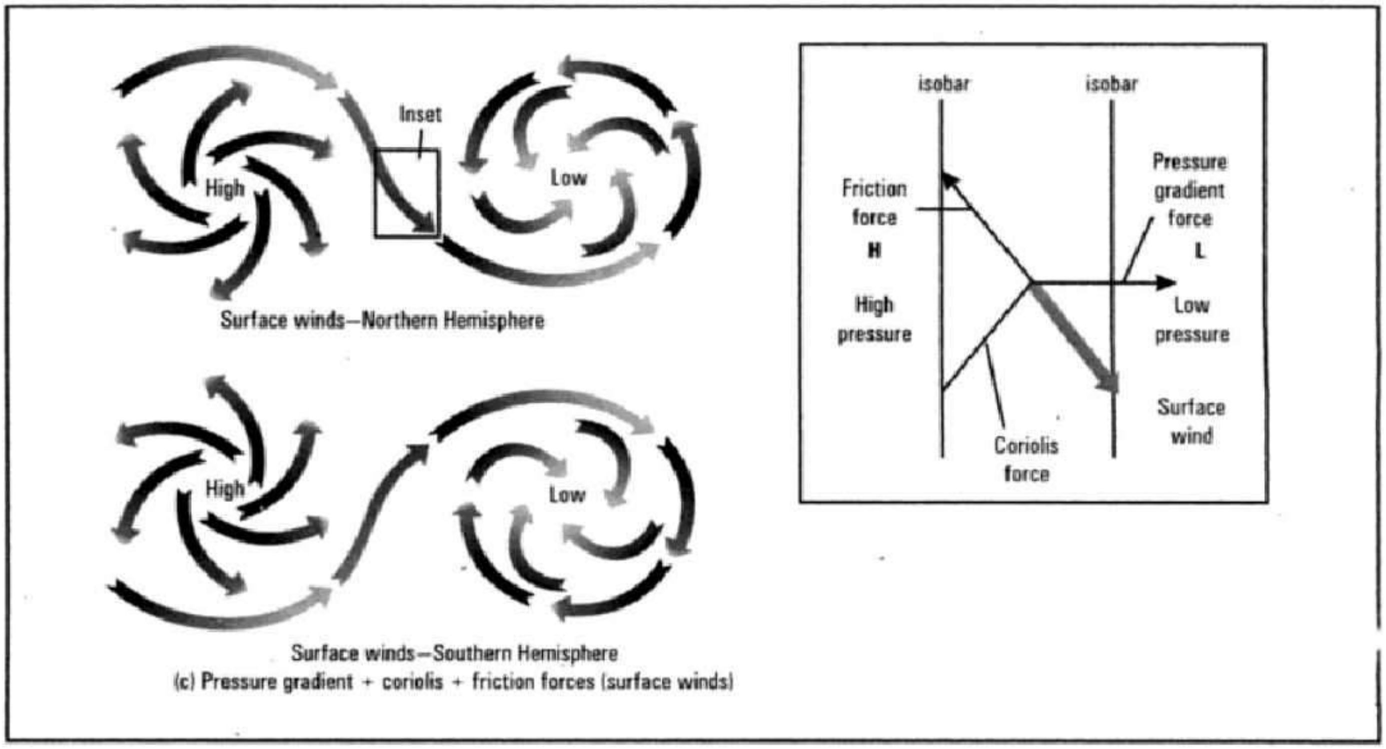
Fig. 3.11 – The Coriolis effect acts to deflect the paths of winds or ocean currents to the right in the northern hemisphere and to the left in the southern hemisphere as viewed from the starting point

500 meters). The geostrophic air blows parallel to the isobars. In other words, the air does not flow directly from high to low pressure, but around the pressure areas instead, remaining parallel to the isobars and producing the characteristic pattern. In the upper troposphere the pressure gradient force equals the coriolis force so that the amount of deflection is proportional to the air movement.

In other words, the geostrophic winds occur when the force exerted on the air by the pressure gradient is equal to the opposing coriolis force (assuming straight or nearly straight isobars, when the isobars are strongly curved, the effect of centrifugal force should be added in). The net result is a wind blowing parallel to the isobars, with speeds proportional to the pressure gradient. Except in low latitudes, where the coriolis force is minimal, the actual wind is the same as that of the geostrophic wind.

Horizontal Distribution of Air Pressure

There is a high degree of variation in the distribution of air pressure. In all, there are seven pressure belts on the globe. On the basis of mode of genesis pressure belts are divided



(c) Pressure gradient + coriolis + friction forces (surface winds)

Fig. 3.12 – Effect of friction force and coriolis force

into two broad categories, i.e. (i) the Low Pressure Belts, and (ii) the High Pressure Belts **(Fig. 3.15)**. A brief description of the pressure belts is given below:

1. Equatorial Low Pressure Belt: The equatorial low pressure belt is located on either side of the geographical equator. This belt is also known as 'Doldrum' in which the air ascends upward. It extends between 5°N and 5°S latitudes. This low pressure belt is however, not stationary and shifts north and south with the change in seasons **(Fig.3.15)**.

2. Subtropical High Pressure Belt: The subtropical high pressure belts are located 25°-35° in both the hemispheres. These high pressure belts are dynamically induced. The convergence of winds at higher altitudes above this zone results in the subsidence of air from higher altitudes. Thus, descent of winds results in the contraction of air volume, increase density, and ultimately cause high pressure **(Fig. 3.15)**.

3. Sub-Polar Low Pressure Belt: The belt of sub-polar low pressure is located between 60°-65° latitudes in both the hemispheres. This low pressure belt is dynamically induced. From the polar high pressure areas, the surface air spreads outward due to rotation of the Earth, resulting into low pressure belts. In the Northern Hemisphere, these low pressure belts are found mainly along the Aleutian Islands in the Pacific Ocean and between Greenland and

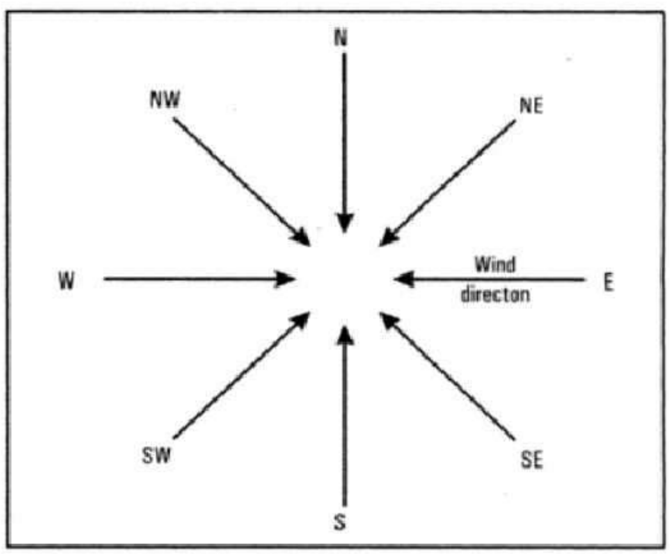


Fig. 3.13 – Winds are designated according to the compass point from which the wind comes. An east wind comes from the east, but the air is moving westward

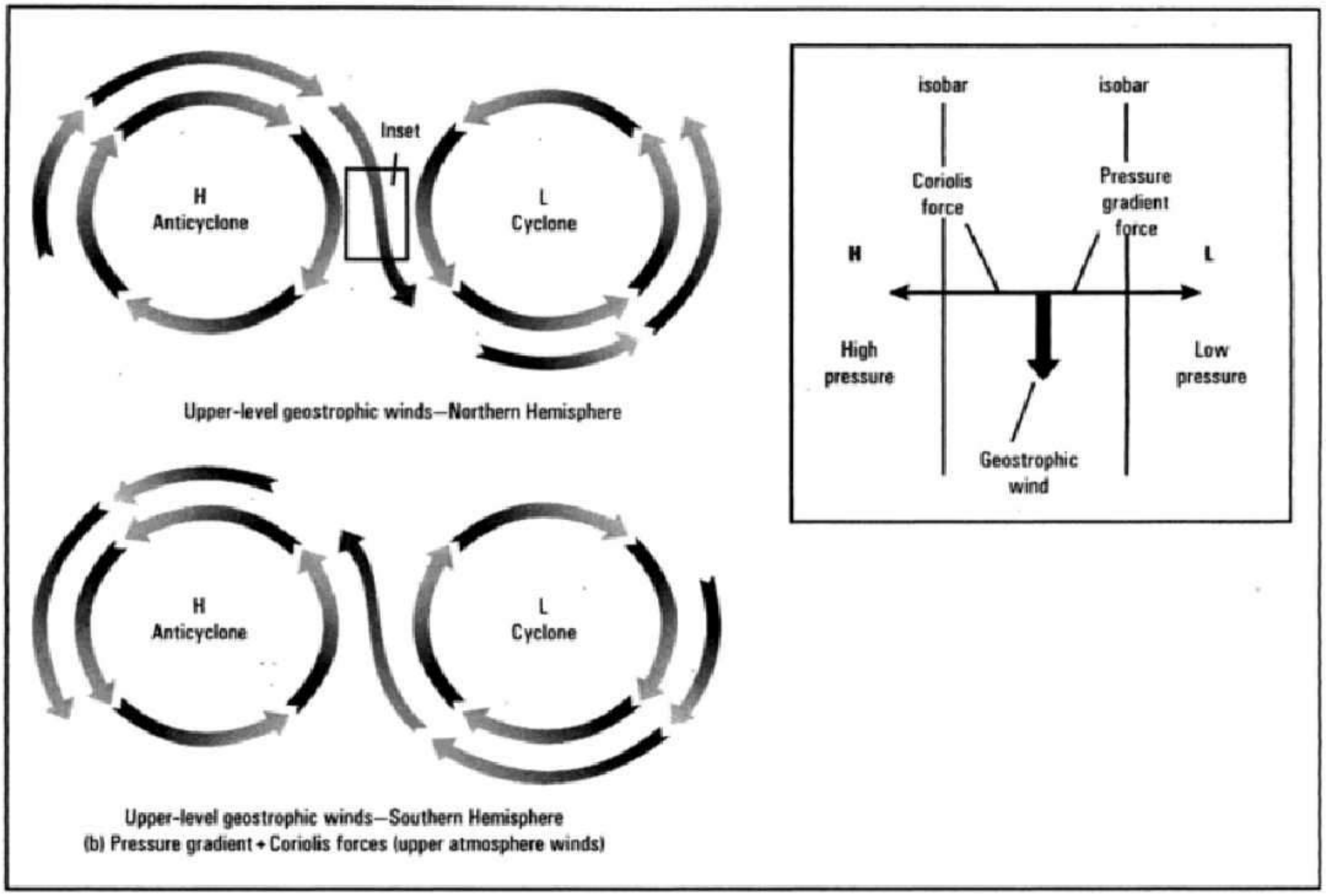


Fig. 3.14 – Geostrophic wind (After R.W.Christopherson, 1995)

Iceland in the Atlantic ocean. This belt is, however, contiguous and more persistent in the Southern Hemisphere **(Fig.3.15)**.

4. Polar High Pressure Belts: High pressure is found at the poles throughout the year. The polar regions receive little energy to put it into motion. The variable cold dry winds moving away from the polar region are anti-cyclonic (clockwise), descending and diverging in the Northern Hemisphere (counterclockwise in the Southern Hemisphere) and forming weak, variable winds called *polar easterlies*. Of the two polar regions, the Antarctic high pressure is significant in terms of strength and persistence. In the Arctic, a polar high-pressure is less pronounced, and when it does form, it tends to locate over the colder northern continental areas in winter (Canadian and Siberian highs) rather than directly over the relatively warmer Arctic Ocean **(Fig. 3.15)**.

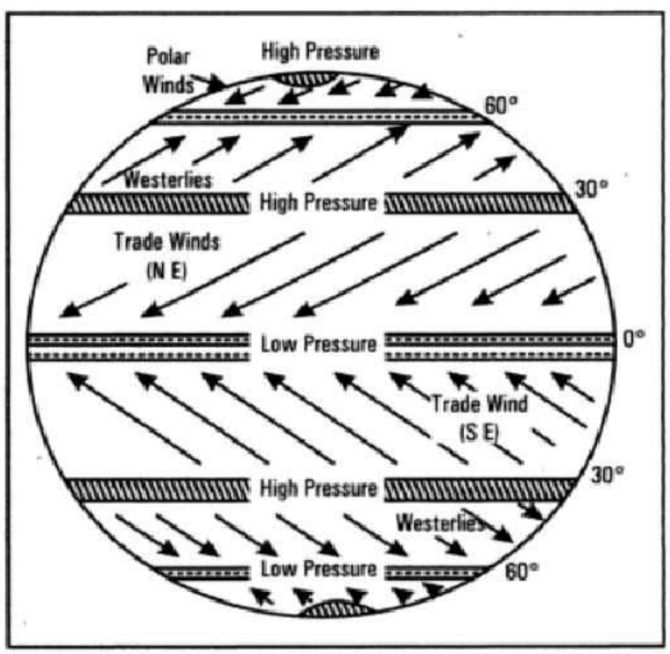


Fig. 3.15 – Air–pressure and wind belts

Shifting of Pressure Belts

The seven pressure belts described above, seldom remain stationary in their latitudinal zones. There are daily, seasonal and annual change in air pressure because of northward and southward movement of the Sun (summer and winter solstices); contrasting nature of the heating, and cooling of land and water surfaces. The lowest pressure, generally develops between 2 and 4 p.m. due to maximum temperature, while the highest pressure is recorded between 4-6 a.m. due to minimum temperature.

All the pressure belts move northward with the northward movement of the Sun during the summer solstice when the Sun's rays are vertical at the Tropic of Cancer. On the other hand, all the pressure belts move southward during the winter solstice when the Sun is vertical at the Tropic of Capricorn. The pressure belts occupy their normal ideal position at the vernal equinox (21st March) and autumnal equinox (23rd September) when the Sun is vertical at the equator. Seasonal shifting of pressure belts has been shown in **Fig. 3.16**.

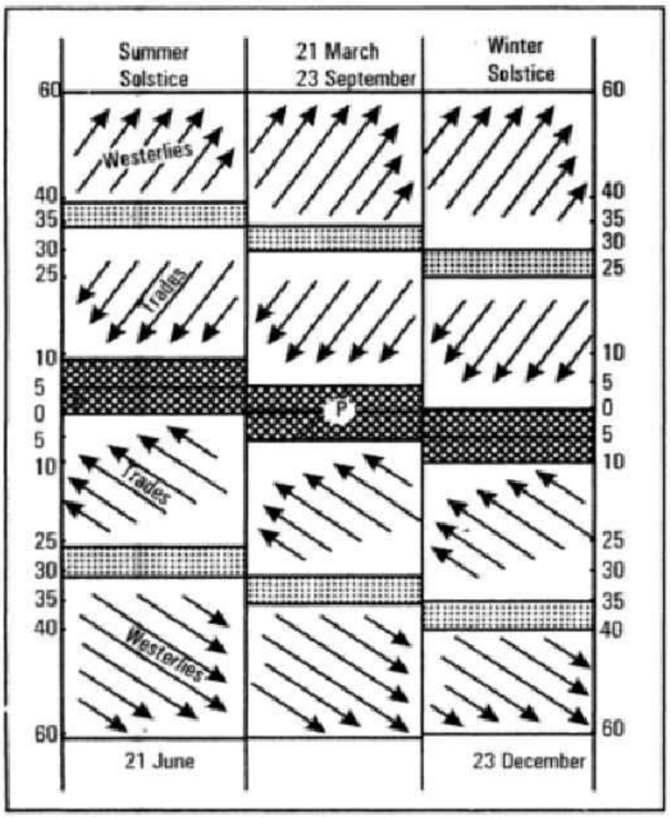


Fig. 3.16 – Shifting of pressure and wind belts

The seasonal shifts in the location of pressure belts has great climatic and weather significance. The seasonal shifting of pressure belts and winds introduce changes in the weather conditions of transitional zones and give birth to certain typical climates, namely Monsoon climate, Mediterranean climate, and West European climate, etc.

Average Conditions of Air Pressure

The average conditions of air pressure during January and July have been shown in **Figs. 3.17-A and 3.17-B**. The pressure shown in these figures are the averages of over 30 years. They are corrected for the elevation of the recording station, so that pressures are shown for sea level. The average barometric pressure is about 1013 mb. Values greater than that are '*high*' (red lines), while those lower are '*low*' **Fig. 3.17.**

July Patterns of Air Pressure

The month of July is the period of summer in the Northern Hemisphere. In the month of July, there are several areas having low pressures especially the Central Asia, Siberia, the Northen Plains of India, and the western parts of North America. On the oceans, high pressure is recorded around the Hawaiian Islands (Pacific Ocean) and the Sea of Azores (North Atlantic Ocean). In the month of July, all the high pressure cells develop over the ocean in both the hemispheres **(Fig. 3.17-A).**

January Patterns of Air Pressure

It may be observed from **Fig. 3.17-B** that in the month of January, the equatorial low pressure is found in a narrow zone south of the equator. The subtropical high pressure belt has been pushed southward. In the month of January high pressure is recorded in Siberia and Canada, and the low pressure along the Aleutian Islands and in the vicinity of Iceland. The higher latitudes of the Southern Hemisphere record high pressure.

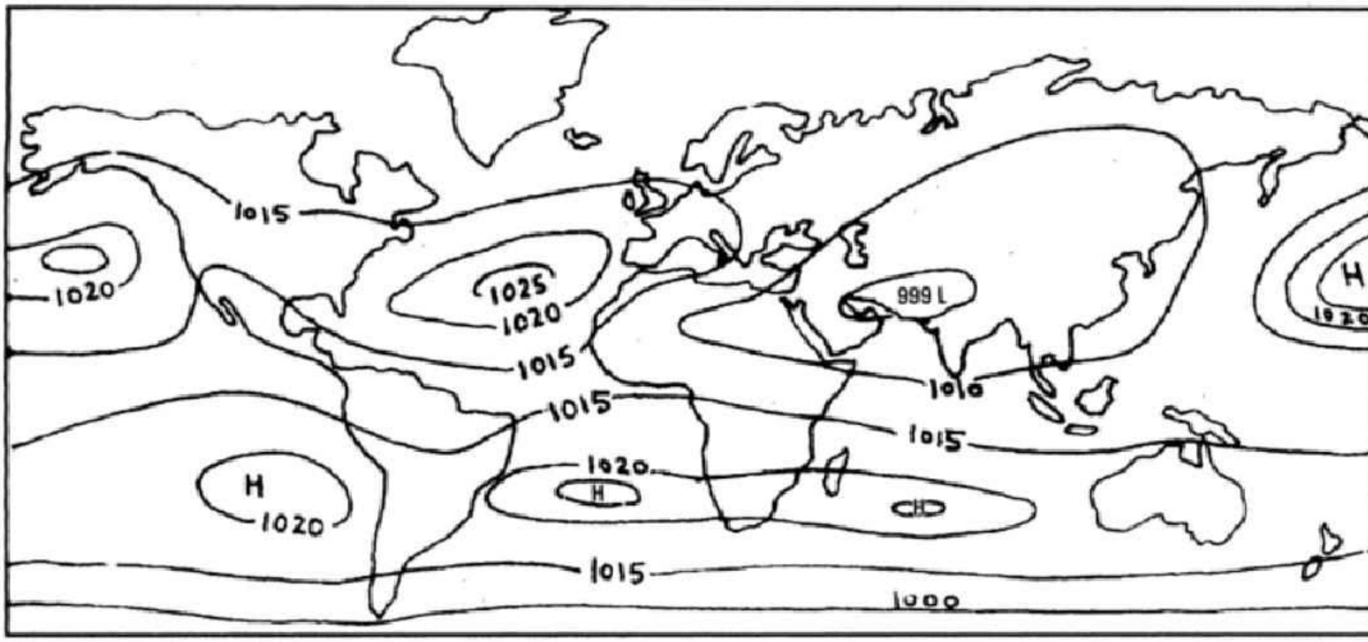


Fig. 3.17 A – Distribution of air pressure in July (Figures in millibars)

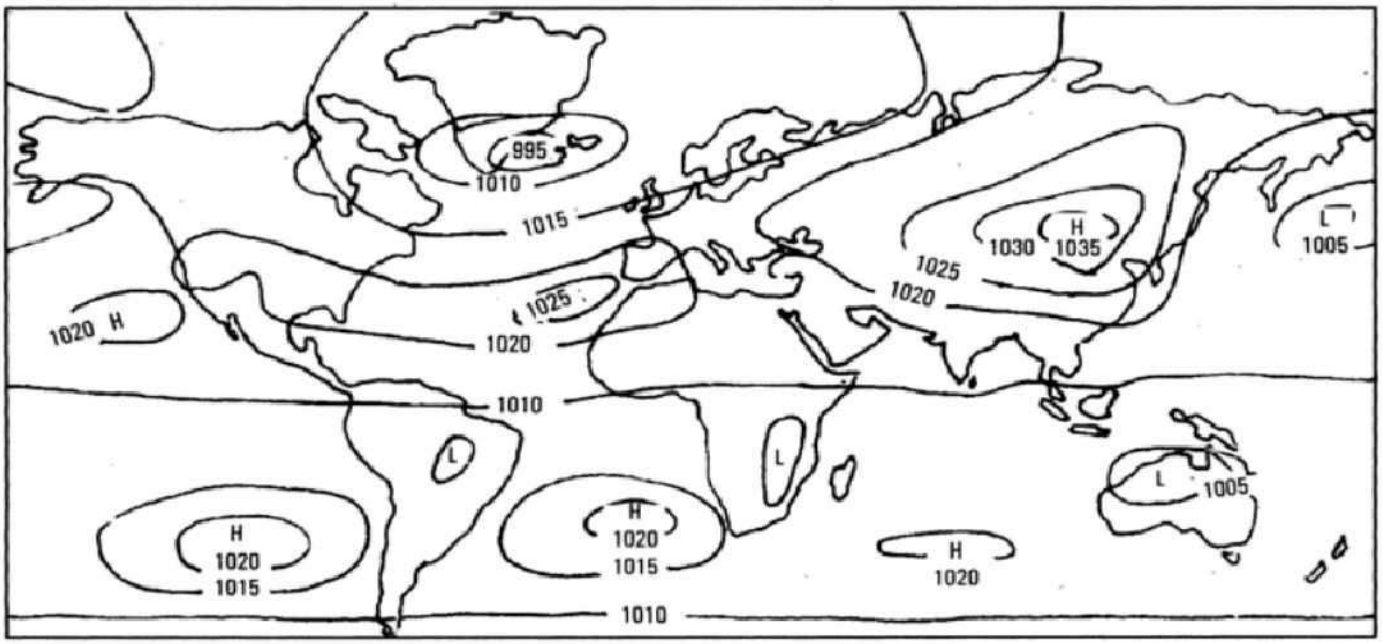


Fig. 3.17 B – Distribution of air pressure in January (Figures in mb)

Meridional Circulation

Air does not simply flow from equator to the poles, it circulates in giant cells known as Hadley and Ferrel cells. As air warms in the equatorial region (Doldrum), it expands, becoming less dense and rises. The ascending air cools and condenses, causing heavy rainfall in the equatorial region. This cool air then sinks, forming high pressure belts in the subtropics. At surface level in the tropics, these sinking currents are deflected poleward as the westerlies and toward the equator as the trade winds (easterlies). In the polar regions, they become the polar easterlies.

The concept of meridional circulation of atmosphere was put forward by *George Hadley in 1735*. He based the model on the basic

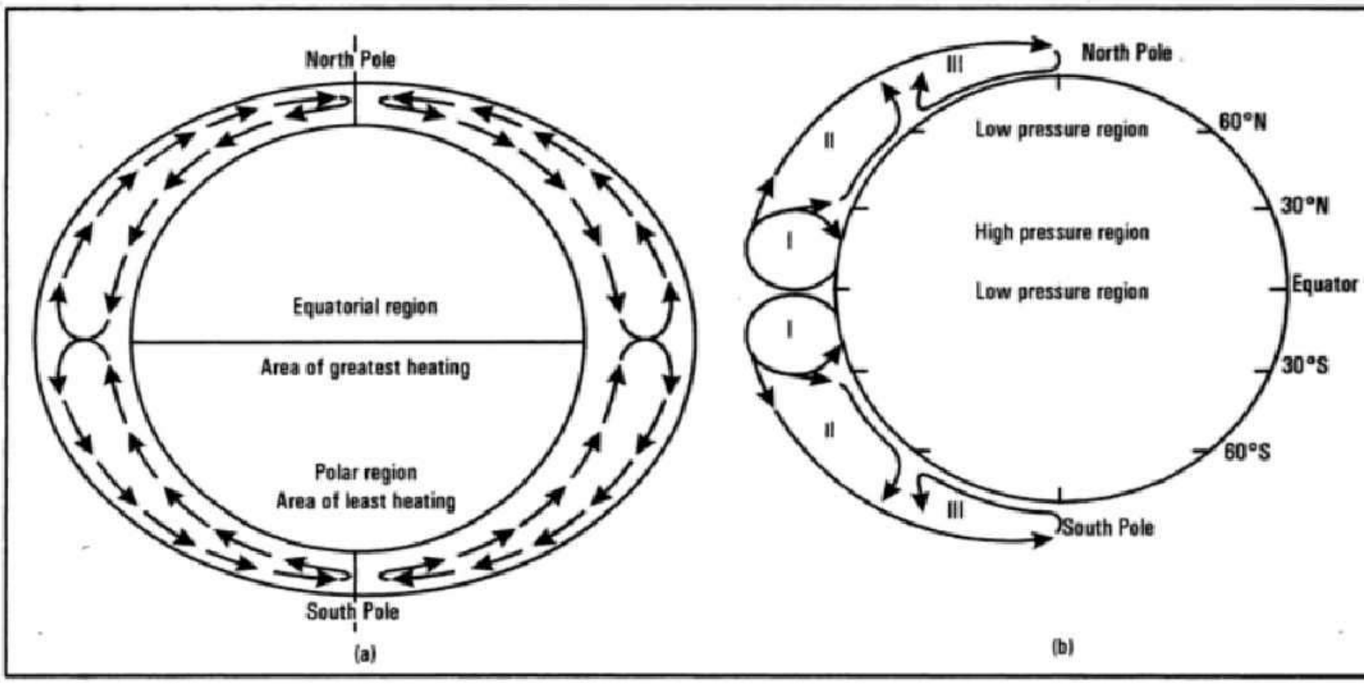


Fig. 3.18 – (a) The fundamental driving mechanisms of the general circulation (b) A three–cell model that results from differential heating, the earth's rotation, and the fluid dynamics of the atmosphere

pressure differences brought about by uneven heating of the Earth's surface. Hadley postulated that cold air descended at the poles and flowed along the Earth's surface toward the warmer equator. This flow will be countered by rising warm air at the equator and a flow aloft toward the poles so that two large Hadley cells existed in each hemisphere **(Fig. 3.18-a)**.

Observation of global wind patterns and, later, theoretical work showing that the rotation of the Earth prevents the development of a single convective cell led to a modified view. Hadley's model was altered by *Palmen in 1951* to include a three-cell structure between the poles and the equator. In the opinion of Palmen there are the following three cells in each hemisphere **(Fig. 3.18 –b)**.

Tropical or Hadley Cell

There is one Hadley cell in each hemisphere between roughly 30° N and S latitudes. They are known as Hadley cells in honour of George Hadley, the London lawyer and philosopher who worked out an overall scheme of wind circulation in 1735. The heated air rising near the equator in the Inter-Tropical Convergence Zone (ITCZ), flowing pole-ward aloft, descending at a latitude of 30°-40°, especially in the eastern half of the very intense subtropical high pressure areas at these latitudes, and then flowing either pole-ward or equator-ward near the Earth's surface. Because of the Earth's rotation the equator-ward moving currents are deflected towards the right and become the north-east. In the Southern Hemisphere they are deflected towards the left and therefore their direction is from south-east towards north-west **(Fig. 3.19)**.

Ferrel Cell

The mid-latitude circulation cells of each hemisphere are named *Ferrel cells* after William Ferrel, the American who discovered their inner working in mid-nineteenth century. The polar front cell is found in the mid-latitudes between 30° and 60° N and S. In these latitudes the pattern of circulation of air is just the reverse of the tropical (Hadley) cell. In this cell, the surface air flow is directed towards the pole, and because of Coriolis force, the winds blow almost from west to east **(Fig. 3.19)**.

Polar Cell

Moreover, air that has grown cold over the poles begins moving toward the equator at the surface. Between 50° and 60° latitude in each hemisphere, this air has taken up enough heat and moisture to ascend. However, this polar air is more dense than the air in the adjacent Ferrel cell and does not mix easily with it. At high altitude, the ascending air from 50° to 60° latitudes turns poleward to complete a third circuit. These circuits are known as Polar cells **(Fig. 3.19)**.

Thus, three large atmospheric circulation cells – (i) Hadley cell, (ii) Ferrel cell, and (iii) Polar cell–exist in each hemisphere. Air circulation within each cell is powered by uneven solar heating and influenced by the coriolis effect.

Winds be classified into: (i) Permanent winds, (ii) Periodic winds, (iii) local winds, and (iv) variable winds (cyclones and anticyclones).

(i) Permanent Winds

The trade winds, anti-trade winds, and polar winds are known as the permanent winds. These winds follow a define track throughout the year.

(a) Trade Winds Easterlies

Winds with an easterly component which blow from the subtropical high pressure areas around 30° of latitude towards the equator. They derive their name from the Latin *'trado'*, meaning constant direction, and has given rise to the phrase *'to blow trade'* meaning *'to blow along a regular track'*. Although only surface winds, they are a major component in the general circulation of the atmosphere as they are the most consistent wind system on the Earth. The trade winds blow with great regularity over the oceans throughout the year **(Fig. 3.20)**.

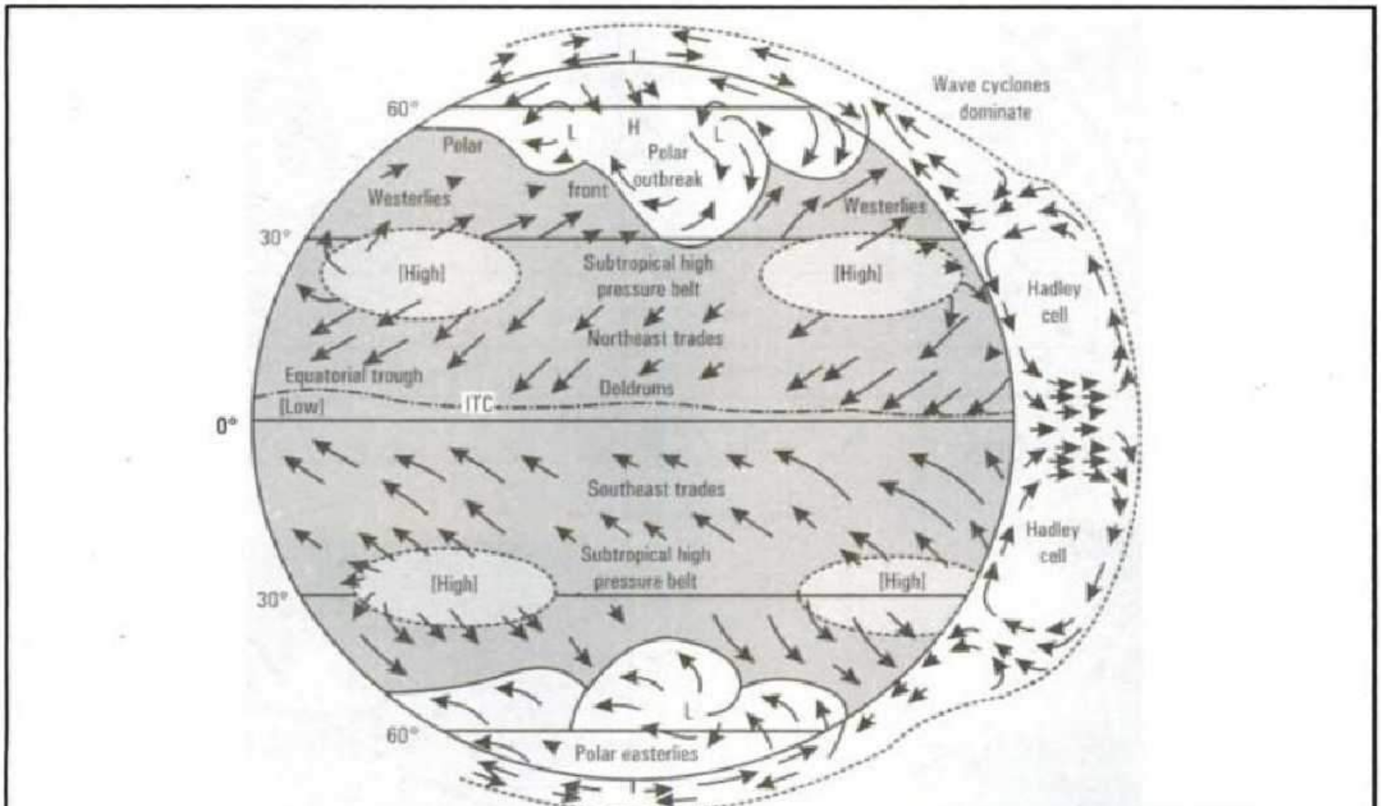


Fig. 3.19 – This schematic diagram of global surface winds and pressures shows the features of an ideal Earth, without the disrupting, effect of oceans and continents and the variation of the seasons. Surface winds are shown on the disk of the Earth, while the cross section at the right shows winds aloft

The main function of the trade winds is to remove surplus heat from the subtropical high pressure belt by evaporating great quantities of heat from the tropical oceans. This process helps in maintaining the global heat balance. Although weather in the trade wind region is normally fine and quite, tropical cyclones are often experienced in this belt. In general the average speed trade winds varies between 15 and 30 km per hour, while calms are extremely rare and clear sunny conditions are usual.

Horse Latitudes

The subtropical high pressure belt of the Ocean of North Pacific and North Atlantic oceans is known as the horse latitudes. This is a belt of weak, variable winds and frequent calms.

Anti-Trade Winds or Westerlies

The westerly winds, which blow with great frequency and regularity in the region lying on the poleward sides of the subtropical high pressure areas or horse latitudes are known as the *anti-trade winds* or westerlies. In other words, they are the permanent winds blowing from the subtropical high pressure belts (30°-35°) to the sub-polar low pressure belts (60°-65°). The general direction of the westerlies is from south-west to north-east in the Northern Hemisphere, and from north-west to south-east in the Southern Hemisphere **(Fig. 3.20).**

The weather in the areas of the westerlies are marked by constant procession of depressions (temperate cyclones) and

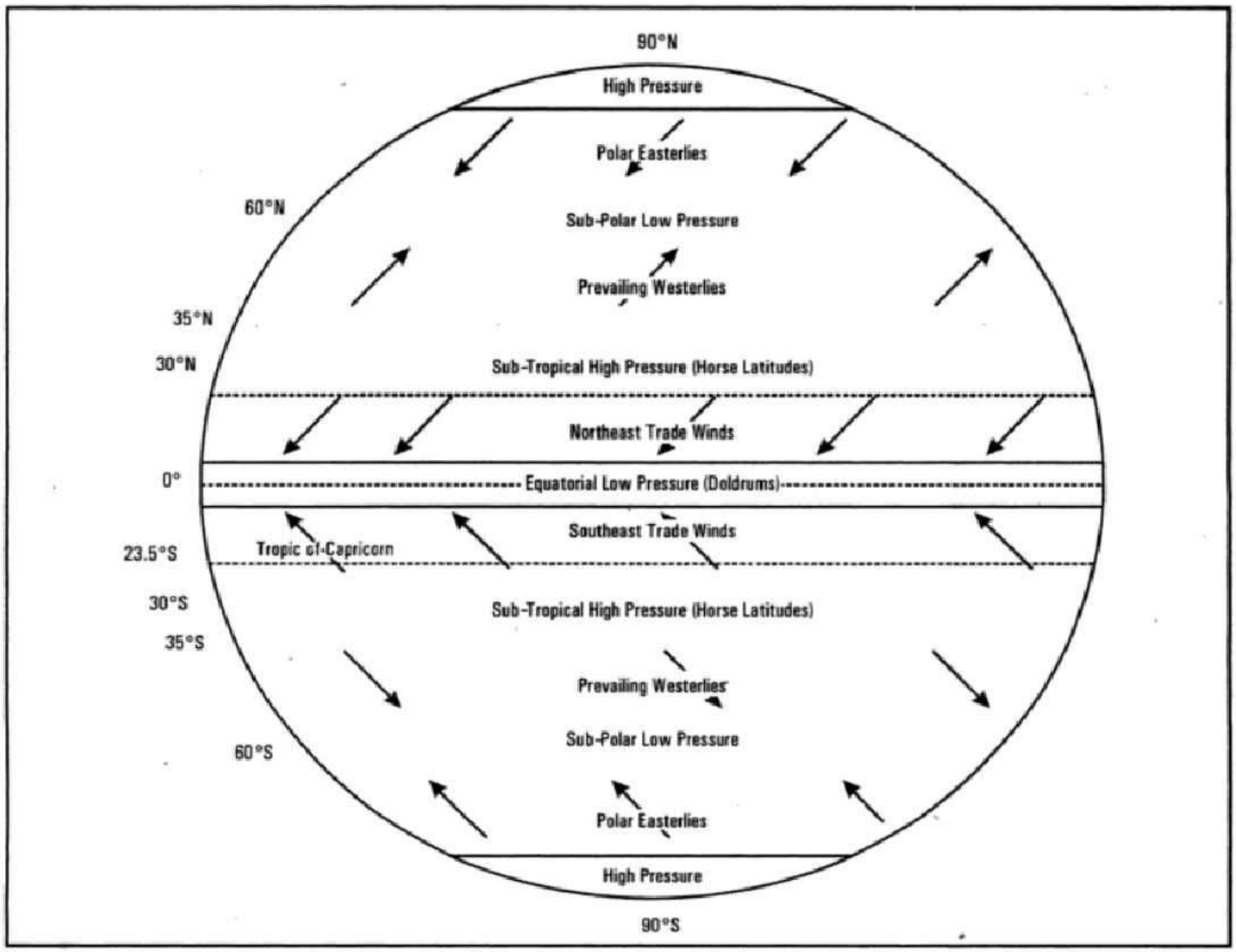


Fig. 3.20 – Major pressure belts and wind system

anticyclones moving eastward. In the winter season, the North Atlantic Ocean is probably the stormiest region of the world at any season, but in summer, the winds and weather are much less violent. In the Southern Hemisphere, the westerlies blow with great strength throughout the year, and they have been given the name of *'roaring forties'*.

Roaring Forties

In the region between the latitudes of 40°S and 50°S the prevailing westerlies blow unobstructed by land. The westerlies in this region blows with great regularity and strength. The frequency of depressions brings storminess, cloudiness, and rough seas – a notoriously hazardous shipping zone. The westerlies in this belt are often called as roaring forties.

Polar Easterlies

The polar easterlies blow between the 60° and 90° in the polar regions. They are generally sporadic and of low velocity. From the polar areas cold air tends to move towards equator. The polar easterlies are quite pronounced in the Southern Hemisphere. In the Northern Hemisphere, pressure and wind conditions are so complicated that these polar winds are extremely irregular. Being cold and dry, polar winds give very little precipitation **(Fig. 3.20)**.

(ii) Periodic Winds - Monsoon

Derived from the Arabic word *Mausim*, meaning season, the term originally referred to the winds of the Arabian Sea, which blow for about six months from the north-east and for six months from the south-west. The term is now used for other markedly seasonal winds, e.g. the tropospheric monsoon. In the monsoon climate there is a complete reversal of wind direction after every six months, i.e. the wind blows for six months from sea towards land and six months from land towards sea **(Fig. 3.21)**.

The monsoon is the product of many factors working together. One is that the Inter Tropical Conversence Zone (ITCZ) migrates to between 25° and 30°. A second is that the land mass interior records a large change in pressure that enforces the migration of the ITCZ. It is also likely that the Himalaya mountains and the Tibetan Plateau are a very significant topographic barriers, which split the circulation over Asia.

In the winter, the jet stream is over the mountains. The polar high expands and covers much of north-central Asia. Divergence from this strong system north of the Himalayas produces extremely strong offshore surface winds. South of the Himalayas and the jet stream, the anticyclonic flow is much weaker, although offshore flow is most common. In the summer as the temperature differential over the continent diminishes, the jet stream breaks down. The subtropical high and ITCZ shifts rapidly northward and bring the sudden shift of winds onshore over the Indian subcontinent. North of the Himalyas, a weaker convergent system develops with attendant onshore flow of air.

The precipitation is primarily convectional rainfall randomly distributed within the flowing moist air. Some travelling cyclones associated with the ITCZ add further rainfall. The peak season of rainfall moves northward over the subcontinent as the zone of convergence moves northward toward the slopes of the Himalayas.

The salient characteristics of the monsoon climate are to be found mainly in the Indian Subcontinent., where over much of the region annual changes may conveniently be divided as follows:

(i) The season of north-east monsoon:

(a) January and February, winter season;

(b) March to May, hot weather season.

(ii) The season of south-west monsoon:

(a) June to September, season of general rains;

(b) October to December, season of retreating monsoon. (For a systematic description of India seasons, read *'Geography of India'* published by Tata McGraw-Hill).

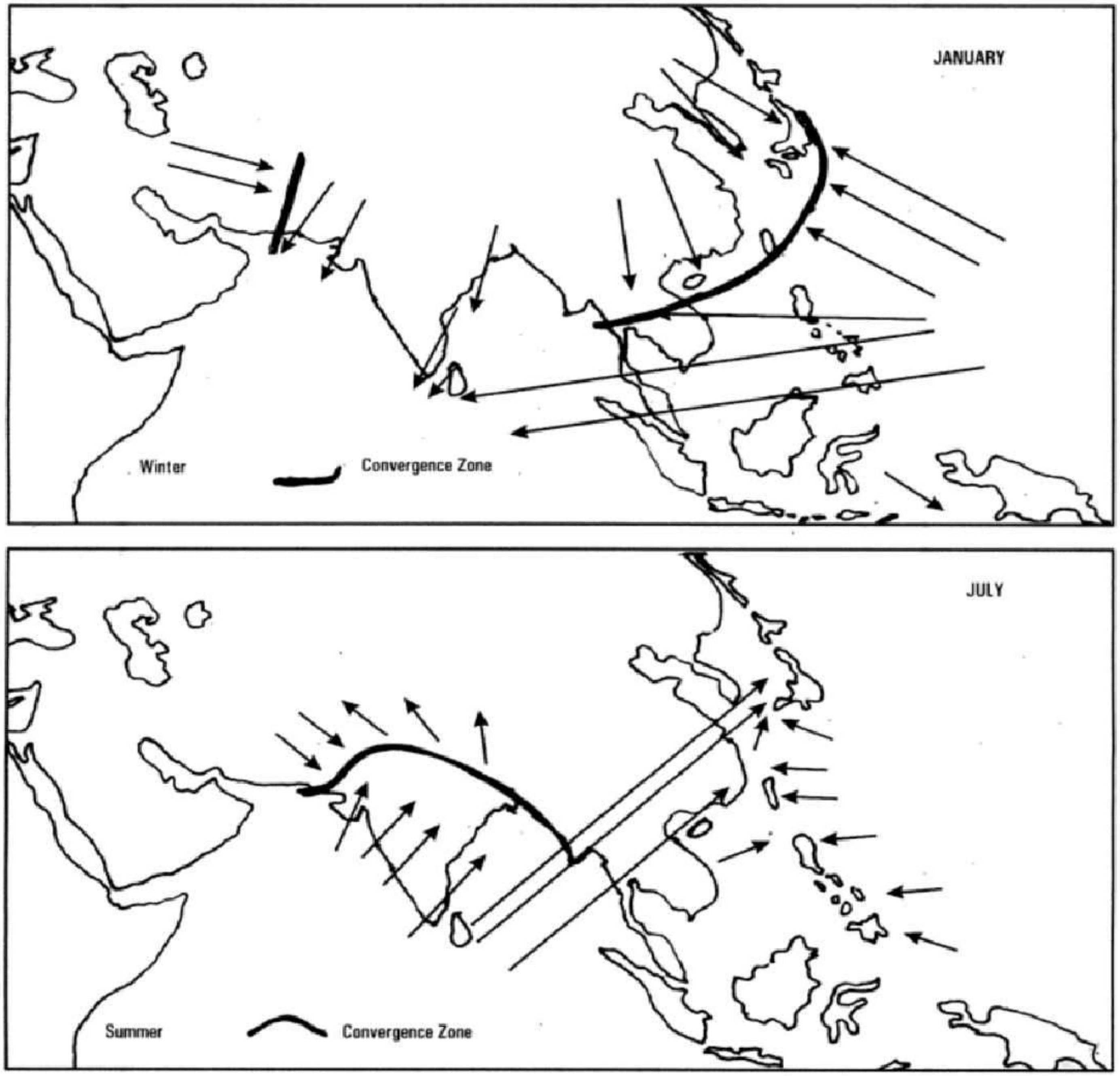


Fig. 3.21 – Winter and summer monsoons in Asia

(iii) Local Winds

Daily variations in atmospheric pressure develop in many parts of the world and lead to distinctive local wind patterns. These variations in pressure result from moving air caused by changing surface temperature through the day, and they result in daily changes in wind direction and velocity **(Fig. 3.22).** There are many locally named winds, and only selected examples have been described briefly in the following:

Sea Breeze

In the hours of sun-rise, land temperatures rise rapidly while water temperatures rise slowly. When the air overlying above the shoreline heats, it expands and its density decreases. The air rises over the land surface and cold air flows

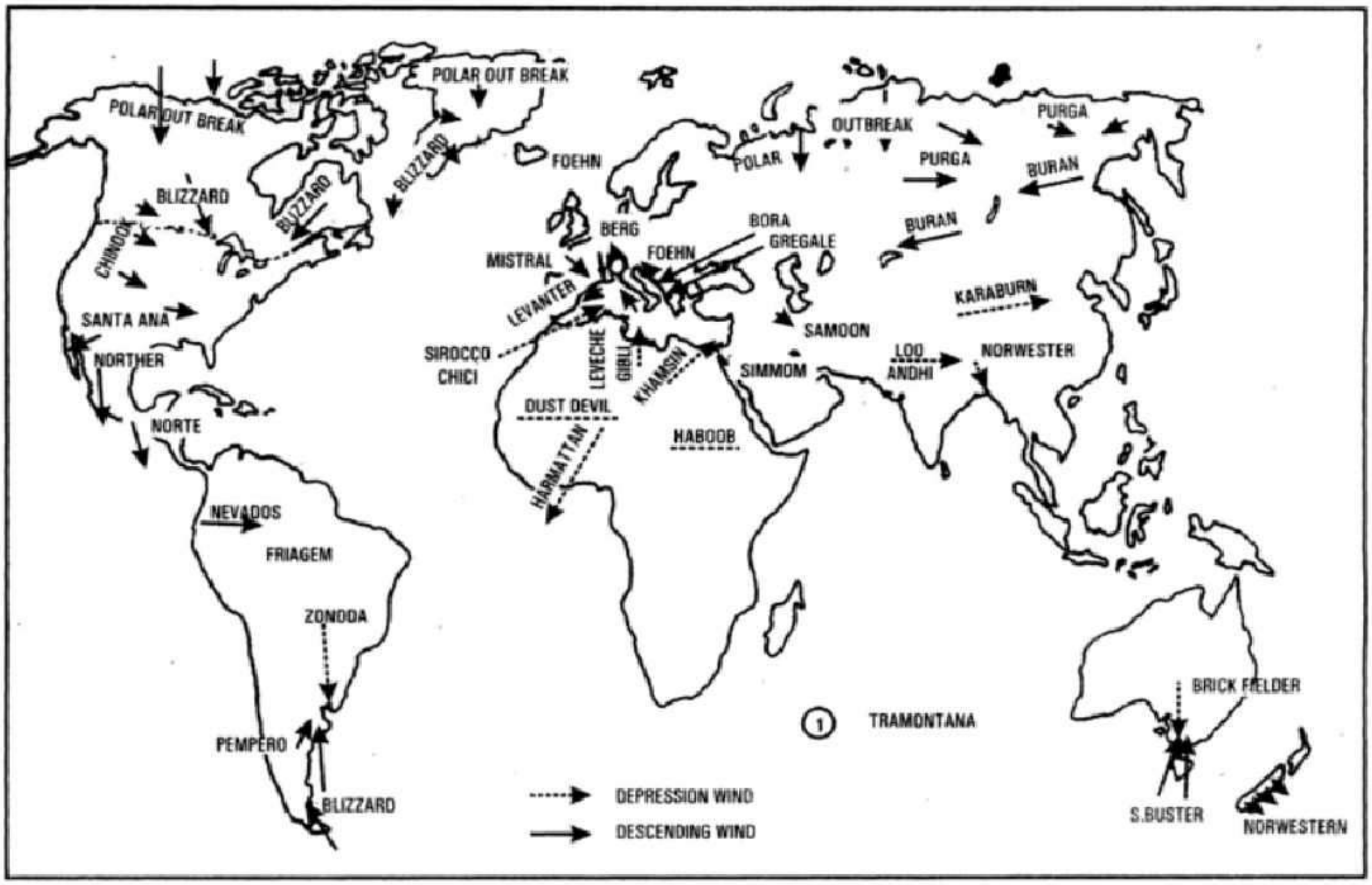


Fig. 3.22 – Main local winds of the world

in from the sea to replace it. This flow of air landward is known as *sea breeze* **(Fig. 3.23-A)**. The sea breeze casually begins several hours after sunrise, about 11 A.M. and peaks in the afternoon when temperatures are the highest. This air may penetrate inland up to 30 km or more along an ocean coast and to a lesser extent around lakes. The sea breeze is gusty and brings a decrease in temperature and an increase in humidity.

Land Breeze

A wind blowing from land to sea (an off shore wind) which develops in coastal areas towards nightfall **(Fig. 3.23-B)**. Pressure is relatively higher above the land than above the sea as the land cools more rapidly in the evening. The temperature and pressure relationships reverse with the higher pressure over the land. At night, however, the contrast between water and land is not as large as it is in the daylight hours. The water surface actually does not gain heat at night, but retains the heat acquired during the daylight period and, thus, remains relatively warm compared with the land. There is usually a lag in the development of the breeze due to the general inertia of the system. The sea breeze does not set in until well after the temperature differences develop.

The land breeze and the sea breeze have a close influence on the lives of fishermen and those who work indoor and outdoor along the coastal areas in the tropics. The fishermen go into the sea to catch fish in the early morning hours when the wind blows from land towards sea, and return to their home around mid-day when the sea breeze support their return journey. It has been observed that the efficiency of workers in the coastal areas of tropics is higher in the afternoon as compared to the forenoon period. This is mainly because the afternoon weather is pleasant and enjoyable.

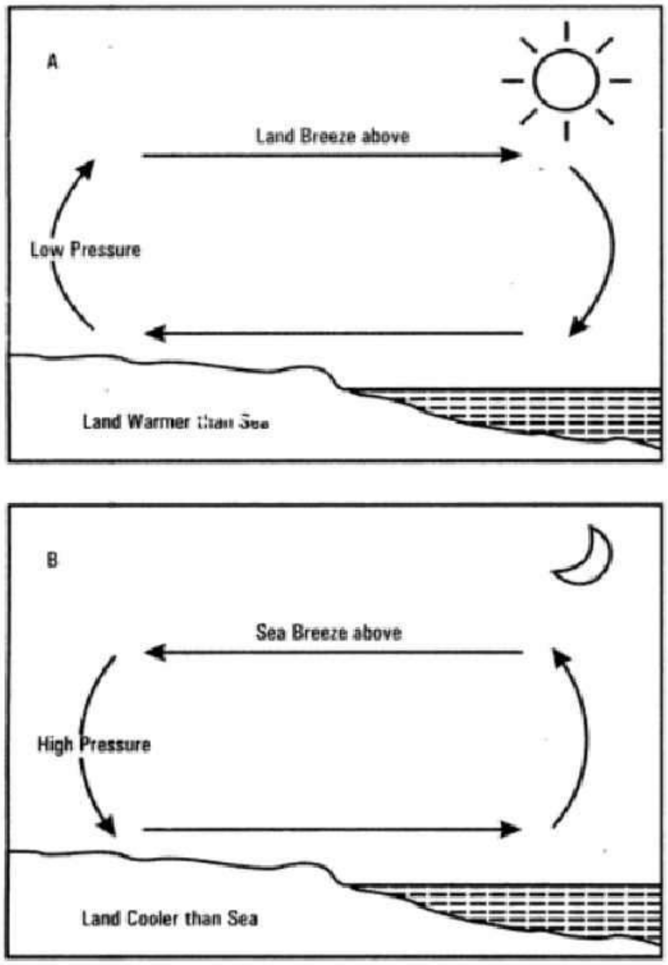


Fig. 3.23 – A– Sea-Breeze and B – Land-Breeze

Mountain and Valley Winds

There is a reversal in the direction of winds in the mountains and their valleys. These winds are known as the mountain and valley winds **(Fig. 3.24).** In the daytime, the valley and slopes of mountains receive heat from the sun. The air near the surface heats, expands, and rises up the mountains . This breeze, called the *valley wind* for the place of origin, is a warm wind and a daytime or late afternoon phenomenon. The clouds often seen forming over the hills in the afternoon are the result of condensation taking place as the air rises to cooler heights over the mountain. At night the valley walls become cool. As the air at the surface cools, it flows down the slope due to greater density. This is the mountain wind, also known as the night breeze. In some mountain regions subject to frost, the valley slopes are the preferred places of orchards. The air moving up and down the valley slopes reduces the chance of the stagnant conditions conducive to frost formation.

Chinook Winds

Chinook is a local wind that blows on the downward slopes of Rockies. The name comes from the Chinook Red Indians, who live along the lower reaches of the Columbia River. In the language of Red Indians Chinook means 'Snow eating wind'. 'The Chinook is a relatively warm and dry wind. It develops with the uplift of relatively mild stable air ascending windward slopes of mountains. The wind develops fairly quickly with a sharp rise in temperature and a drop in relative humidity. These winds are mostly identified with the sudden change in temperature brought about by these winds. For example, in two minutes, the temperature at Spearfish in South Dakota (1943), rose from -20°C to 7°C. This was a total rise of 27°C in 2 minutes. These winds occur most often in a narrow zone about 300 kilometers east of the crest of the Rockies from New Mexico north into Canada. The form on the leeward sides of mountain ranges is shown in **Fig. 3.25.**

The primary source of heat in the Chinook is the heat of compression. Chinooks form when there is a strong westerly flow of air across the mountains. When there is a strong wind, a trough or cell of low pressure forms on the east side of the mountains. As the air is stable, the low pressure trough pulls the wind down the eastern slope of mountains to its original altitude. The subsiding air heats at the dry adiabatic rate of 10°C/kilometer.

The Chinook is strengthened if precipitation takes place in the air stream as it rises over the windward side of the mountains. Condensation adds heat to the air. When the air descends on the lee-side of the mountains, it is warmer than at the same height on the west side.

A cloud, called a Chinook wall cloud, forms over the Rockies when a Chinook is blowing. The cloud forms and remains over the mountain crests providing a visible sign of the

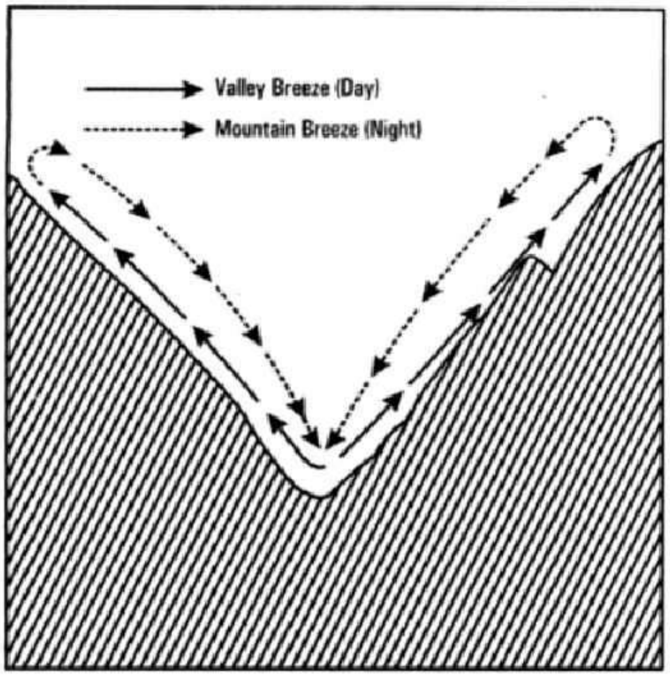


Fig. 3.24 – Mountain and valley winds

wind system. As the air descends the eastern flank of the mountains, the clouds evaporate in the warmer air and a clear sky may exist above the Chinook.

Chinook winds are gusty and can reach velocities as high as 160 km per hour. The Chinook has the capacity to absorb much water. Because they are warm and dry, in the winter they may sublimate large amounts of snow. It is not unusual for these winds to remove 15 cm (6 inch) of snow a day.

They may remove half meter of snow in a single day. It is for this reason that these winds are called *snow-eaters*. The same wind occurs in other parts of the world. It is the Foehn wind in the Alps Mountains of Europe. In Argentina, the wind is a Zonda. The main characteristics of some of the local winds have been presented in **Table 3.1**.

Table 3.1: *Characteristics of Selected Local Winds*

Name (origin)	*Location*	*Characteristics*
Bora	Adriatic Coast	Cold, gusty, north-easterly wind. Frequency at Trieste (Italy), 36 days in one year. Mean winter speed 50 km per hr, summer 40 km per hr. The speed may reach 100 kilometers per hour in winter. Adiabatically warmed wind.
Chinook, in the language of Red Indians-*ice-eater* (from Chinook Indian Territory-USA-Canada)	Eastern slopes of Rockies	A warm wind that may, at times, result in sudden and drastic rise in temperature. May attain 10°-20°C in spring with relative humidity of 10 per cent. Predominant in spring. Adiabatically warmed wind.
Etesian (Gr. Etesia, annual)	Eastern Mediterranean	Cool, dry, north-easterly wind that recurs annually. Summer and early autumn. Associated with regional low pressure system.
Fohn German, possibly from Latin *favonium, meaning* =favouring wind)	Alpine lands (Also in Santa Ana, Southern California)	Similar to Chinook. Characterised by warmth and dryness. Most frequent in early spring.
Haboob (Arabic)	Southern margin of Sahara (Sudan)	Hot, damp wind often containing sand and dust. Of relatively short duration (3 hrs). Average frequency of 24 per year. Early summer with the advance of the ITCZ.

Harmattan	West Africa	Hot, dry wind, characteristically dust laden. All year, but most notable in the winter season. Associated with air flow from the Sahara desert. It is also known as doctor as it reduces the relative humidity in the coast countries of Gulf of Guinea.
Khamsin (Arabic)	North Africa and Arabia	Hot, dry, south-easterly wind. Regularly blows at a 50-day period (Khamsin=50). Temperature varies between 40°-50°C. Same wind with adiabatic modifications includes *Gibli* (Libya), *Sirocco* (Mediterranean), *Leveche* (Spain). Late winter, early spring. Regional low pressure systems.
Levanter (from Levant, eastern mediterranean	Western mediterranean)	Strong easterly wind often felt in the Straits of Gibraltar and Spain. Damp, moist sometimes giving foggy weather for perhaps two days. Fall, early winter to late winter, spring. Regional low pressure systems.
Mistral (master wind)	Rhone Valley below Valence	Strong, cold wind channeled down Rhone Valley. May reach a speed of 100 km per hour. It can cause sudden chilling in coastal regions. (Note also the *Bise*, and equivalent cold north wind in other parts of France.) Most frequent in winter. Regional low pressure systems.
Norther	Texas, Gulf of Mexico to W. Caribbean	Cold, strong, northerly wind whose rapid onset may suddenly drastically lower temperatures. Frequent in winter. Related to circulation pattern over the USA.
Pampero	Pampas of South America	Southern Hemisphere equivalent of the Norther. Winter. Related to large scale pressure patterns.
Zonda	Argentina	A warm, dry wind on lee of the Andes. Can attain 120 kilometer per hour. Comparable to *Chinook* and *Fohn*. In dry weather, carries much dust. Winter.

Source: John, E. et.al., 2002, **Climatology–An Atmospheric Science**, *Low Price, 2nd edn. Delhi, Pearson Education, pp.98-99.*

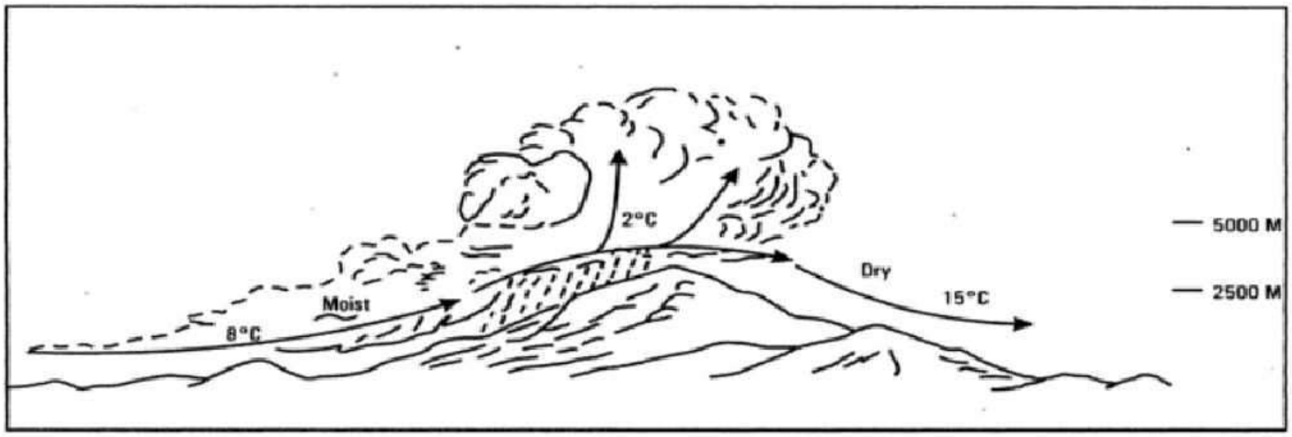


Fig. 3.25 – Chinook or Fohn wind

(iv) Variable Winds

The winds which change their direction after every few hours are known as variable winds. Variable winds include (i) cyclones, and (ii) anticyclones.

Cyclones

Any rotating low pressure system is known as a cyclone. In other words, a thermally or dynamically caused low pressure area of converging and ascending air flows is known as a cyclone. The cyclones may be classified under two headings: (i) temperate cyclone, and (ii) tropical cyclone.

Temperate Cyclone

The temperate cyclones occur in the mid-latitudes of both the hemisphere. These cyclones are born along the polar front, particularly in the region of Icelandic and Aleutian sub-polar low-pressure areas in the Northern Hemisphere.

Fronts

The leading edge of an advancing air mass is known as a front. It is a line of contrasting weather conditions. Fronts may be classified in the following three categories:

Cold Front

The leading edge of a cold air mass, identified on a weather map as a line marked with a series of triangular spikes, pointing in the direction of frontal movement **(Fig. 3.26).**

Warm Front

The leading edge of an advancing warm air mass, which is unable to push cooler, passive air out of the way; tends to push the cooler, underlying air into a wedge shape; noted on weather maps with a series of rounded knobs placed along the front in the direction of the frontal movement **(Fig. 3.26)**.

Occluded Front

In a cyclonic circulation, the overrunning of a surface warm front by a cold front and the subsequent lifting of the warm air wedge off the ground; initial precipitation is moderate to heavy **(Fig. 3.26).**

Cyclogenesis

Development and strengthening of mid-latitude wave cyclone is known as cyclogenesis. On the average, a temperate cyclone takes 3-10 days to progress through the stages of

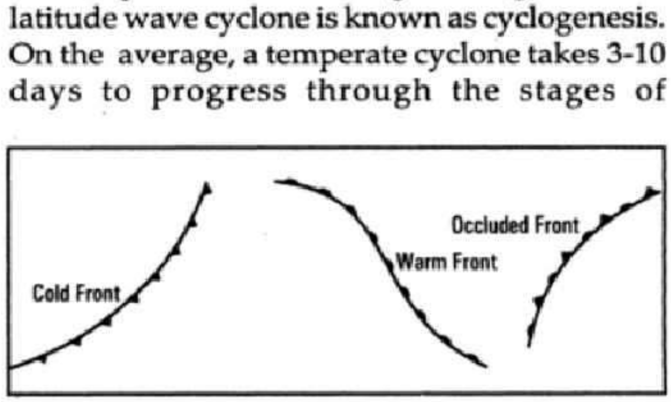


Fig. 3.26 – Types of fronts

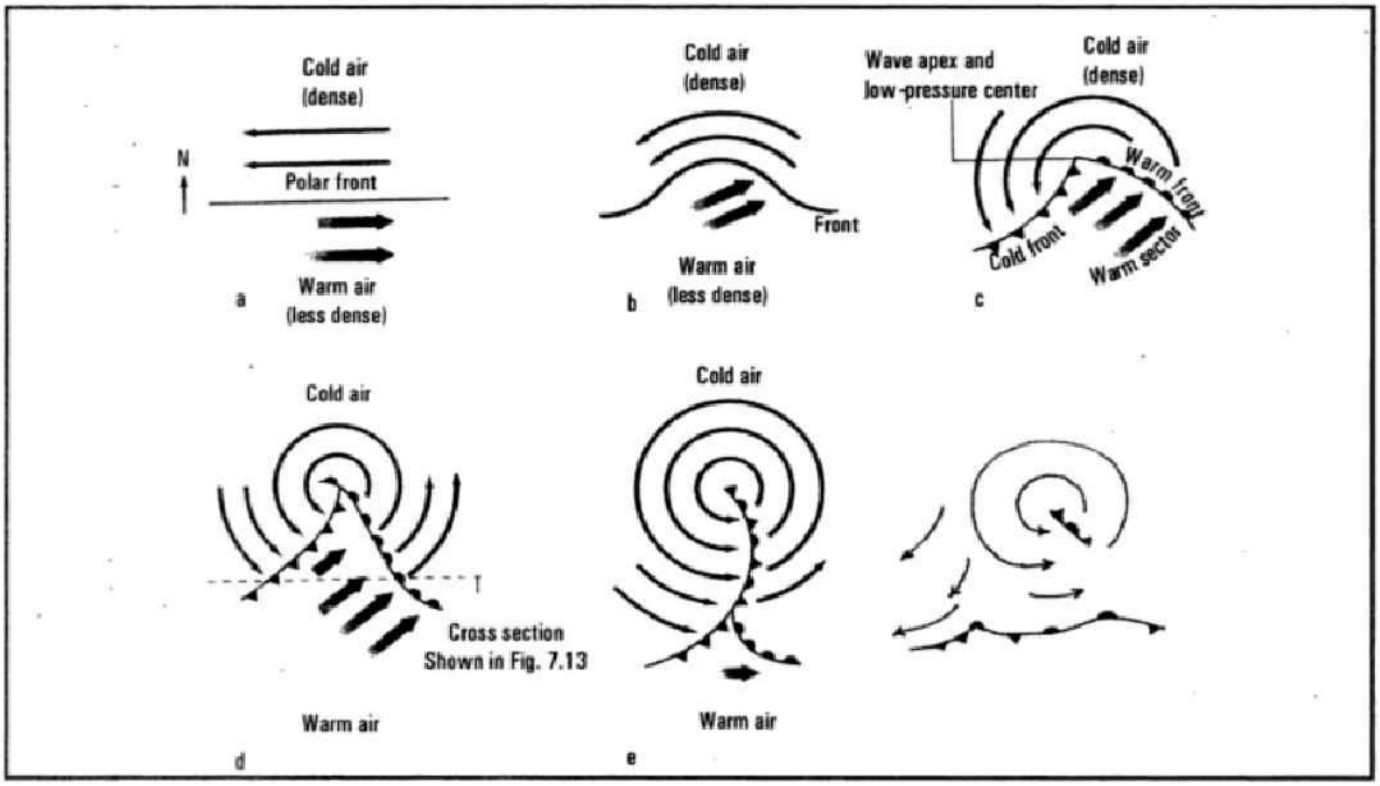


Fig. 3.27 – Origin of extra tropical cyclone (after T. Garrison, Oceanography, 1995, p.125)

development. Along the polar front, cold and warm air masses converge and conflict. The polar front forms a discontinuity of temperature, moisture and winds that establishes potentially unstable conditions.

Polar Front Theory (Frontal Theory)

The polar front theory about the origin of temperate cyclones was put forward by V. Bjerknes and J. Bjerknes in 1918. The period of 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. 3.27)**.

Stage I: The first stage involves the convergence of two air masses of contrasting physical properties and directions.

Stage II: It is called the '*incipient stage*' during which the warm and cold air masses penetrate into the territories of each other.

Stage III: It is mature when the cyclone is fully developed and isobars become almost circular.

Stage IV: Warm sector is narrowed in extent due to the advancement of cold front at a faster rate than warm front, and cold front comes nearer to warm front.

Stage V: This stage starts with the occlusion of cyclone when the advancing cold front finally overtakes the warm front and occluded front is formed.

Stage VI: In the final stage (VI) warm sector completely disappears, occluded front is eliminated and ultimately cyclone dies out **(Fig. 3.27)**.

Characteristics of Temperate Cyclones

(i) The mid-latitude, the temperate cyclone moves in a counter clockwise direction in the Northern Hemisphere and clockwise in the Southern Hemisphere.

(ii) The temperate cyclone may be 1600 km wide, thus a single cyclone may cover the whole of Europe.

(iii) The isobars are elliptical in shape.

(iv) The cold air-mass moves faster than the warm air mass.

(iv) These cyclones move at a gentle pace of 5 to 25 km per hour.

(v) They give light showers which are highly beneficial for the crops and human health and efficiency.

(vi) In the ending part of the cyclone there is thunder and lightning.

(vii) Each cyclone is followed by clear weather (anticyclone).

Weather Associated with Temperate Cyclones

The weather conditions in different parts of the cyclone vary significantly. Before the arrival of a temperate cyclone, air pressure decreases, the Sun and the Moon are generally encircled with *halo*, the high wispy cirrus clouds appear first on the western horizon. Temperature increases suddenly when the cyclone comes very close to the observation point, wind direction changes from easterly to south-easterly. Subsequently, the cloud cover thickens and the sky becomes overcast with dark, thick and low clouds, mainly nimbostratus clouds.

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, the precipitation is also gradual, but of long duration. The Sun is not visible for several hours. In the region of warm front, precipitation is characterised by foggy air and poor visibility. In winter, ice pellets or freezing rain may occur when rain falls from the warm air through the cold air-mass below **(Fig. 3.28)**. At the advent of the cold front, temperature registers marked decrease with the arrival of cold front. The cold air pushes the warm air upward and there is change in wind direction from south-westerly and westerly direction.

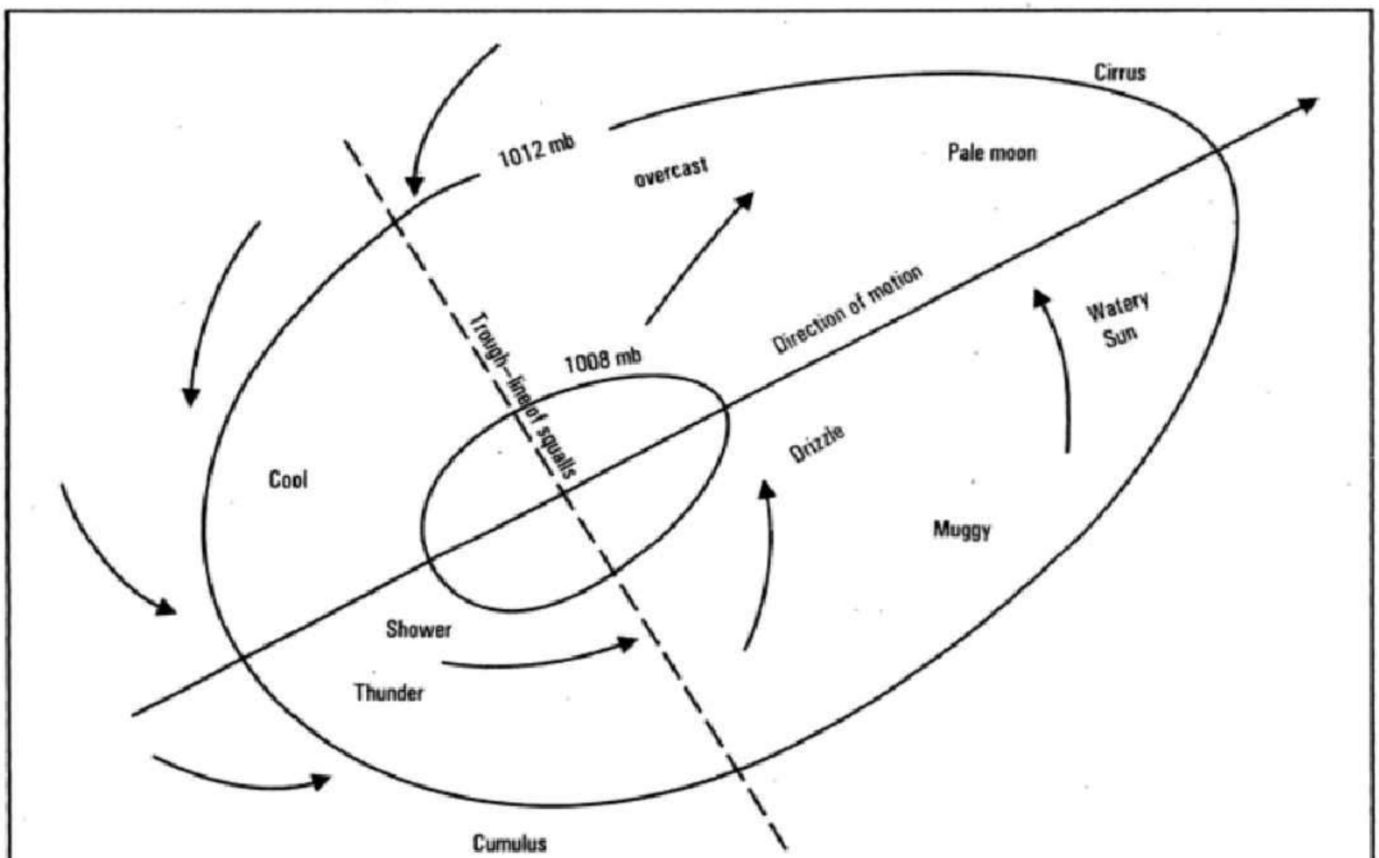


Fig. 3.28 – Weather in temperate cyclone

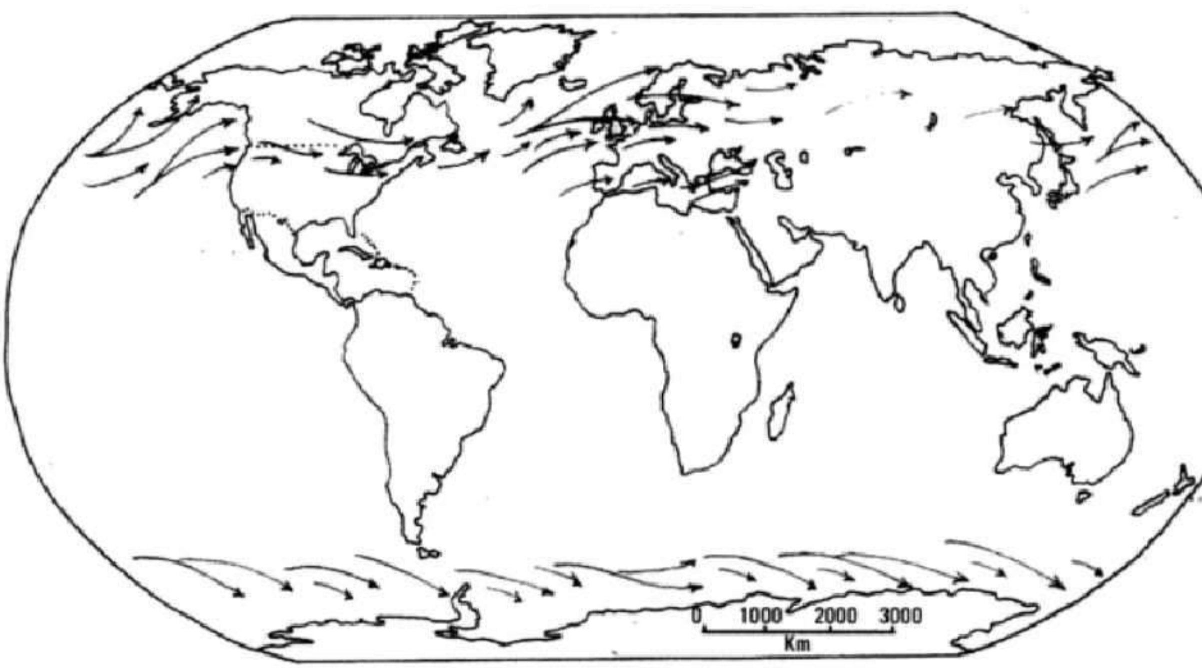


Fig. 3.29 – Principal paths of temperate cyclones

Sky is again covered with clouds which soon results into precipitation. The cold front sector precipitation is in the form of heavy downpour with cloud thunder and lightning, but the precipitation is of short duration and less widespread. The thunder and lightning are the indication of end of the cyclone and arrival of an anticyclone (blue sky).

Geographical Distribution of Temperate Cyclones

The major areas and tracks of temperate cyclones have been shown in **Fig. 3.29**. In general, the temperate cyclones occur in the higher mid-latitudes. In the Southern Hemisphere, there is a sharp peak in the frequency between 50° and 60° S. In the Southern Hemisphere they blow with more regularity, and there is little difference between summer winter tracks. In the Northern Hemisphere, there is a strong maximum in the frequency of temperate cyclone at 60°N in summer and 50°N in winter. This seasonal shift of about 10 degrees latitudes is due to the seasonal shift in the pressure belts.

In the Southern Hemisphere, the belt of maximum frequency of cyclones is almost contiguous around the world. Contrary to this, in the Northern Hemisphere, the zonal arrangement is much disturbed mainly due to the influence of continents and oceans (**Fig. 3.29**).

Tropical Cyclones

It is a circular storm (or vortex) that rotates counter clock-wise in the Northern Hemisphere, and clockwise in the Southern Hemisphere. It is a powerful manifestation of energy and moisture systems in the eastern parts of continents in the tropical latitudes. These cyclones originate entirely within tropical air-masses, especially in the western parts of the oceans where the surface temperature varies between 25° and 27°C (**Fig. 3.30**). The tropics extend from the Tropic of Cancer at 23.5° N to the Tropic of Capricorn at 23.5°S. Approximately, 80 tropical cyclones occur annually world-wide.

Origin of Tropical Cyclone

The origin of the tropical cyclones is not well understood. The origin of the tropical cyclones is, however, quite different from that of the temperate cyclones. The air of the tropics is essentially homogeneous, with no fronts or conflicting (warm and cold) air masses. In addition, the warm air and warm seas ensure an abundant supply of water vapour and thus the necessary latent heat to fuel these storms.

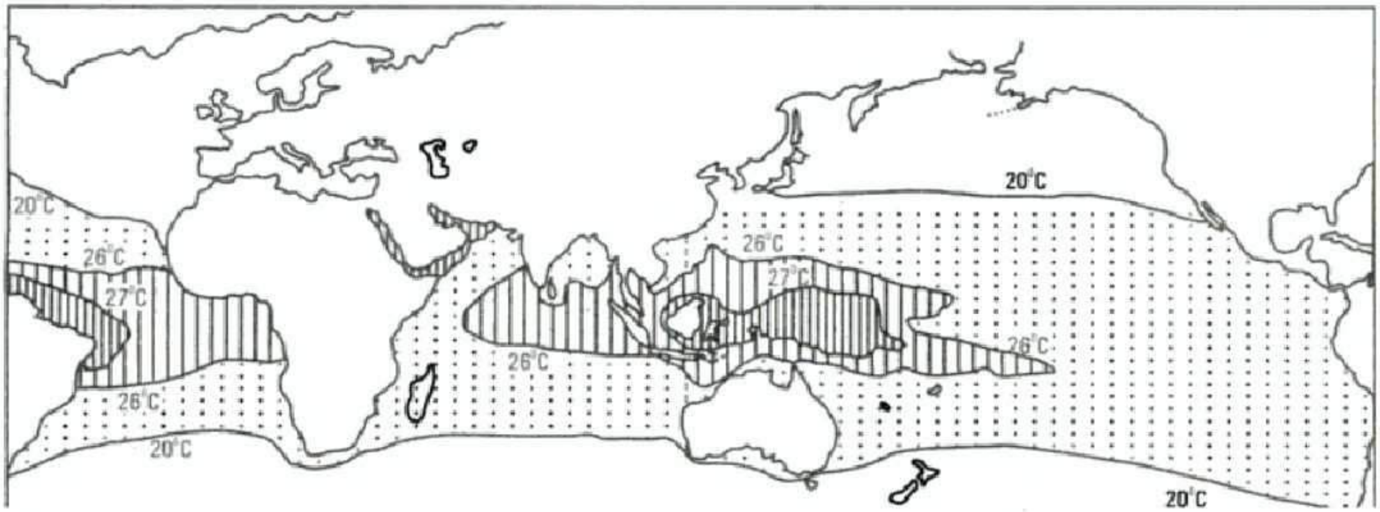


Fig. 3.30 – Average annual temperature. The western Pacific and western Atlantic Oceans record high temperatures in all seasons, (After R. W. Christopherson, Geosystems, 1995, p. 92)

Thus, these cyclones form within one warm, humid air mass between 10° and 25° in both the Hemispheres.

A tropical cyclone usually develops from a small tropical depression. Tropical depressions form in easterly waves, areas of lower pressure within the easterly trade winds. When air containing the disturbance is heated by the proximity of tropical water with a temperature of about 26°C or more, circular winds begin, and some of the warm humid air is forced upward. The coriolis effect also helps in the origin of tropical cyclones **(Fig. 3.31)**. Condensation begins in the ascending air and the tropical cyclone takes shape.

The centre of the most tropical cyclones move westward and poleward at a speed 10 to 40 km per hour. The typical tracks of some of the tropical cyclones are shown in **Fig. 3.32** In brief, in tropical cyclones, the condensation energy generates air movement (wind).

Characteristics of Tropical Cyclone

The main characteristics of tropical cyclones are given below:

1. The isobars are circular in shape.
2. Their diameter varies between 150 and 300 metres.
3. The central area is designated as the 'Eye' of the cyclone.
4. They do not have fronts (cold front and warm front).
5. They drive their energy from the latent heat.
6. Their velocity varies between 50 and 300 km per hour.
7. They occur in the autumn season.
8. The clouds in the tropical cyclone are cumulonimbus having vertical extension up to about 12 km.
9. They give torrential rainfall.
10. They are destructive causing great damage to life and property.

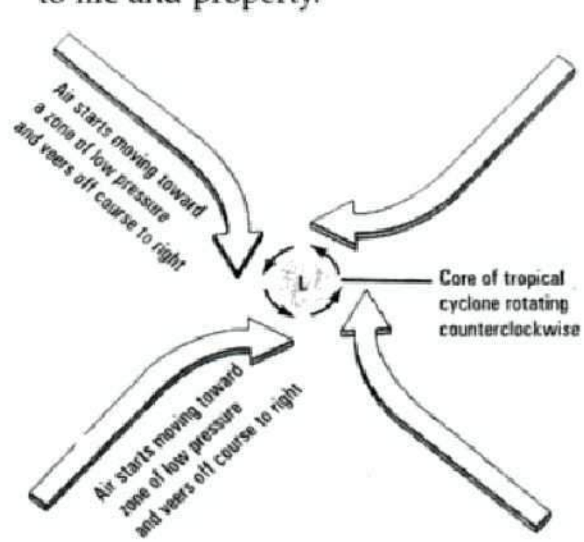


Fig. 3.31 – The dynamics of a tropical cyclone, showing the influence of the Coriolis effect. Note that the storm turns the "wrong" way (that is, counterclockwise) in the Northern Hemisphere for the "right" reasons

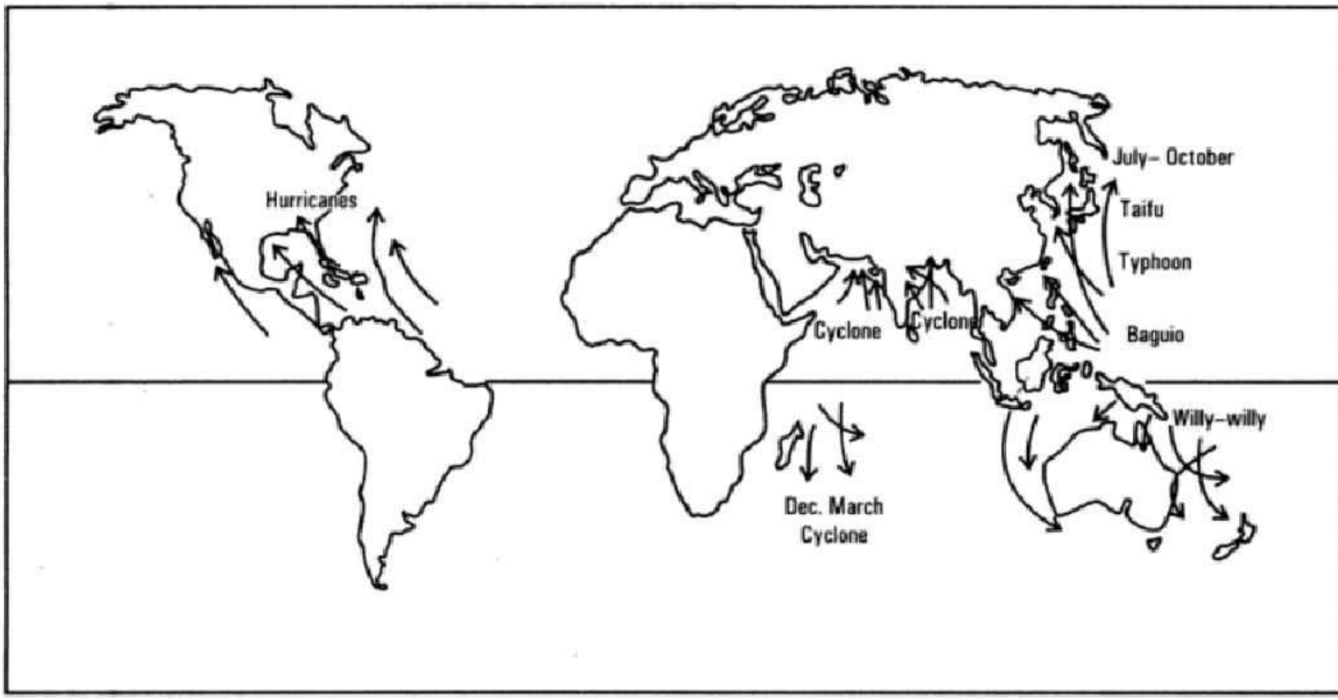


Fig. 3.32 – Areas of tropical cyclone

The tropical cyclones are known by different names in different parts of the tropical oceans:
China=Typhoons (Taifung)
Japan= Taifu
Philippines = Baigio
Carribean Sea = Hurricanes
Australia = Willi-Willis
Indian Ocean= Cyclone

Structure of a Tropical Cyclone

The inner most part of the tropical cyclone is known as the '*Eye*' of the cyclone **(Fig. 3.33)**. Its diameter ranges from 20 to 50 km. In the central part (Eye) of the tropical cyclone, the winds are light and variable; the clouds are either absent or scattered; the temperature is high; and the weather is sultry. In this central calm area, the sky is blue and there is intermittent sunlight against the background of spiral clouds about 12 km high.

In **Fig. 3.33**, the cloud bands can be seen as dark-shaded elongated patches spiraling away from the region of the cyclone. The central part of the tropical cyclone is surrounded by walls of cumulonimbus clouds. The maximum wind velocities are always recorded adjacent to the centre of the tropical cyclone. Moreover, the heaviest rainfall is recorded in the vicinity of this region. The winds slow down at uniform rate from the eye wall to the centre where rain practically ceases.

The tropical cyclone can cause loss of life and property damage. The destructive force of winds to 400 km per hour is self-evident. Torrential rainfall can cause severe flooding when the storm moves onto land. But the most danger lies in storm surge, a mass of water driven by the storm known as transgression of sea. Occasionally, there may be sea-waves up to 12 m in height.

In general, the tropical cyclones are destructive in nature. In Bangladesh, on 13th November, a tropical cyclone with wind speeds of more than 200 km per hour roared up the mouths of the Padma river, carrying with it masses of seawater up to 12 meters high. Water and wind clawed at the aggregation of small islands, most just above sea level, that makes up this impoverish country. In only 20 minutes at least 300,000 lives were lost, and estimates ranged 1 million dead alongwith huge property damage. Photographs taken soon after the storm showed a horizon-to-horizon morass of flooded, deep-gashed ground tortured by

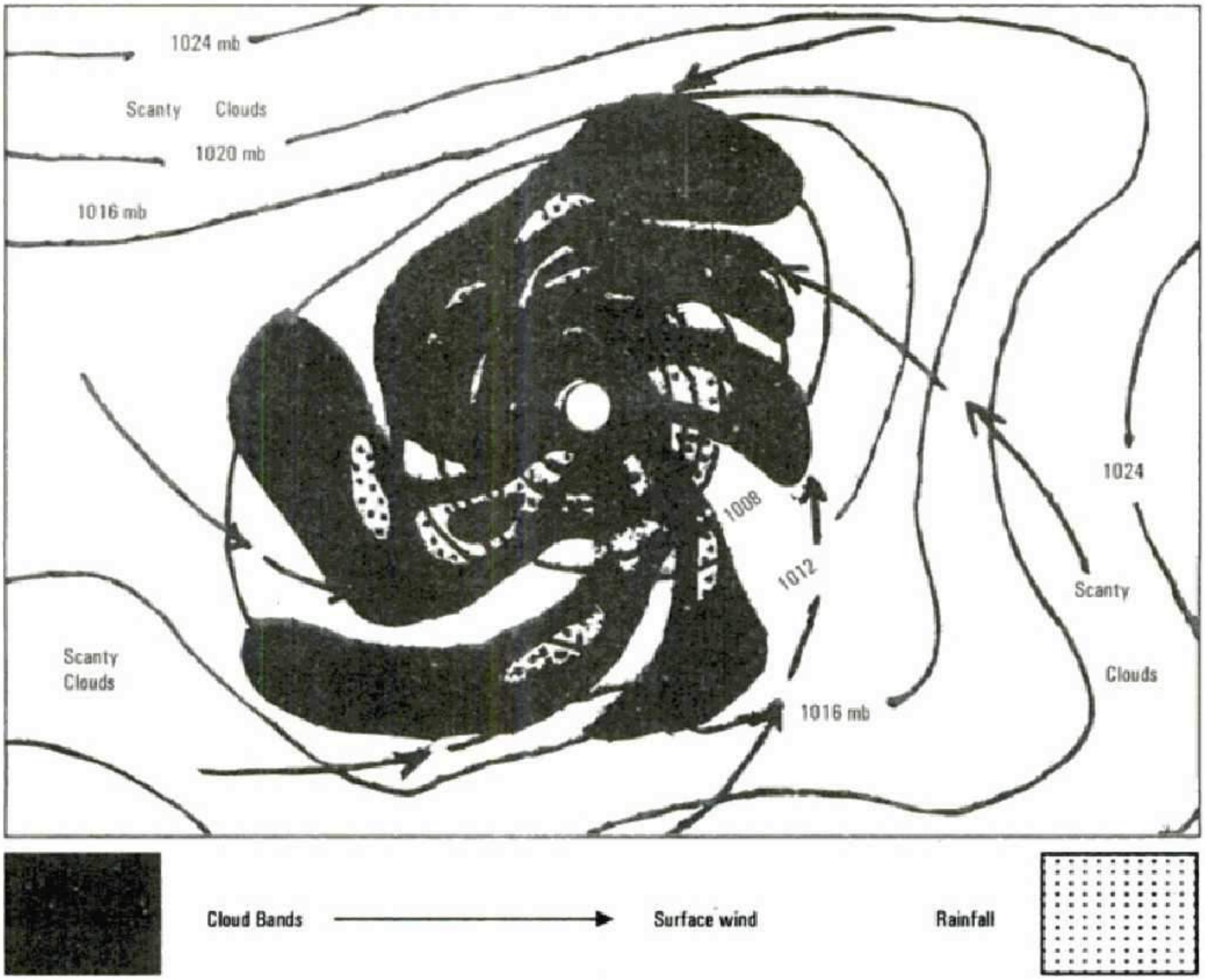


Fig. 3.33 – Cross section of a tropical cyclone

furious winds. There was almost no trace of human inhabitants, farms, domestic animals, or villages. Another great storm, which struck in May 1991, killed another 200,000 people. The economy of the shattered country may never fully recover. The tropical cyclones are dangerous examples of power represented by water's latent heat of fusion.

Tornado

It is an intense, destructive cyclonic rotation, developed in response to extremely low-pressure and associated with mesocyclonic formation. It is a converging spiral of air with wind speeds estimated at several hundred kilometers per hour. It is most violent of atmospheric storms, but it is seldom larger than a kilometer in diameter. The direction of rotation is counterclockwise in the Northern Hemisphere except in rare instance **(Fig. 3.34).** The tornado depends on moisture as an energy supply and occurs mostly in moist tropical air. Funnel clouds form out of other clouds. They work downward toward the ground. The funnel cloud of condensed moisture hanging from the storm cloud makes the tornado readily visible. The cloud may vary widely in thickness and sometimes may be larger at the bottom than at the top. Most often it is gray in colour due to condensed water vapour. In winter, a tornado may touch down on a field of snow and become a brilliant white.

Origin Of Tornados

Tornados occur most often with thunderstorm activity. Ideal Conditions for tornado formation are those found ahead of cold front. Tornados from the collision of mass of warm, very moist air with cooler, drier air from polar regions. For tornadoes to form, several prerequisites are essential, which are given below:

1. There must be a mass of very warm, moist air present at the surface.

2. There must be an unstable vertical temperature structure.

3. There must be a mechanism present to start rotation.

Tornado Forecasting

The main factor in the high death rate is the problem of prediction and detection. Tornadoes are so localised in extent and random in distribution that it is very difficult to forecast them.

Anticyclone

It is an area of above average atmospheric pressure characterised by a generally outward flow of air at the surface. The direction of wind is clockwise in the Northern Hemisphere and anticlockwise in the Southern Hemisphere (Fig. 3.35).

The term anticyclone was used for the first time by *F. Galton in 1861*. It is a dynamically or thermally caused area of high atmospheric pressure with descending and diverging air flow. The salient characteristics of an anticyclone are as under:

(i) The isobars of an anticyclone are generally circular in shape **(Fig. 3.35)**.

(ii) They are much larger in size than that of the temperate cyclones.

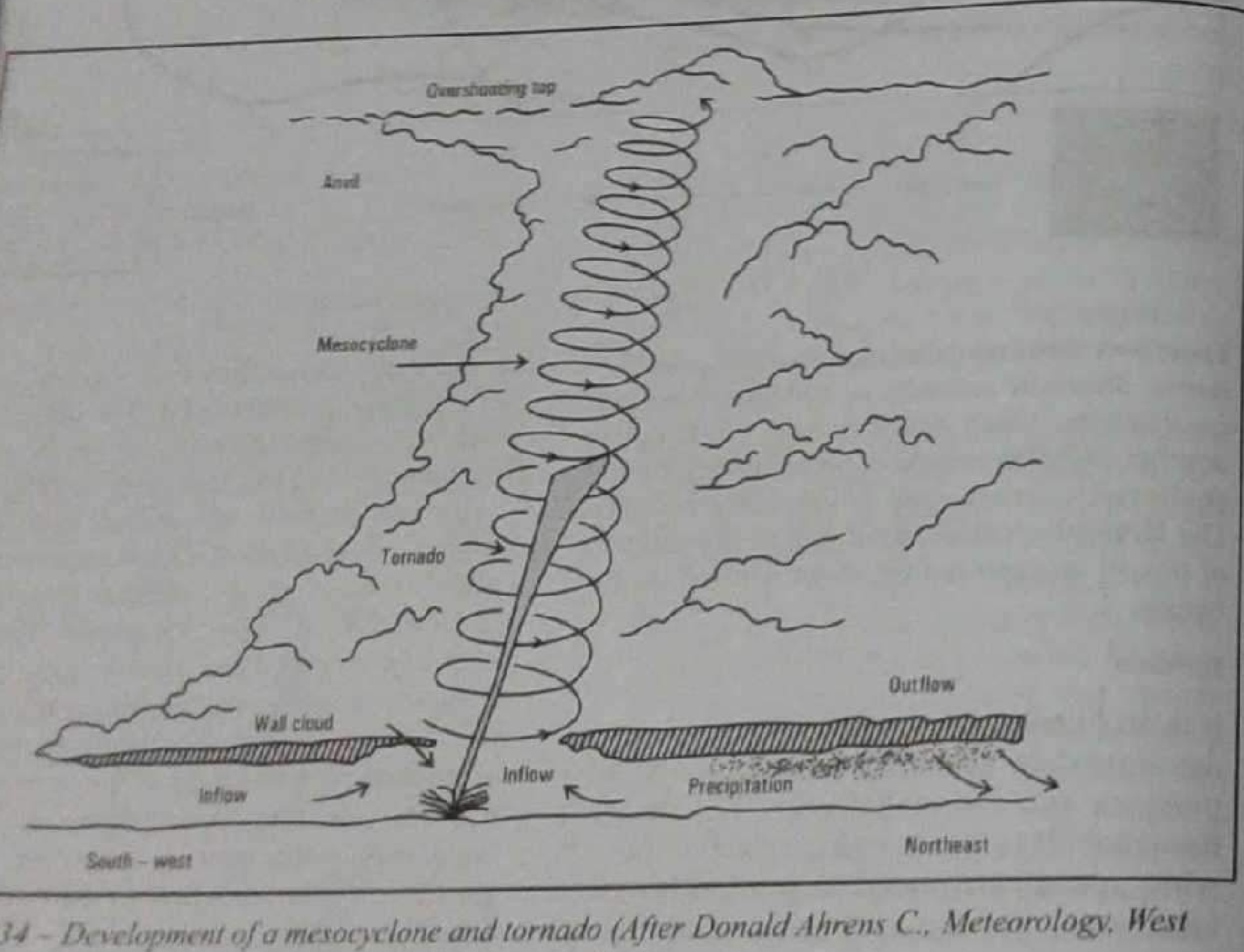


Fig. 3.34 – Development of a mesocyclone and tornado (After Donald Ahrens C., Meteorology, West Publishing Co. 1988)

(iii) Their track is highly variable and unpredictable.
(iv) The high pressure lies in the centre.
(v) The wind blows outward from the centre. The direction of wind is clockwise in the Northern Hemisphere and anticlockwise in the Southern Hemisphere.
(vi) Temperature in an anticyclone depends on the prevailing weather, humidity and the nature of the air-mass.
(vii) Anticyclones do not have fronts.
(viii) Anticyclones are the indicators of blue sky, clear weather and no rainfall.

Types of Anticyclones

Anticyclones may be classified into:

(a) Cold anticyclones

The cold anticyclones generally originate in the Arctic and Antarctic regions and advance in the easterly and south-easterly direction. They are of very low thickness. These anticyclones die out when entering in the tropical regions.

(b) Warm anticyclones

The warm anticyclones originate in the belt of subtropical high pressure where the winds descend in the Hadley's cell. These are associated with light wind, low humidity and cloudless skies.

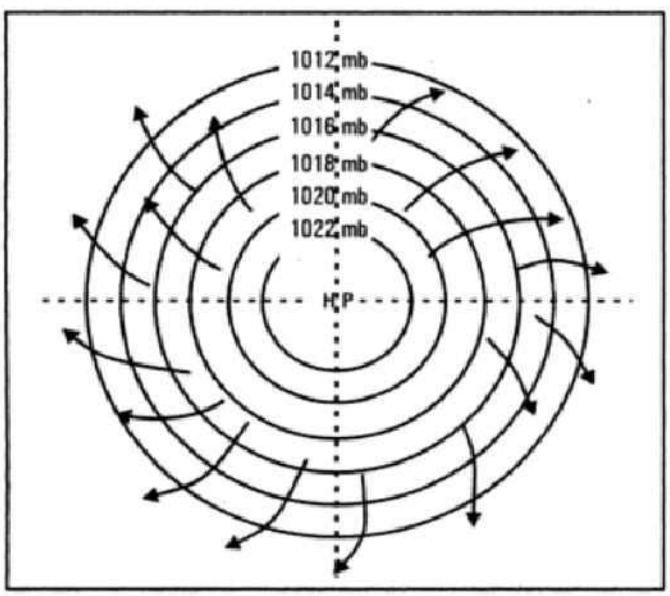


Fig. 3.35 – Anticyclone-air pressure and wind system in the Northern Hemisphere

(c) Blocking anticyclones

The blocking anticyclones develop due to obstruction in the air circulation in the upper atmosphere. This is why they are called as blocking anticyclones. They develop over North-West Europe and the Pacific Ocean between 140-170 W longitudes. They are similar to warm anticyclones as the wind system is concerned, but they move very slowly.

Jet Stream

Jet stream is a strong wind blowing from west to east in the upper part of the troposphere, usually near the level of tropopause (about 12,000 m above the sea level) in sinuous band. The jet streams are normally 160-480 km wide by 900-2150 m thick with a core speed that can exceed 300 kmph. Normally, the speed of a jet stream varies from a mean of 110 km per hour in summer to about 190 kmph in winter. In exceptional cases a speed of 375 kmph has also been recorded. The main types of jet streams are: (i) the sub-tropical jet stream, (ii) the polar front jet stream of the middle latitudes, and (iii) the Arctic/Antarctic Jet streams. The sinuous movement of jet stream has been shown in **Fig. 3.36.**

The global patterns of temperature, pressure, horizontal and vertical circulation of the atmosphere, the behaviour of monsoon, the intensity of precipitation, the weather and climates are largely influenced by the position, thickness, dimensions and movements of the jet streams.

Moisture in the Atmosphere

Hydrological Cycle

A hydrological cycle is a conceptual model of the exchange of water over the Earth's surface. A model of hydrological cycle has been shown in **Fig. 3.37** It shows the large scale changes in

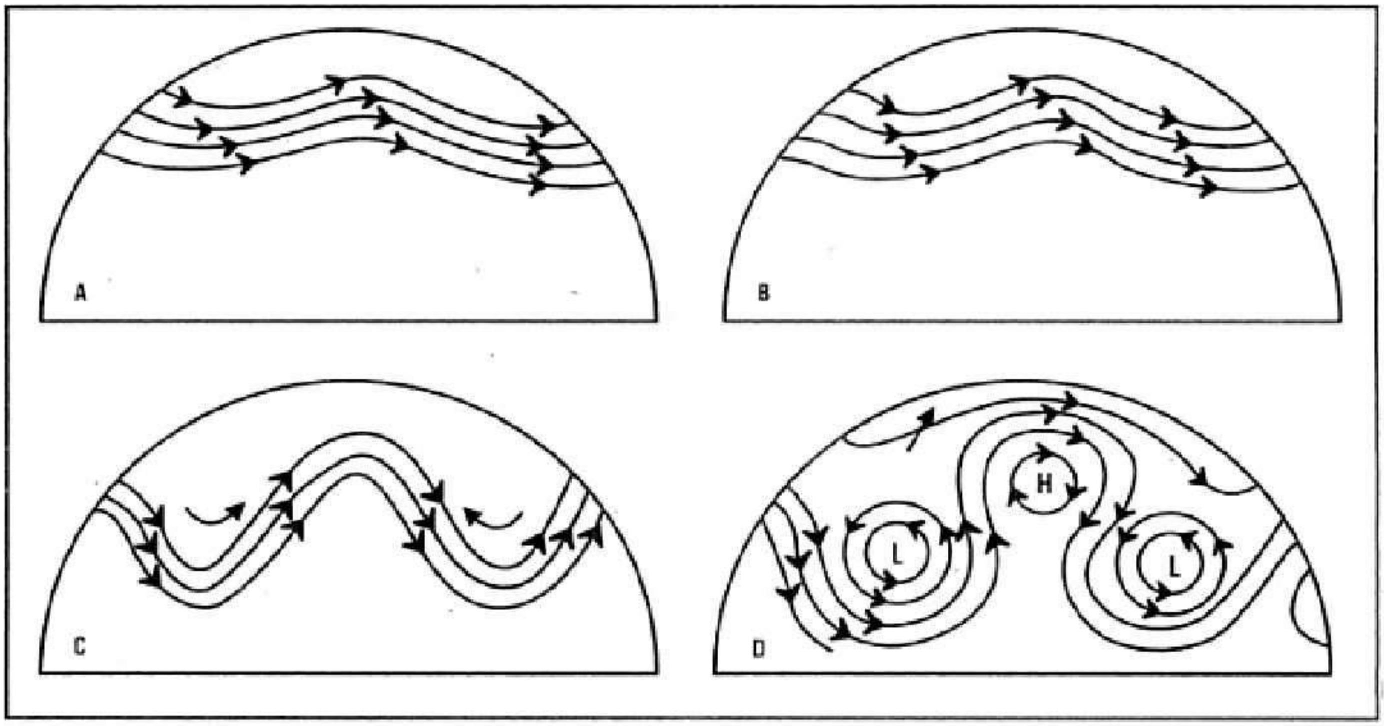


Fig. 3. 36 – Jet stream cycle

the state of water, passing through the processes of evaporation, condensation and precipitation. Transpiration is, in some ways, a special form of evaporation in which moisture returns to air through evaporation via vegetative processes. The evaporation from the vegetation is known as evapotranspiration.

Some of the moisture of the precipitation that falls to surface passes to the soil to become soil moisture, some passes deeper into the ground to become ground water. Other precipitation runs off the surface and is collected in ponds, lakes or flows as surface water in streams and rivers. Eventually, water finds its way to the oceans and starts the cycle over again.

The proportional distribution of water over the Earth's surface has been shown in **Fig. 3.38.** It may be seen from **Fig. 3.38** that 97 per cent of the Earth's water is in the oceans. The remaining 3 per cent is mostly ice found in the large ice-caps of the world (Antarctica and Greenland). Almost all of the rest is ground water. Rivers, lakes, and soil moisture account for less than one per cent of the total water. The atmosphere contains only 0.35 per cent of all water available. Yet this small amount provides the moisture for clouds and precipitation that occurs over the Earth's surface.

Humidity

Humidity is the amount of water vapour in the air, affecting the level of comfort and chance that cloud will form.

Relative Humidity

This is a widely used measure of water vapour in the atmosphere. The calculation of relative humidity depends on the maximum amount of moisture that air can hold – the saturation level. The relative humidity of an air sample is expressed as a percentage which is found by relating the observed vapour pressure at a given temperature to the saturation value of vapour pressure at that temperature. The formula for relative humidity is:

Relative humidity commonly displays a daily cycle which has phase opposite to that of temperature so that the highest values are observed near dawn and the lowest during the

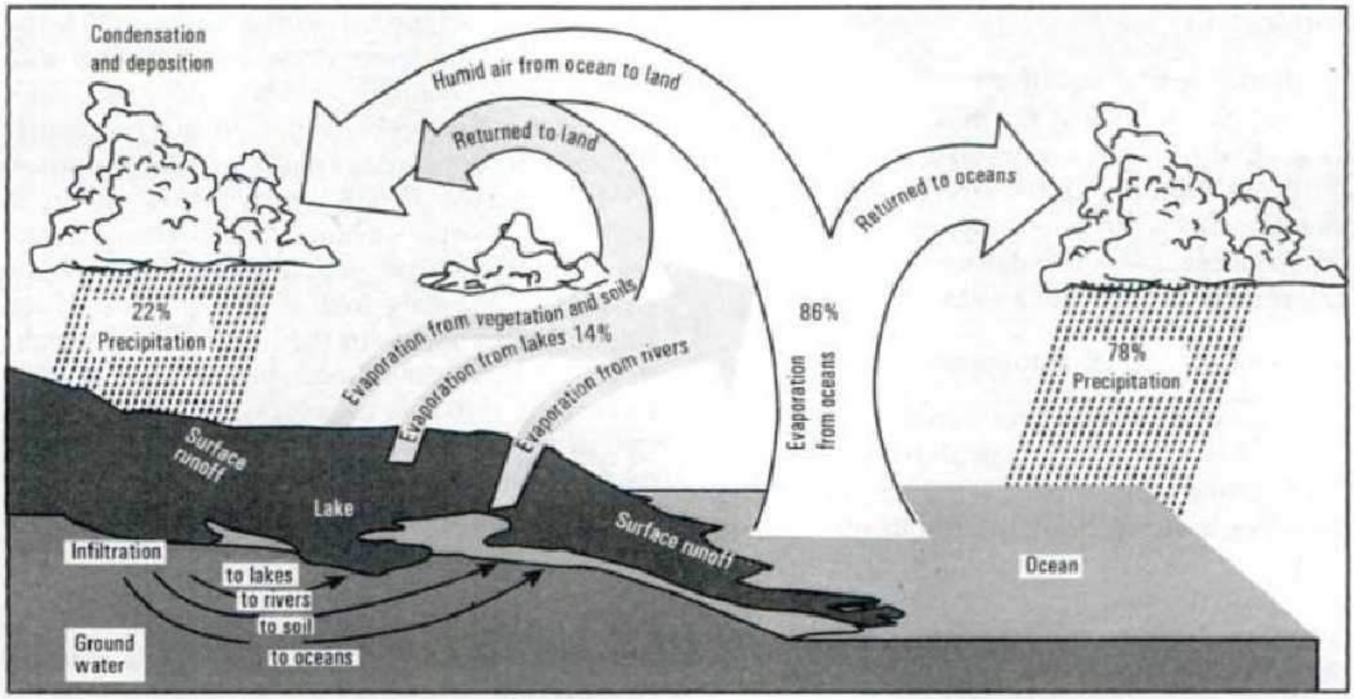


Fig. 3.37 – Hydrological cycle (after A. Strahler, 1997)

$$\text{Relative Humidity} = \frac{\text{Actual water vapour content of the air}}{\text{Maximum water vapour capacity of the air}} \times 100$$

afternoon. Air is said to be saturated, or full, if it is holding all the water vapour that can be hold at a given temperature (100% relative humidity). Saturation indicates that any further addition of water vapour (increase in content) or any decrease in temperature (reduction in capacity) will result in active condensation, fog or precipitation.

Specific Humidity

The mass of water vapour (in grams) per unit mass of air (in kilograms) at any specific temperature.

Absolute Humidity

The density of the water vapour present in a mixture of air and water vapour, that is the ratio of the mass of water vapour to the volume occupied by the mixture, usually measured in grams per cubic centimeter. Cold air cannot contain as much water vapour as warm air, so cold air has a lower absolute humidity than warm air.

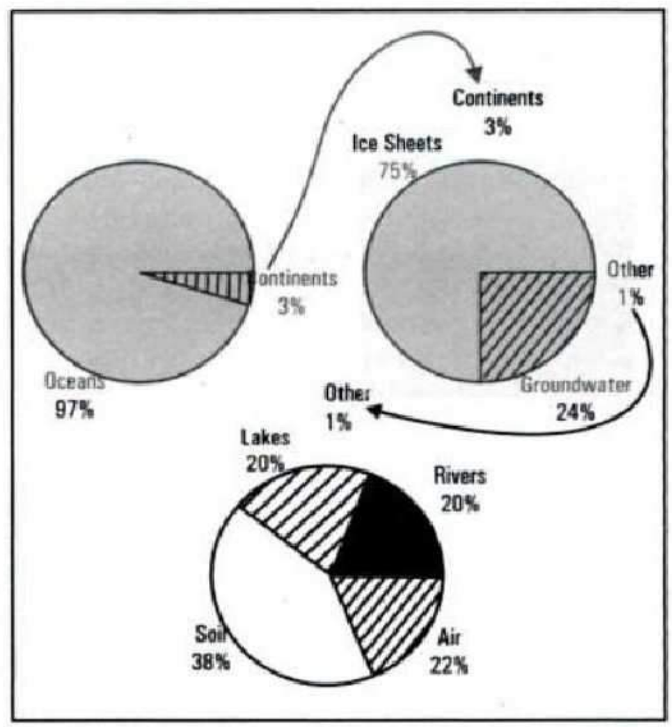


Fig. 3.38 – The proportional distribution of water over the Earth's surface (after John E. Oliver, et. al, 2002, Climatology, p. 62)

Evaporation

The changing of a liquid into a vapour, or gas, at a temperature below the boiling point of that liquid. Evaporation occurs at the surface of a liquid, and energy is required to release the molecules from the liquid into the gas. The use of this energy, known as latent heat, causes the temperature of the liquid to fall.

Transpiration or (Evapotranspiration)

The release of water vapour from the Earth is surface by evaporation and transpiration. Transpiration is the biological process whereby plants lose water vapour, mainly through pores in their leaves. This water is usually replaced by a continuous flow of water moving upwards from the roots. Rates of evapotranspiration vary with factors such as the temperature and humidity of the air, wind speed, plant type and the nature of the land surface. Since evapotranspiration is so variable, physical geographers prefer to use the concept of potential evapotranspiration (PE). This is the greatest amount of water vapour which could be diffused into the atmosphere given unlimited supplies of water.

Condensation

The change of a vapour or gas into liquid form is known as condensation. Condensation in meteorology can be caused by: the cooling of constant volume of air to dew point, the expansion of a parcel of air without heat input, the evaporation of extra moisture into the air, the fall in moisture-holding capacity of the air due to changes in both volume and temperature, and contact with a colder material or air mass. Condensation may be of the following types:

Precipitation

In meteorology, precipitation is the deposition of moisture from the atmosphere onto the Earth's surface. This may be in the form of rain, hail, frost, fog, sleet, or snow. Precipitation develops in two stages. Initially, cloud droplets grow around nuclei through condensation and diffusion. In clouds, warmer than -10°C, the larger droplets then grow by collision and coalescence with the similar ones. In colder clouds the Bergeron-Findeisen mechanism is thought to operate, probably in conjunction with the growth of ice crystals through accretion, as super-cooled water droplets freeze on impact with the ice, and aggregation, as smaller ice crystals stick to larger ones. Much precipitation begins in the form of ice crystals, develops into snow flakes, but melts as it falls, to become rain. On an average 10 inches (25.4 cm) of snow equals to about 1 inch (2.5 cm) of rain, though the actual ratio varies. Dry, powdery snow equals less than wet, heavy snow.

Dew

The direct deposition of water vapour without hygroscopic nuclei on the surfaces of objects on the ground like vegetation is known as dew. Dew occurs, when there is high relative humidity, calm air, high rate of radiation, clear skies. Dew is, however, shortlived as it disappears after the rising of Sun.

Fog

Fog is a cloud layer on the ground, with visibility restricted to less than one kilometer. The presence of fog is an indication that the air temperature and the dew point temperature are nearly identical, producing saturated conditions. Fog generally occurs when there is inversion of temperature. Fog may be classified into:

(i) Advection fog

Active condensations formed when moist air moves laterally over cooler water of land surfaces, causing lower layers of the overlying air to be chilled to the dew temperature.

(ii) Radiation fog

It is formed by a radiative cooling of the surface, especially on clear nights of calm atmosphere in areas of moist grounds; occurs when the air layer directly above the surface is chilled to the dew-point temperature, thereby producing saturated conditions.

Foggy Regions of the World

The occurrence of fog is confined to some favourable regions of the world. The areas in which the frequency of fog is high are shown in **Fig. 3.39.** The regions of New-Foundland, California, Chile Coast, Coast of Namibia, the Western Coast of Australia, the Sea of Okhotsk and Bering Sea record fog almost throughout the year. The interior parts of Europe, North America, Eastern Australia, Central China, and Northern India record the radiation fog during the winter season.

Frost

It is the frozen dew or fog forming at, or near ground level. Air below 0°C is air-frost. Hoar frost, or rime, is a thick coating of white ice crystals on vegetation and other surfaces. Ground frost occurs when the air at ground level is chilled below freezing point. Its frequency is high in the mid-latitudes and mountainous areas during the winter season.

Mist

A suspension of water droplets in the air which restricts visibility to between 1 and 2 km.

Rain

Rain is a form of precipitation consisting of water droplets ranging from 1 to 5 mm in diameter.

Drizzle

Rain made of very small droplets, up to 0.2 mm across, and with a fall speed of around 0.8 m^{s-1}. Dense drizzle is not to be confused with light rain, which has at least 3 mm droplets.

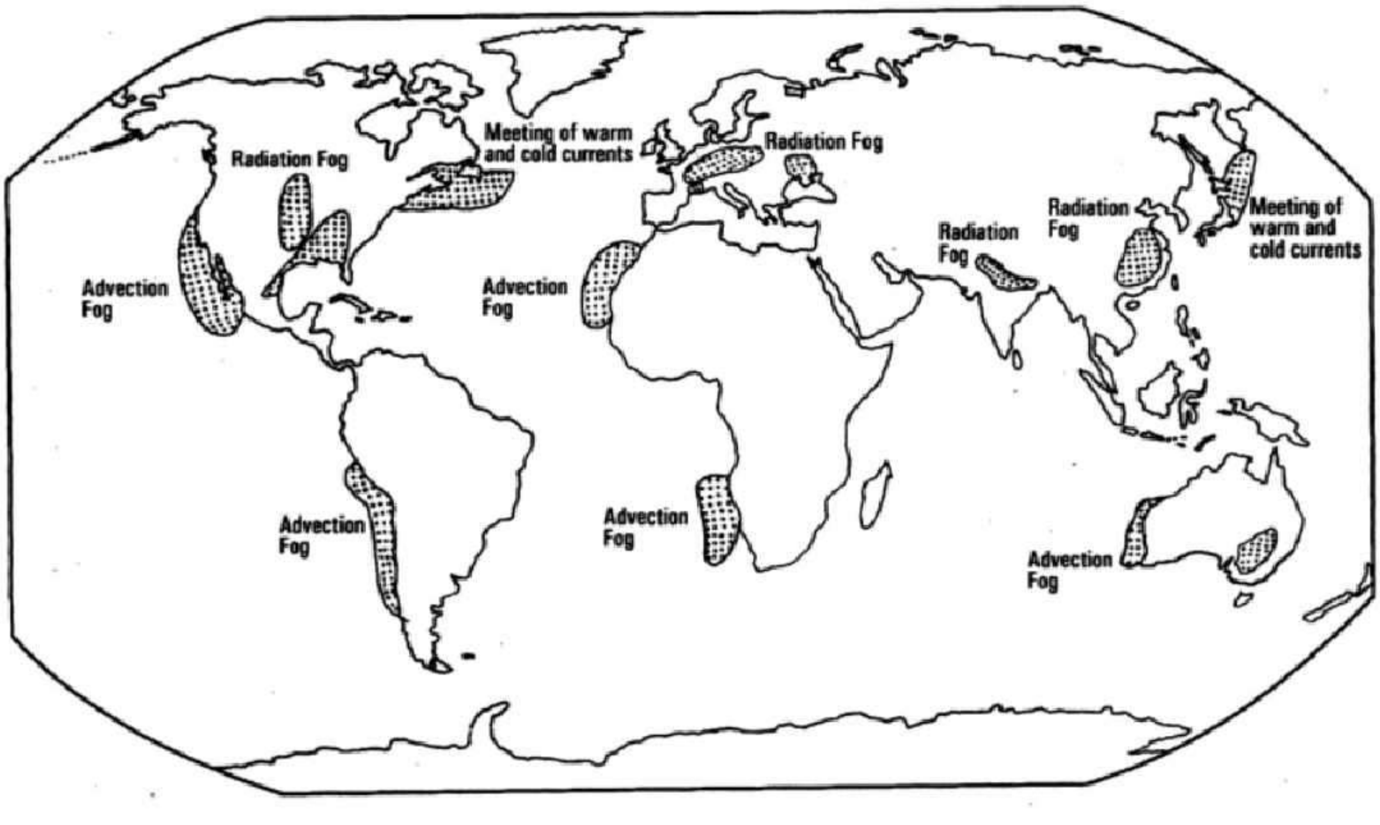


Fig. 3.39 – Main areas affected by fog

Freezing Rain or Freezing Drizzle

This is a rain/drizzle that freezes on impact with the ground, with objects on the Earth's surface, or with aircraft in flight.

Rime

It is an opaque coating of tiny, white, granular ice-particles, caused by rapid freezing of super-cooled water droplets on impact with objects.

Hail

Hail is the precipitation of small balls or pieces of ice (hailstones), with diameters ranging from 5 to 50 mm, falling either separately or agglomerated into irregular lumps. Hailstones are comprised of a series of alternating layers of transparent and translucent ice. They form when a frozen raindrop is caught in the violent updraughts found in warm, wet cumulonimbus clouds. As they rise, they attract ice, and as they fall, the outer layer melts, but refreezes when the droplet is again lifted by updraughs. Onion-like structure of hailstone shows that they must have passed up and down several times. A hailstone will descend when its fall-speed is enough to overcome the updraughts in the cloud.

Hail Snow

Snow is a precipitation of ice crystals most of which are branched. At temperatures higher than about -5°C, the crystals are generally agglomerated into soft-flakes.

Snow Pellets

Snow pellets are composed of white and opaque grains of ice. The grains are mostly spherical and have a diameter of 2-5 mm. The grains are brittle when falling on a hard surface bounce and break up. Snow pellets are also known as soft hail or graupel.

Snow grains

Snow-grains are very small grains of white, opaque ice. Snow grains are also called graupel.

Ice pellets

These are comprised of transparent or translucent pieces of ice that are spherical or irregular. They are composed of frozen raindrops or largely melted and refrozen snowflakes.

Ice-prism (diamond-dust) : Ice prisms are ice-crystals often tiny that they seem suspended in air. Such crystals may fall from a cloudy or cloudless sky. Mostly visible when they glitter in sunshine (hence diamond dust), they occur at very low temperatures.

Fog, ice-fog and mist : Fog, ice-fog and mist are also considered forms of precipitation.

Clouds Forms and Classification

Cloud is a visible, dense mass of suspended water droplets and or ice crystals suspended in the air. Clouds are generally formed when air is forced to rise at a front, over mountains, or because of convection.

Types of Clouds

The first classification of clouds was given by **Luke Howard (Englishman) in 1803.** He distinguished three principal cloud forms:

1. Stratus (from Latin stratum=layer) cloud – lying in a level sheet.
2. Cumulus (from Latin cumulus = pile) cloud–having flat bases and rounded tops, and being lumpy in appearance.
3. Cirrus (from Latin=hair) cloud – having a fibrous or feathery appearance. This system was revised several times. The international standard is now under the auspices of the World Meteorological Organization (WMO), which published *The International Cloud Atlas*.

There are ten basic types of clouds as given in *The International Cloud Atlas* **(Fig. 3.40).** The principal types of clouds are as under:

High Clouds (above 7000 metres)

1. Cirrus (Ci)

Detached clouds in the form of white, delicate filaments, or white or mostly white patches or narrow bands. These clouds have a fibrous (hair-like) appearance or a silky sheen or both **(Fig. 3.40).**

2. Cirrocumulus (Cc)

These are thin, white patch, sheet, or layer of clouds without shading composed of very small elements in the form of grains, etc., merged or separate, and more or less regularly arranged; most of the elements have an apparent width or less than 1° – approximately the width of the little finger at arms length **(Fig. 3.40).**

3. Cirrostratus (Cs)

Transparent, whitish cloud veil of fibrous or smooth appearance, totally or partially covering the sky or mackerel sky, and generally producing *halo* phenomena.

Middle Clouds (2000 to 7000 metres)

4. Atocumulus (Ac)

White or gray, or both white and gray, patch, sheet, or layer of cloud, generally with shading, composed of rounded masses, rolls, etc., sometimes partly fibrous or diffuse, and may or may not be merged; most of the regularly arranged small elements usually have an apparent width of between 1°and 5° – approximately the width of three fingers at arms length **(Fig. 3.40).**

5. Altostratus (As)

Grayish or bluish cloud sheet or layer of striated, fibrous, or uniform appearance, totally or partly covering the sky, and having parts thin enough to reveal the Sun at least vaguely, as through ground glass. The Sun is dimly visible, the altostratus clouds, however, do not show *halo* phenomena.

Low Clouds (Below 2000 m)

6. Nimbostratus (Ns)

Gray cloud layer, often dark, the appearance of which is rendered diffuse by more or less continually falling rain or snow, which, in most cases reaches the ground. It is thick enough throughout to bolt out the Sun. Low ragged clouds frequently occur below the layer with which they may or may not merge **(Fig. 3.40).**

7. Stratocumulus (Sc)

Gray or whitish, or both gray and whitish, patch- sheet or layer of cloud that almost always has dark parts, composed of tessellations, rounded masses, rolls, etc., that are non-fibrous (except for *virga*) and may or may not be merged **(Fig. 3.40).**

8. Stratus (St)

Generally gray cloud layer with a fairly uniform base, which may give drizzle, ice prisms, or snow grains. When the Sun is visible through the cloud, its outline is clearly discernible. Stratus does not produce halo phenomena (except possibly at very low temperatures). Sometimes stratus appears in the form of ragged patches **(Fig. 3.40).**

9. Cumulus

Detached clouds, generally dense and with sharp outlines, developing vertically in the form of rising mounds, domes, or towers, of which the bulging upper part often resembles a cauliflower. The sunlit part of these clouds are mostly brilliant white; their bases are relatively dark and nearly horizontal. Sometimes cumulus is ragged **(Fig. 3.40).**

10. Cumulonimbus (Cb)

Heavy and dense clouds, with considerable vertical extent, in the form of a mountain huge towers. At least part of its upper portion is usually smooth, or fibrous of striated, and nearly always flattened; this part often spreads out in the shape of an anvil or plume. Under the base of this cloud, which is often very dark, there frequently low ragged clouds either merged with it or not. The cumulonimbus clouds give torrential rainfall. Lightning and thunder are also the common features of these clouds **(Fig. 3.40).**

Lightning and Thunder

An estimated 8 million lightning strikes occur each day on the Earth. Lightning refers to flashes of light caused by enormous electrical discharges – tens to hundreds of millions of volts – which briefly superheat the air to temperatures of 15,000° to 30,000°C. The violent expansion of this abruptly heated air sends shock waves through the atmosphere – the sonic bangs known as thunder. The greater

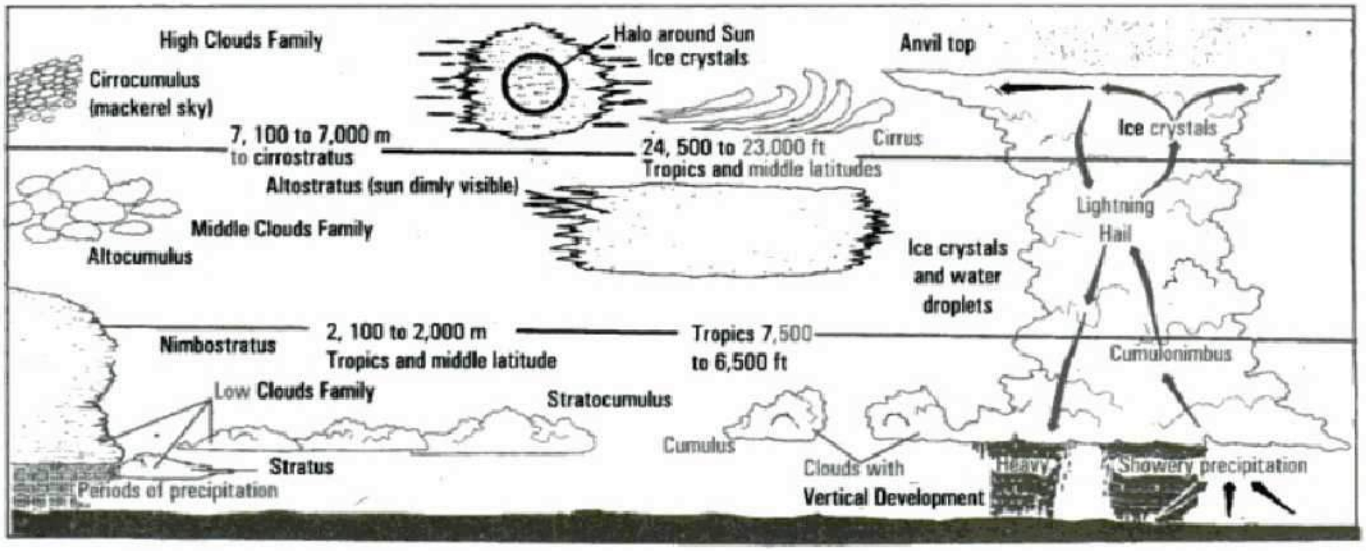


Fig. 3.40 – Cloud types

the distance a lightning stroke travels, the longer the thunder echoes. Lightning at great distance from the observer may not be accompanied by thunder and is called *heat-lightning*. Lightning poses a hazard to aircraft and to people, animals, trees, and structures. At the time of lightning people should remain indoor.

Types of Rainfall

The meteorologists generally classify rainfall into the following three categories:

(i) Convectional or Convective Rainfall: The rain which is caused by the process of convection in the atmosphere is known as convectional rainfall. When the surface layers of the atmosphere are heated, the moisture-laden air rises in a convection current. The moist heated air expands, its density falls, and it rises convectionally. It is thereby cooled adiabatically and its temperature falls below the dew point, thereby forming clouds. Such clouds are generally of cumulonimbus type, which generate heavy rainfall. This type of rainfall generally occurs throughout the year in the equatorial region, where high temperatures and high humidity produce convectional currents. Rainfall of this type is also associated with the cold front of an unstable polar air-mass, cloud burst and thunderstorms, especially in the monsoon regions **(Fig. 3.41-a)**.

(ii) Orographic Rainfall: This is also known as *relief rainfall*. It occurs when moisture-laden air masses are forced to rise over high ground (mountains). The air is cooled, the water vapour condenses, and rainfall occurs. Some experts maintain that relief merely intensifies the precipitation caused by convection or formed at fronts. The term *orographic intensification* is, therefore, used occasionally **(Fig. 3.41-b)**.

(iii) Cyclonic or Frontal Rainfall: Rain associated with the passage of cyclone or depression is known as cyclonic rainfall. It occurs mainly in temperate latitudes when a warm, moist air mass moves upwards over colder heavier air. A distinction can be made between the prolonged drizzling rain which falls from the *warm front* and the shorter by heavier bursts of rain associated with the passage of *cold front*. In Europe and North America, most of the winter rainfall is frontal in origin. Winter rainfall in the northern parts of India is also the result of cyclonic depressions **(Fig. 3.41-c)**.

Regional Distribution of Precipitation

The mean annual precipitation for the entire Earth is about 100 cm (approximately 40 inches). Precipitation data for the oceans is

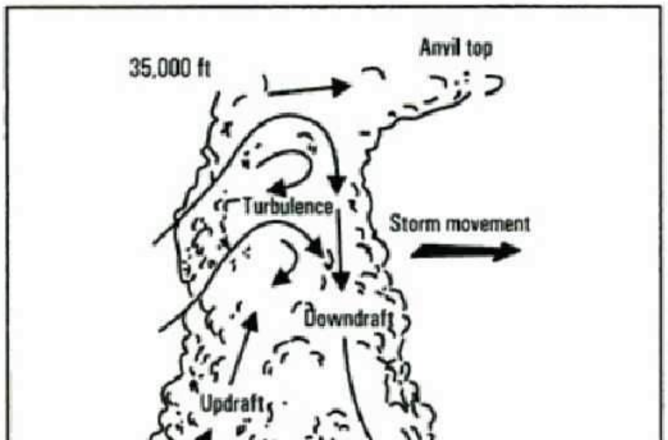


Fig. 3.41 – Three types of lifting mechanisms

extremely limited, and those for mountain ranges, forest areas, and wind swept coasts are largely estimates. The distribution of precipitation on the Earth is highly uneven. Several climatic factors like latitudes, temperature, pressure, relative humidity, air masses, differential heating and orographic features influence the distribution of rainfall.

The latitudinal distribution of rainfall has been shown in **Fig. 3.42**. It may be seen from this figure that the equatorial region records the highest average annual rainfall. The amount of rainfall decreases towards the poles. In the monsoon climate, the highest rainfall is recorded in the summer months being July to September in the Northern Hemisphere and January to March in the Southern Hemisphere. The average annual rainfall is low in the subtropical high pressure belt in which the air of the Hadley's Cell descends from above. All the hot deserts and semi-arid areas of the world are confined to this belt. The average annual rainfall in the subtropical high pressure belt is less than 25 cm. In the temperate region (belt of westerlies), the amount of rainfall varies between 100 and 125 cm which decreases from west to east. In the polar areas, characterised by cold air masses, the amount of average rainfall is less than 25 cm **(Fig. 3.43)**.

The distribution of land and water imposes an important control over the distribution rainfall. Regions located in the interior lands and the leeward sides of the mountains receive low rainfall as compared to the coastal and windward sides. In general the Southern Hemisphere (Water Hemisphere) records more rainfall than the Northern Hemisphere.

El-Nino

El Nino phenomenon occurs when the usual east-to-west equatorial current in the Pacific weakens or reverses, pushing warm waters to the west coast of South America. In an El-Nino year, there appears a warm water current along the coast of Peru which replaces the normally cold rising water. Fishermen of Spanish origin named this event as El-Nino. It implies *'the Little One'* after the Christ Child, as the event appears most often in late December. El-Nino has occurred frequently since first reported in 1541.

In some years, El-Nino becomes stronger and exceptionally warmer than usual. It produces rain over the coastal Atacama desert of Chile and Peru. The rain brings a period of profound vegetation growth. The desert provides abundant grazing for herds of sheep and goats.

In the lower latitudes of the Pacific, surface temperature of the ocean averages around 26° to 27°C. These surface temperature changes take place mostly within 8°C of the equator. In an El-Nino year the surface temperature increases more than 3°C. During El-Nino, the area of warm water expands eastward and the area of convergence and precipitation drifts

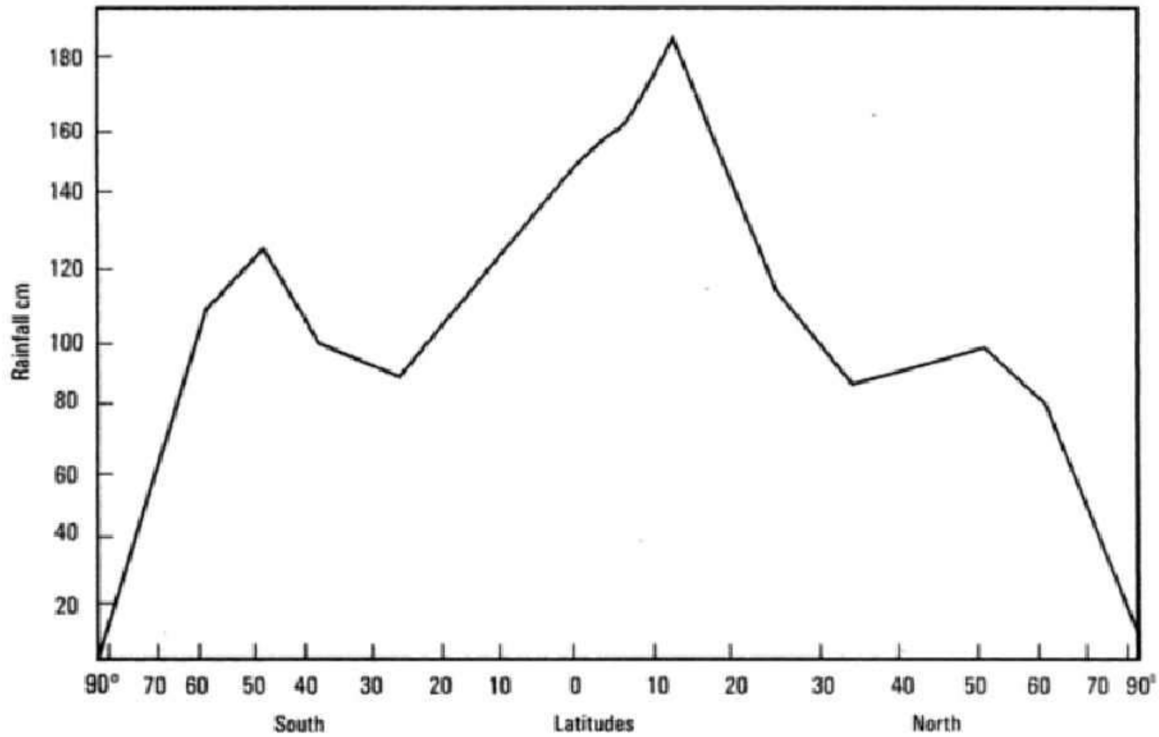


Fig. 3.42 – Latitudinal distribution of precipitation

eastward **(Figs. 3.44-45).** Consequently, rainfall increases over the eastern Pacific Ocean along the west coast of South America. Pressure differences decrease and the trade winds die down. Pressure difference between Darwin (Australia) and the island of Tahiti shows the southern oscillation. During El-Nino, pressure increases at Darwin, consequently, rainfall decreases while, in opposition to this air pressure decreases at Tahiti and rainfall increases.

The consequences of 1982-1983 – the most severe El-Nino year recorded the following effects:

1. Monsoon failed in South Asia (India, Bangladesh, Sri-Lanka, Nepal, Bhutan and Myanmar), and South-East Asia (Indonesia, Vietnam, Thailand, Malaysia, China, etc.).
2. Drought in South East Asia, and the *Sahel* region of Africa.
3. Drought in Australia and New Zealand.
4. Heavy rains, floods, and landslides in Peru, Ecuador, Columbia and Chile (Andes Mt.).
5. Increased frequency of tropical cyclones in Tahiti.
6. Above normal temperatures in Alaska and North-Western Canada.
7. The warmest winters in USA in 25 years.
8. Floods in Cuba and Louisiana (USA).
9. Death of coral reefs in Pacific Ocean and in the Caribbean Sea.
10. Reduction of fish along the coast of Peru.
11. High mortality of seabirds in the islands of Pacific Ocean.
12. Increased cases of malaria. Outbreak of fevers in South and South -East Asian and Latin American countries.

Forecasting El-Nino

El-Nino occurs every few years like many cyclic phenomena. The frequency appears to be on the increase. Since they have been documented, they have averaged one after every seven years. There is great difficulty in the El-Nino forecasting as it does not have a fixed interval. Each event begins and develops differently.

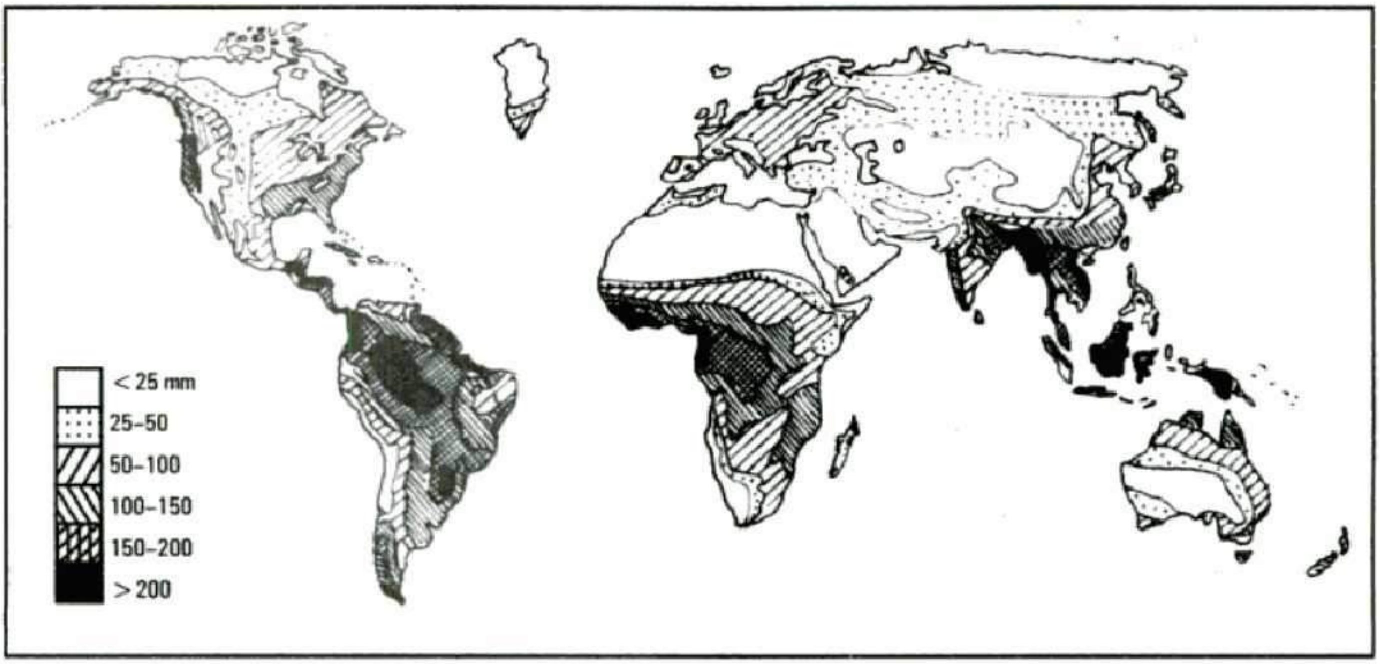


Fig. 3.43 – Mean precipitation over the Earth

There are currently several hypotheses about their origin. One suggests that it is the result of huge amounts of heat released on the sea-floor as a result of magma pouring out onto the sea floor of the Pacific Ocean. Another suggestion is that ENSO is a result of high snowfall over Asia the previous winter, i.e., when there is a lot of snow on the Eurasian land mass in a given winter, there will be much more snow- melt. A high volume of melt-water reduces the normal summer heating of the land mass. Unfortunately, it will probably take at least several more ENSO events before any hypothesis can be postulated and tested.

La Nina

When the temperature along the equator in the Pacific Ocean falls by around 4°C, it brings unusually cool weather to the eastern Pacific. The fishermen of Peru call this sudden cooling of the equatorial water La-Nina, Spanish for *'the girl'*. The name was applied to the phenomenon for the first time in 1986. La-Nina exaggerates the normal southern oscillation. During the La-Nina, the trade winds are stronger, the water off South America is colder, and water in the western Pacific near the equator is warmer than normal **(Fig. 3.46)**. In the western Pacific, surface pressures are lower and heavy rainfall occurs. In the year of La-Nina, South-East and South Asia get more summer precipitation than usual. In such a year

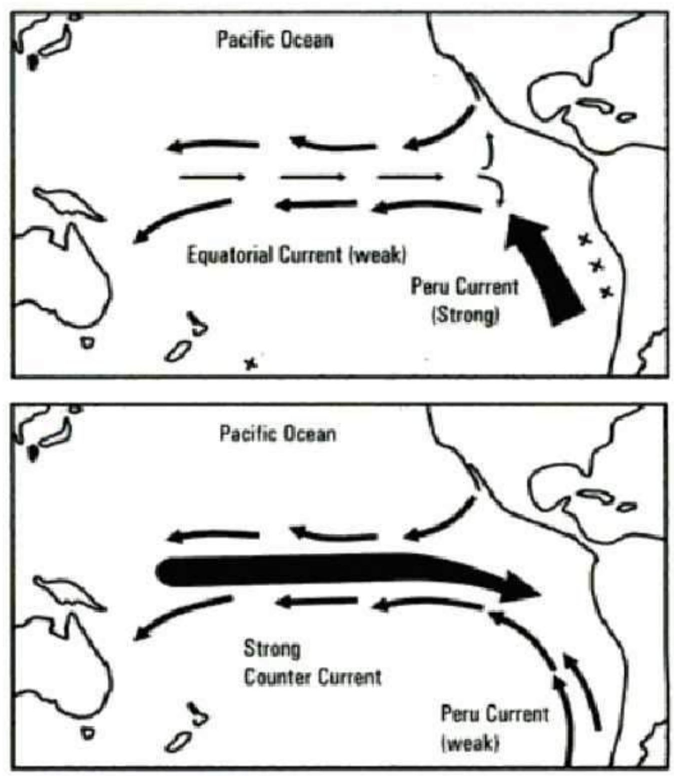


Fig. 3.44 – EL-Nino

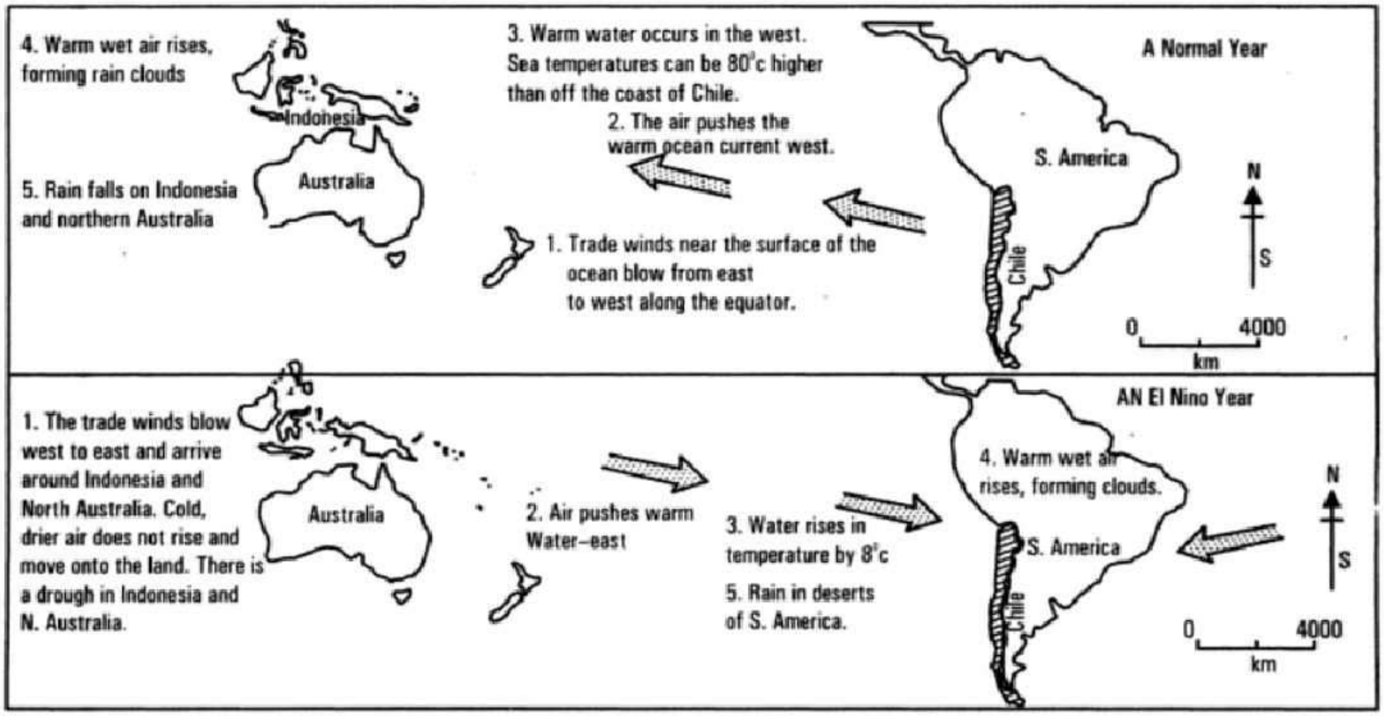


Fig. 3.45 – El–Nino

the frequency of tropical cyclones is high as a result of which thousands of people get killed along the coast of Bangladesh and the eastern coast of India (Orissa, Andhra Pradesh , Tamil Nadu, and West Bengal).

Ozone Layer Depletion

Ozone is mainly confined to the stratosphere. Ozone is a molecule formed of three atoms of oxygen. Ozone forms naturally when lightning strikes through air; large quantities are generated spontaneously in the stratosphere (the uppermost layer of atmosphere). A diffuse layer of ozone mixed with other gases – the ozone layer – surrounds the world at a height of *20 to 40 kilometers* (*12 to 25 miles*).

'Harmless' synthetic chemicals released into the atmosphere–primarily chlorofluorocarbon (CFCs) used as cleaning agents, refrigerants, fire-extinguishing fluids, spray-can propellants, and insulating foams are converted by the energy of sunlight into compounds that attack and partially deplete the Earth's atmospheric ozone. The CFCs are complex synthetic molecules of chlorine, fluorine, and carbon. They are very stable (inert) under conditions of Earth's surface and they possess remarkable heat properties, making them valuable as refrigerants and as propellants in aerosol sprays.

Ozone levels in the stratosphere has decreased by at least 3% in USA, 4% in Australia, and New Zealand and 50% near the North and South Poles. The amount of depletion varies with latitude (and with the seasons) because of variations in the intensity of sunlight **(Fig. 3.47)**.

The decrease in ozone alarms scientists because stratospheric ozone intercepts come of high energy ultraviolet radiation coming from the sun. Ultraviolet radiation injuries living things by breaking strands of DNA and unfolding protein molecules. Species normally exposed to sunlight have evolved defenses against average amount of ultraviolet radiation, but increased amounts could overwhelm these defenses. Land plants such as soybeans and rice would be subjected to sunburn that decreases their yields. Even plankton in the upper most two meters of ocean would be adversely affected. Recent researches

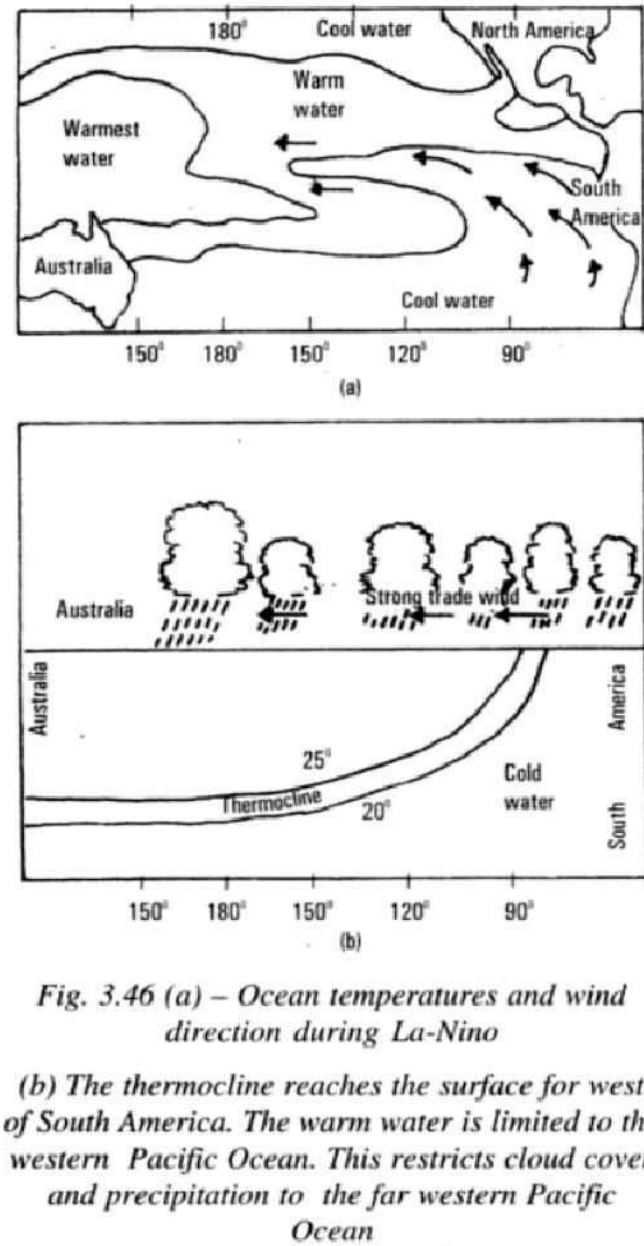


Fig. 3.46 (a) – Ocean temperatures and wind direction during La-Nino

(b) The thermocline reaches the surface for west of South America. The warm water is limited to the western Pacific Ocean. This restricts cloud cover and precipitation to the far western Pacific Ocean

indicate an alarming decrease in phytoplankton primary productivity of between 6% and 12% in the coastal waters around Antarctica.

The human beings would not escape the adverse effects of ozone depletion. About one per cent decrease in atmospheric ozone would probably be accompanied by a 5% to 7% increase in human skin cancer. Strong ultraviolet light can also suppress the immune system and cause eye cataracts.

The world community is seriously concerned about the adverse effects of ozone depletion and the production of CFC gases is being reduced. Unfortunately, the CFC gases stay in the atmosphere for up to 110 years and so, their damaging effect will continue. It may already be too late.

Climatic Change

The Earth is currently in a warm phase between ice ages. Warmer temperatures result in higher sea levels as more of the polar ice caps melt. Most of the world's population lives near sea coasts, so any changes which might cause sea levels to rise, could have a potentially disastrous impact.

The Greenhouse Effect

The greenhouse effect is a natural phenomenon. Gases such as carbon are known as "greenhouse gases" because they allow shortwave radiation to enter the Earth's atmosphere, but help to stop long-wave radiation from escaping. This traps heat, raising Earth's temperature. An excess of these gases, such as that which results from burning of fossil fuels, helps trap more heat and can lead to global warming.

The most important greenhouse gases are water vapour and carbon dioxide **(Fig. 3.48)**. Their presence in the atmosphere allows the Earth to maintain an average temperature of approximately 15°C. Without them, the surface temperature of the planet would be about -19°C, and the Earth could not support life. Consequently, it is clear that we owe our very existence to the greenhouse effect. With the onset of the Industrial Revolution, however, the CO_2 content of the air began to rise, and people began to worry that this phenomenon might have a 'dark side' we had not anticipated. Some of the experts predict that the doubling of the atmospheric CO_2 concentration will enhance the planet's natural greenhouse effect to such an extent that it will lead to catastrophic global warming, which would melt the polar ice caps, flood coastal lowlands, produce simultaneous floods and droughts, cause havoc with agriculture, and lead to all manner of economic, social and political instability. Because of these dire potential consequences, CO_2 is often portrayed as a pollutant in the popular media.

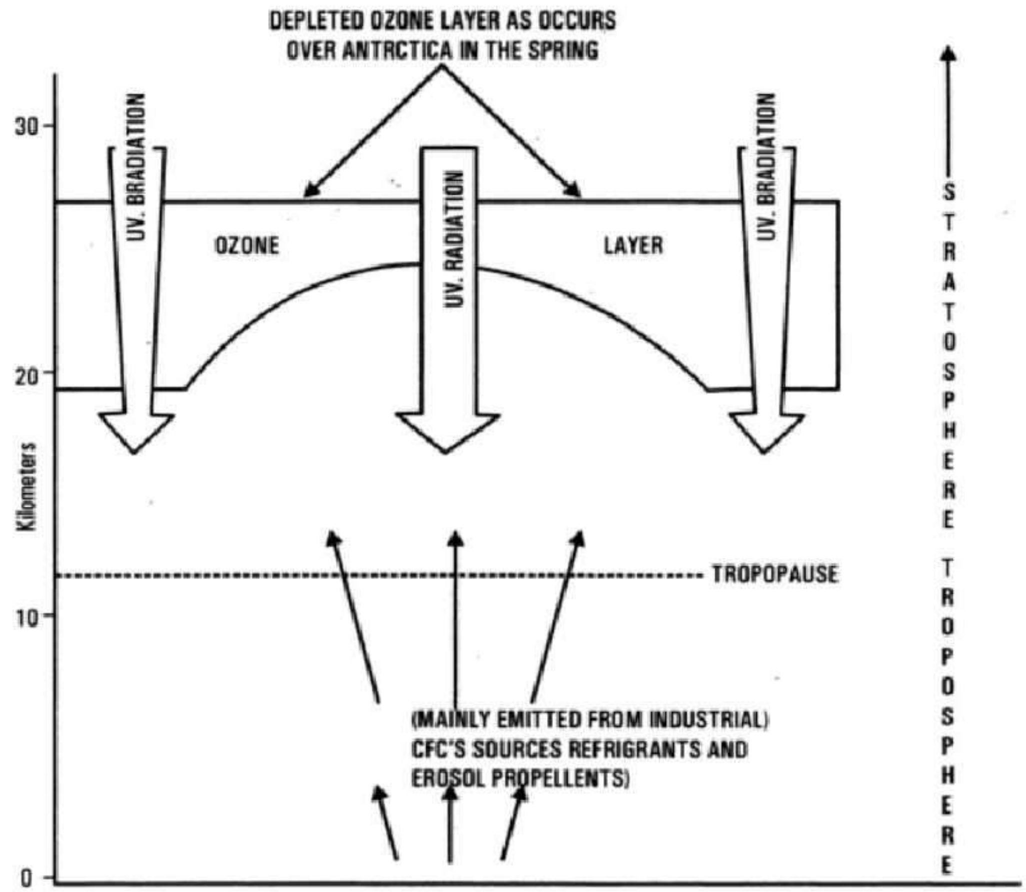


Fig. 3.47 – Ozone Layer Depletion

Fig. 3.47 – Ozone layer depletion

The scientists are trying to determine whether increasing concentration of atmospheric greenhouse gases will have any effect on global temperature or climatic patterns. Scientists who use computer models to study these questions commonly report that a temperature rise of 2° to 4°C will result from a doubling of temperature's CO^2 content, leading to catastrophic events such as the melting of Earth's polar ice caps, which could produce widespread flooding and famine. Consequently, the greenhouse effect has become a topic of both scientific and political debate; and will probably remain so for years to come.

Global Warming

The average temperature of the Earth is about 14°C. The Earth's temperature, however, fluctuates slowly over time. The global temperature trend has been generally upward in the last 18,000 years since the last ice-age, but the rate of increase has recently accelerated **(Fig. 3.49).** This rapid warming may be the result of an enhanced *greenhouse effect*, the trapping of heat by the atmosphere. Glass in a greenhouse is transparent to light but not to heat. The temperature inside a greenhouse rises because the heat is unable to escape. On Earth greenhouse gases – carbon dioxide, methane, CFCs, and others — take the place of glass. Heat that would otherwise radiate away from the planet is absorbed and trapped by these gases, causing a rise in surface temperature **(Fig. 3. 50).**

Evidence of Global warming : There is a unanimity amongst most of the scientists that the Earth is warming at an unusual rate. There are many temperature dependent phenomena that indicate the Earth is warming. Some of important proofs of global warming are as follows:

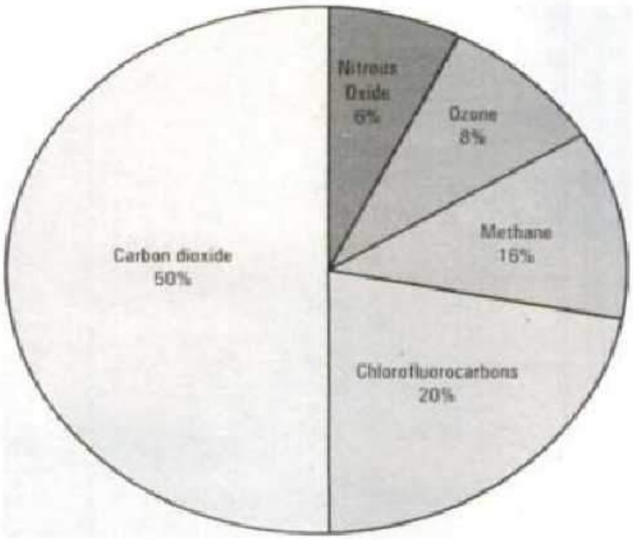


Fig. 3.48

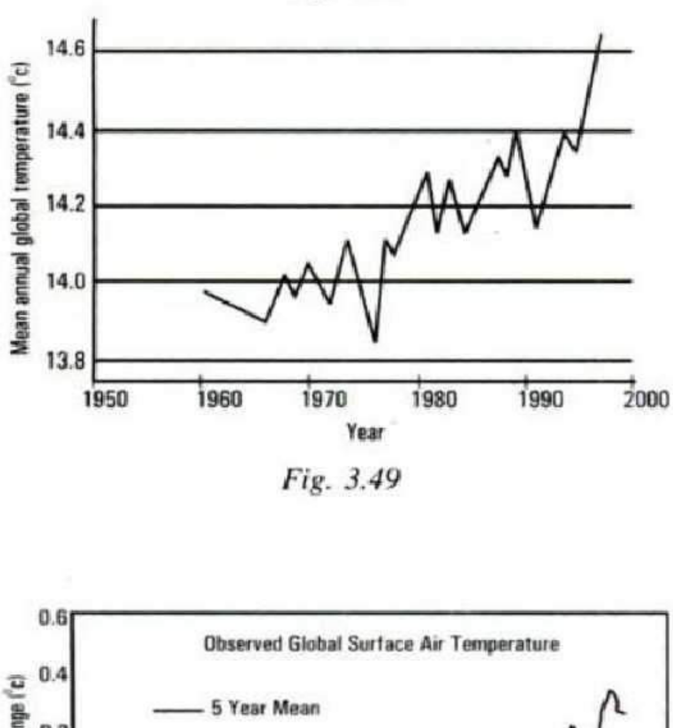
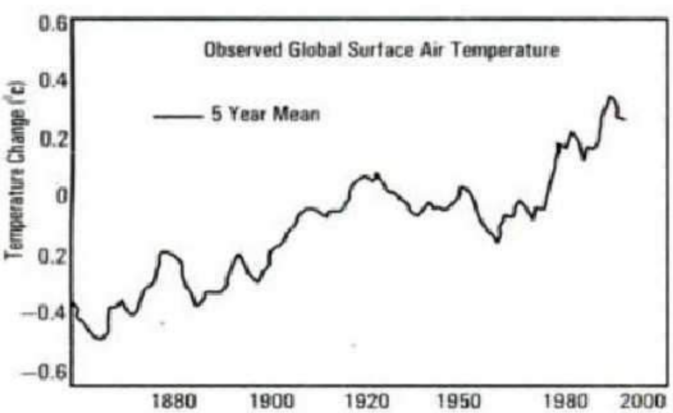


Fig. 3.49



Source: H. Wilson & J. Hansen

Fig. 3.50 – Increase in global surface air temperature

1. Antarctica's ice sheets are breaking up.
2. Earth's mountain glaciers are melting. Glaciers of the Alps Mountains of Europe shrank by about 50% in the 20th century. Bering Glacier in Alaska is retreating. Garhwal Himalaya glaciers are rapidly retreating.
3. Sea level is rising.
4. The temperature of global ocean is rising.
5. Northern Hemisphere's permafrost is melting.
6. Arctic pack ice is thinning and retreating.
7. The tree-line in mountain ranges is moving upward.
8. Many tropical diseases are spreading towards the poles and the higher elevations in the tropics.
9. Snowfall was recorded in the desert of Dubai and Abu-Dhabi in 2005.
10. Vegetation appearing on the free slopes of Antarctica.
11. The frequency of El-Nino years is increasing.
12. 1998 was the warmest year of record.
13. Seven of the 10 warmest years of record occurred since 1990.
14. The 1990s was the warmest decade on record.
15. The 20th century was the warmest century of the millennium.
16. The population of Adelie penguin on Antarctica dropped 40% in the last century
17. The corals are dying at an unprecedented rate. The dying corals is attributed to the process caused by bleaching, which occurs when temperatures become abnormally high. The bleaching is actually the result of the death of microscopic algae that both colour and feed the coral.

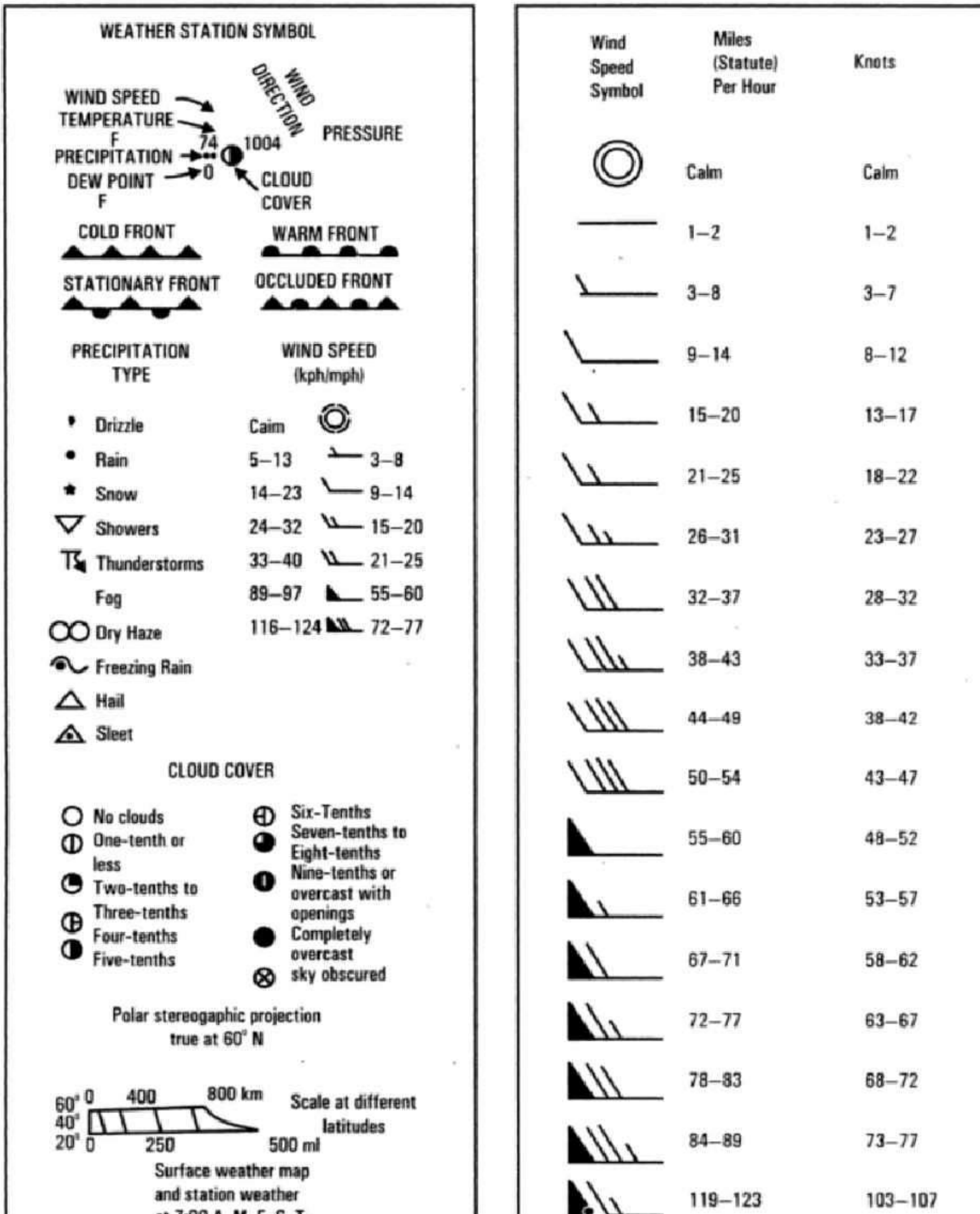


Fig. 3.51 – Forms of meteorological symbols, approved by the International Meteorological Organisation, Warsaw, 1935

Table 3.2: *Some Technical Terms of Climatology.*

Isoline	*Lines of*
Isallobar	Equal pressure tendency showing similar changes over a given time.
Isamplitude	Equal amplitude variation.
Isanomaly	Equal barometric pressure.
Isobar	A line on a map connecting points having the same atmospheric pressure.
Isocryme	Equal lowest mean temperature for specified period (e.g. coldest month)
Isohel	Equal sunshine.
Isohyet	Equal amounts of rainfall.
Isokeraun	Equal thunderstrom incidence.
Isomer	Equal average monthly rainfall expressed as percentage of the annual average.
Isoneph	Equal degree of cloudiness.
Isonif	Equal snowfall.
Isophene	Equal seasonal phenomena (e.g. flowering of plants).
Isoryme	Equal frost incidence.
Isoterp	Equal physiological comfort.
Isotherm	Equal temperature.

Source: Jone E., et al.2003, **Climatology: An Atmospheric Science,** *Pearson Education*

Weather

Weather is a condition of the atmosphere at a given time and place. Weather involves temperature, precipitation, humidity, wind and associated factors.

Climate

The long term atmospheric characteristics of a specified area. It is a summary of mean weather conditions over a time period usually based on 30 years of record. Climates are largely determined by location with respect to land and sea-masses, to large scale patterns in the general circulation of the atmosphere, latitude, altitude, and to local geographical features. The climatic characteristics are usually represented by numerical data on temperature, pressure, wind, rainfall and humidity.

Temperature

Temperature is a measure of how hot or cold the air is near Earth's surface.

Terms to Remember

Anticyclone: A dynamically or thermally caused area of high atmospheric pressure with descending and diverging air-flow.

A wet–day: When at least 1 mm of rainfall is recorded.

Convection: Vertical transfer of heat from one place to another through the actual physical movement of air; involves a strong vertical motion.

Convectional rainfall: A form of rainfall induced when warm, moist air is heated at the ground surface, rises, cools and condenses to form water droplets and eventually rainfall.

Dew-point temperature: The temperature at which a given mass of air becomes saturated, holding all the water it can hold. Any further cooling or addition of water vapour results in active condensation.

Cumulonimbus: These are thunder clouds which result into torrential rainfall.

Horse latitudes: Subtropical high pressures on oceans.

Katabatic: Air drainage from elevated regions, flowing as gravity winds.

Normal Lapse Rate: The average rate of temperature decrease with increasing altitude in the lower atmosphere; an average value of 6.4°C per km, or 1000 m.

Orographic lifting: The uplift of migrating air masses in response to the physical presence of mountain, a topographic barrier. The lifting air cools adiabatically as it moves upslope; may form clouds and produce increase precipitation.

Orographic precipitation: The precipitation occurring because the physical presence of mountain which obstructs the moisture-laden air-mass.

Roaring forties: Blowing in and around 40°S, these are the fast westerly winds. In the higher latitudes, they are known as furious fifties, shrieking sixties because of their violent speed.

Squall: A very shortlived wind.

Thermal equator: A line joining the points with highest mean temperature.

Tornado: An intense, destructive cyclonic rotation, developed in response to extremely low pressure, associated with mesocyclone formation.

Tyndal effect: Scattering of light by dust particles.

Typhoon: A tropical cyclone in excess of 65 knots (74 mph) that occurs in the western Pacific, mostly along the China coast.

Table 3.3: Weather Instruments

Weather Instrument	*Function*
Antinometer	Solar radiation
Altimeter	Measuring of altitude (height)
Anemometer	Wind speed
Atmometer	An instrument for measuring the rate of evaporation
Barograph	Continuous recording of atmospheric pressure
Barometer	Pressure
Cathetometer	Height
Cryometer	Very low temperatures
Evaporimeter	Rate of evaporation
Fathometer	Ocean depth
Hydrometer	Specific gravity of liquid
Hygrometer	Relative humidity
Hypsometer	Absolute height above the sea level
Lysimeter	Actual evapotranspiration
Manometer	Pressure of gases
Nephoscope	Height, movement and velocity of clouds
Photometer	Luminous intensity of the source of light
Psychrometer	Relative humidity
Pyrometer	Very high temperature
Radio micrometer	Heat radiation
Raingauge	Precipitation
Salinometer	Salinity of solution
Solarimeter	Intensity of solar radiation
Thermometer	Temperature
Thermostat	Regulates temperature to a particular point
Wet and Dry Bulb Thermometer	Relative humidity
Wind-vane	Wind direction

REFERENCES

Ahrens, C.D., 2001, ***Essentials of Meteorology,*** 3rd ed. Pacific Grove, CA, Brooks/Cole.

Barry, R.G., and Chorley, R.J., 1998, ***Atmosphere, Weather, and Climate***, London, Routledge.

Boucher, K, 1975, ***Global Climate***, New York, Halstead Press.

Bryant, R.,2002, ***Physical Geography***,1990, New Delhi, Rupa Co.

Chang,C.P. 1987, ***Monsoon Meteorology***, Oxford University Press.

Christopherson, R.W., 1995, ***Elemental Geosystems: A Foundation in Physical Geography***, Englewood Cliff, New Jersey, Prentice Hall.

Cole, F.W., 1980, ***Introduction to Meteorology***, New York, John Wiley and Sons.

Critchfield, H.J. 2002, ***General Climatology***, New Delhi, Printice Hall.

Concise Atlas of the World, 2001, London D.K.

David, S.G. Thomas and Andrew Goudie, 2006, ***The Dictionary of Physical Geography***, Oxford, Blackwell Publishing.

Garrison, T.,1999, ***Essentials of Oceanography,*** Wadsworth Publishing Company.

Goody, R.M. and Walker, J.C.G, 1972, ***Atmosphere***, Englewood Cliffs, NJ, Prentice Hall.

Goudie, A.S., 1983, ***Environmental Change,*** New York, Oxford University Press.

Hidore, J.J. 1996, ***Global Environmental Change***, New Jersey, Printice Hall.

Husain, M., 2010, ***Geography: Glossary of Terms***, McGraw Hill Education.

Husain, M., 2009, ***Fundamentals of Physical Geography***, Jaipur, Rawat Publications.

Hrens, C.D., 2001, ***Essentials of Meteorology,*** 3rd ed. Pacific Grove, CA, Brooks/Cole.

REFERENCES

John E. Oliver, John J. Hidore, 2002, ***Climatology – An Atmospheric Science***, Second Edition, Delhi, Pearson Education.

Lal, D.S., 2003, ***Climatology***, Allahabad, Sharda Pustak Bhawan.

Macdonald, G.A., 1983, ***Volcanoes,*** 2nd ed., Englewood Cliffs, N.J., Prentice Hall.

Mayhew, Susan,1997, ***Oxford Dictionary of Geography***, India.

McIntosh, D.H. and Thomas, A.S., 1969, ***Essentials of Meteorology***, London, Wykeham Publications.

Miller, A., et.al, 1983, ***Elements of Meteorology,*** Columbus, Merril.

Oliver, J.E., J.J. Hidore, 2003, ***Climatology: An Atmospheric Science***, second ed.

Oliver,J.e,Fairbridge, R.W., 1987, ***Encylopaedia of Climatology***, New York, Van Nostrand Reinhold.

Oliver, J.E., J.J. Hidore, 2003, ***Climatology: An Atmospheric Science***, second ed. Delhi,Pearson Education.

Peterson, J.,1969, ***Introduction to Meteorology***, New York, McGraw-Hill.

Riehl, H., 1978, ***Introduction to Atmosphere***, New York, McGraw-Hill.

Singh, S.2005, ***Climatology***, Allahabad, Prayag Pustak Bhawan.

Strahler, A. et.al.1997, ***Physical Geography, Science and Systems of the Human Environment,*** New York, John Wiley & Sons. Inc.