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1. Introduction and General Considerations

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1. Introduction and General Considerations

1.1 Introduction to Oceanographical Aspects of Storm Surges

Storm surges are oscillations of the water level in a coastal or inland water body in the period range of a few minutes to a few days, resulting from forcing from the atmospheric weather systems. By this definition, the so-called wind-generated waves (often referred to as wind waves) and swell, which have periods of the order of a few to several seconds, are excluded. The term "storm surge" is commonly used in European literature, especially in the literature pertaining to the water level oscillations in the North Sea. In North American literature, the terms "wind tides" and "storm tides" are also used to refer to the same phenomenon.

Unfortunately, the term "wind tides" has occasionally been used as a synonym for low storm tides and – in aeronomy – to refer to atmospheric tides (which have the same astronomical origin as oceanic tides). Hence, the term will not be used here. The term "storm tide" is used in North American literature in a confusing manner: at times it is used in the same sense as storm surge, and at other times it is used to denote the sum of the storm surge and the astronomical tide. Here, the term will be used only in the latter sense and describes the whole event. Sometimes the term "storm tide" is meant to be the highest peak due to interaction of tide and storm surge. This parameter will be denoted here as "high water level" (HWL). As an alternative to the term "storm surges", the term "meteorological ocean tides" will be used. In some sense, storm surges are similar to astronomical tides: although storm surges are not periodic in the sense that tides are, they do exhibit certain periodicities, and since the forcing functions are due to meteorological causes, it is not inappropriate to call them meteorological ocean tides. Here, the word "ocean" is used to denote a water body of any scale, and not necessarily the oceans. In Russian literature (e.g. see Lappo and Rozhdestvenskiy, 1979), the term "meteorological ocean tide" is commonly used.

The spectrum of ocean waves is shown schematically in Fig. 1.1, and it can be seen that storm surges are centered at about 10^{-4} cycles per second (cps or Hz), which gives a period of about 3 h. However, depending mainly on the topography of the water body and secondarily on other parameters, such as the direction of movement of the storm, strength of the storm, stratification of the water body, presence or absence of ice cover, nature of tidal motion in the water body, etc., the periods in the water level oscillations may vary consider-

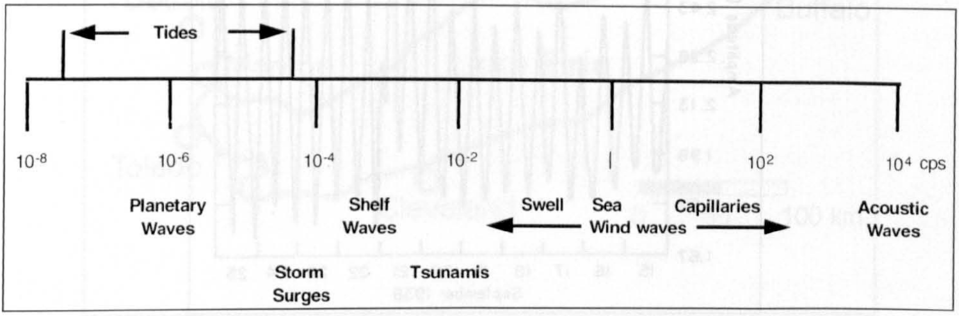

Fig. 1.1: Frequencies of oceanic wave motion in cycles per second (cps) (Platzman, 1971)

ably. Even the same water body, storm surge records at different locations can exhibit different periods.

Although storm surges belong to the same class known as long waves, as do astronomical tides and tsunamis, there are at least two important differences. First, whereas tides and tsunamis occur on the oceanic scale, storm surges are simply a coastal phenomenon. Second, significant tsunamis and tides cannot occur in a completely closed small coastal or inland water body, but storm surges can occur even in completely enclosed lakes, or in canals and rivers.

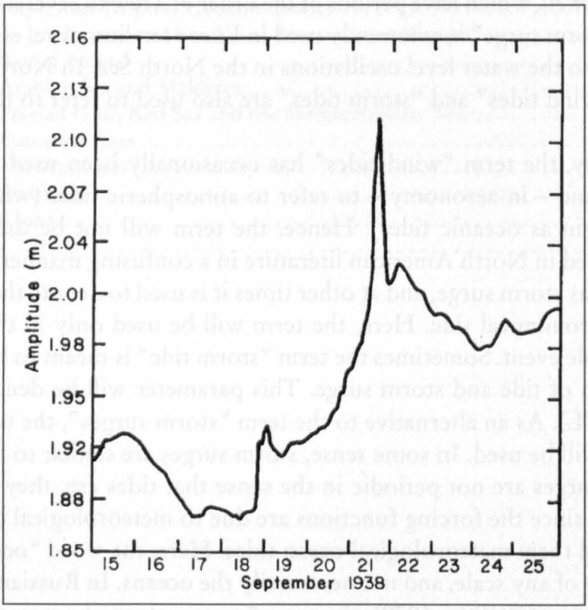

Fig. 1.2: Storm Surge at Forest Hills, New York (PAULSEN et al., 1940)

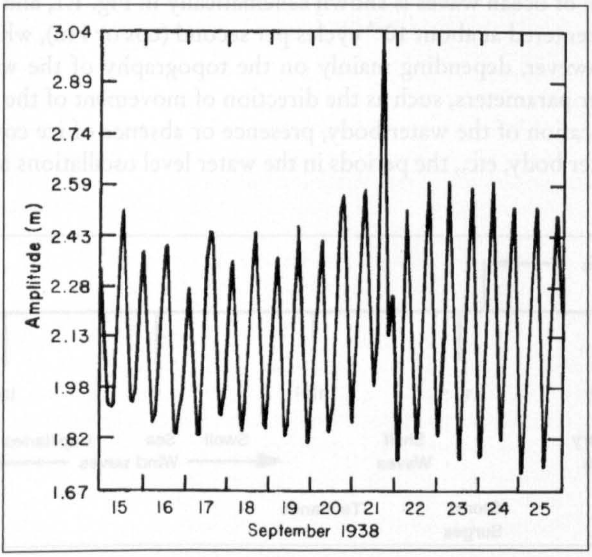

Fig. 1.3: Storm Surge at Rockaway Park, New York (PAULSEN et al., 1940)

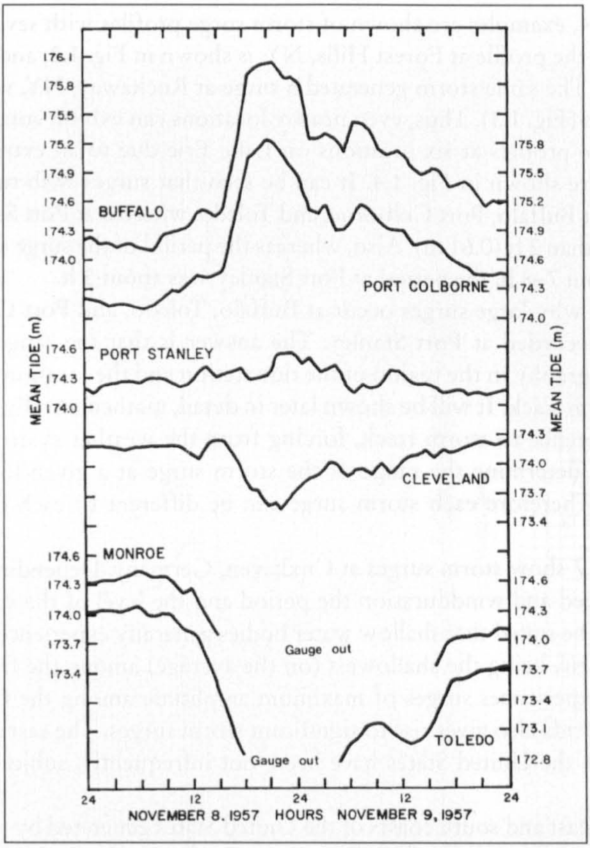

Fig. 1.4: Observed storm surges at six locations on Lake Erie. Mean tides are shown on the left ordinate for Buffalo, Port Stanley, and Monroe and on the right ordinate for Port Colborne, Cleveland, and Toledo. Mean tides are metres above the Great Lakes Datum with reference to the mean tide at New York (HUNT, 1959)

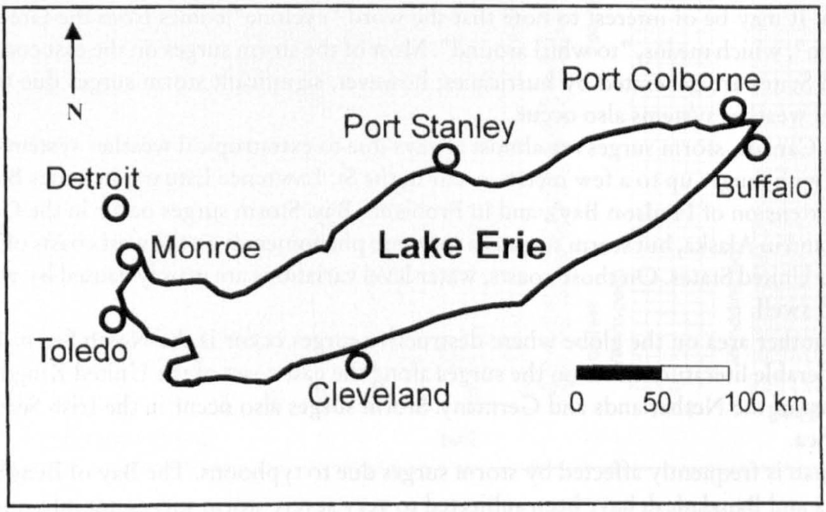

Fig. 1.5: Map of Lake Erie

In Fig. 1.2–1.4, examples are shown of storm surge profiles with several different periods. For example, the profile at Forest Hills, NY, is shown in Fig. 1.2, and a period of about 2.5 d can be seen. The same storm generated a surge at Rockaway, NY, with periods of the order of 1 d or less (Fig. 1.3). Thus, even nearby locations can exhibit considerably differing periods. The surge profiles at six locations on Lake Erie due to an extratropical storm in November 1957 are shown in Fig. 1.4. It can be seen that surges with ranges of up to 8 ft (2.4 m) occurred at Buffalo, Port Colborne, and Toledo, whereas at Port Stanley the range of the surge was less than 2 ft (0.61 m). Also, whereas the period of the surge at Buffalo and Port Colborne was about 7–8 h, the period at Port Stanley was about 3 h.

One may ask why large surges occur at Buffalo, Toledo, and Port Colborne and only small surges are recorded at Port Stanley. The answer is that the range of the surge depends on the topography in the region of the tide station and the location of the tide station relative to the storm track. It will be shown later in detail, mathematically, how topography, position with reference to storm track, forcing from the weather systems, plus a host of secondary factors determine the range of the storm surge at a given location in a specified water body. Therefore each storm surge can be different to each other at one location.

Fig. 1.6 and 1.7 show storm surges at Cuxhaven, Germany. Depending upon the winddirection, windspeed and windduration the period and the level of the surge differs considerably. But it can be stated that shallow water bodies generally experience surges with greater ranges. Lake Erie, being the shallowest (on the average) among the five Great Lakes of North America, experiences surges of maximum amplitude among the Great Lakes. Lake Okeechobee in Florida also gives rise to significant storm surges. The east coast and the Gulf of Mexico coast of the United States have been, not infrequently, subjected to destructive storm surges.

Surges on the east and south coasts of the United States generated by tropical storms are referred to as “hurricanes”. Similar tropical storms in the Pacific are referred to as “typhoons”. (The Japanese refer to them also as “Reppus”.) In Australia, they are called “willy-willies”, in the Philippines “Baguios”, and in Arabia “Asifat”. Tropical cyclones in the Indian Ocean, Bay of Bengal, and the Arabian Sea are popularly referred to as “depressions”, although there is a strict classification based on maximum wind speed attained in the weather system. It may be of interest to note that the word “cyclone” comes from the Greek word „kyklon“, which means, “to whirl around”. Most of the storm surges on the east coast of the United States are generated by hurricanes; however, significant storm surges due to extratropical weather systems also occur.

In Canada, storm surges are almost always due to extratropical weather systems. Storm surges with ranges up to a few metres occur in the St. Lawrence Estuary, in James Bay (southern extension of Hudson Bay), and in Frobisher Bay. Storm surges occur in the Canadian Arctic and in Alaska, but storm surge is a very rare phenomenon on the west coasts of Canada and the United States. On those coasts, water level variations are mainly caused by wind waves and swell.

Another area on the globe where destructive surges occur is the North Sea in Europe. Considerable literature exists on the surges along the east coast of the United Kingdom and the coast of the Netherlands and Germany. Storm surges also occur in the Irish Sea and the Baltic Sea.

Japan is frequently affected by storm surges due to typhoons. The Bay of Bengal coasts of India and Bangladesh have been subjected to very severe storm surges not infrequently. It will be seen later that the peculiar topography (i.e. triangular or V-shaped basin), shallowness

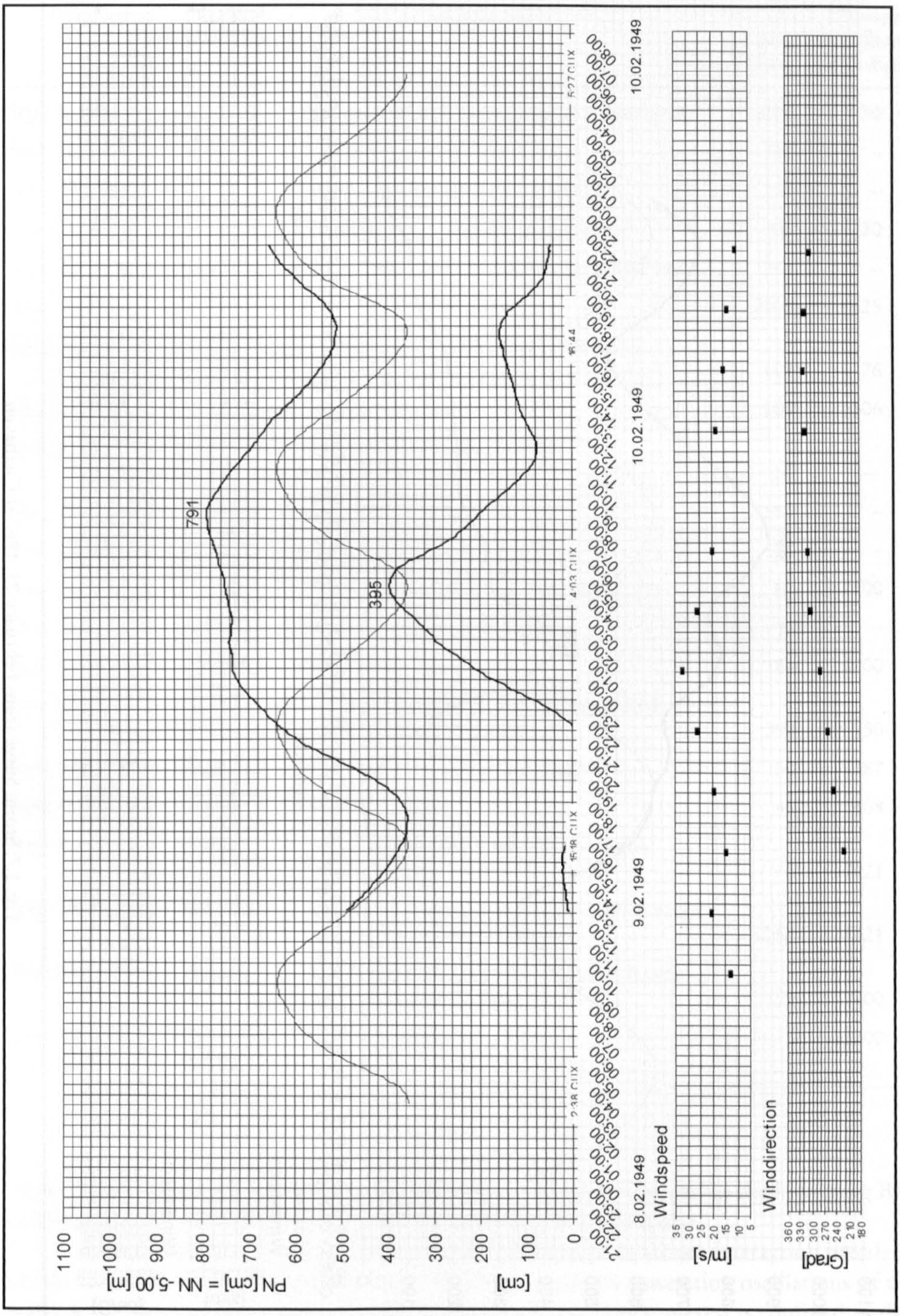

Fig. 1.6: Storm Surge from February 10, 1949 at Cuxhaven

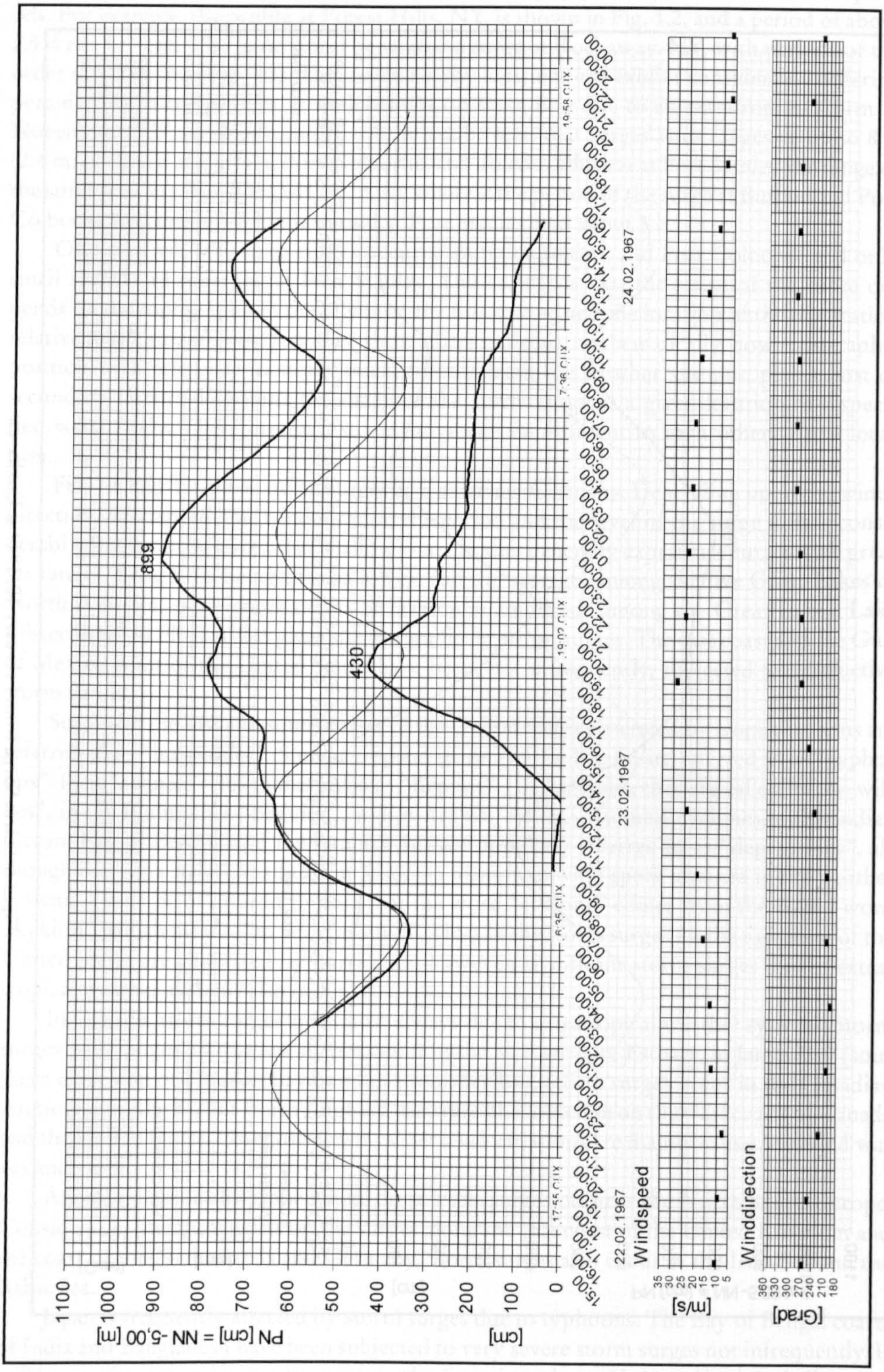

Fig. 1.7: Storm Surge from February 23, 1967 at Cuxhaven

Table 1.1: Some of the most disastrous hurricanes affecting the United States (1900–1979)

Date	Name of hurricane	Area affected	No. of people killed	Damage in millions of dollars
Sept. 8, 1900	–	Storm surge at Galveston greater than 6.5 m	6000	30
Sept. 20, 1909	–	Louisiana coast (Grand Isle)	353	–
Sept. 29, 1915	–	Mississippi Delta (New Orleans)	284	–
Sept. 14, 1919	–	Florida Keys, Corpus Christi (Texas)	600–900	20
Sept. 20, 1926	–	Miami and Pensacola to Southern Alabama	243	–
Sept. 16, 1928	–	Palm Beach, Okeechobee	2000	25
Sept. 1, 1935	Labor Day storm	Florida Keys (winds greater than 332 km · h^{-1})	408	76
Sept. 21, 1938	–	New England and Long Island	600	306
Aug. 7–11, 1940	–	South-eastern United States (Georgia to Tennessee)	50	—
Sept. 14–15, 1944	–	Atlantic coast	390	–
Sept. 19, 1947	–	Florida, Louisiana, Mississippi	51	–
Aug. 31, 1954	Carol	North Carolina to New England	60	500
Oct. 13–17, 1954	Hazel	South Carolina to New York	95	–
Aug. 16–20, 1955	Diane	Northeast United States	184	1000
June 27, 1957	Audrey	Texas to Alabama (4-m surge inundated Louisiana 40 km inland)	390	150
Sept. 9–11, 1960	Donna	Florida, New York, New England	50	387
Sept. 7–12, 1961	Carla	Texas	46	408
Sept. 8, 1965	Betsy	Florida, Louisiana, mid-Atlantic States, New England	75	1421
Aug. 15–16, 1969	Camille	Louisiana, Mississippi, Virginia (7.4-m surge on Pass Christian, Mississippi)	>250	1421
Mid-June, 1972	Agnes	Florida, Virginia, Maryland, Pennsylvania, North Carolina to New York	122	2100
Late Aug.–early Sept. 1979	David and Frederic	Alabama, Mississippi, Florida	5	2300

of the water body, together with a large tidal range make storm surges on the low-lying Bay of Bengal coast more dangerous than in any other region of the globe.

It is recognised by now that the storm surge problem is an air-sea interaction problem; i.e. the atmosphere forces the water body, which responds by generating oscillations of the water level with various frequencies and amplitudes. Our present interest is confined to that part of the oscillation between a few minutes and a few days. Study of the storm surge problem will begin with a consideration of the global weather systems.

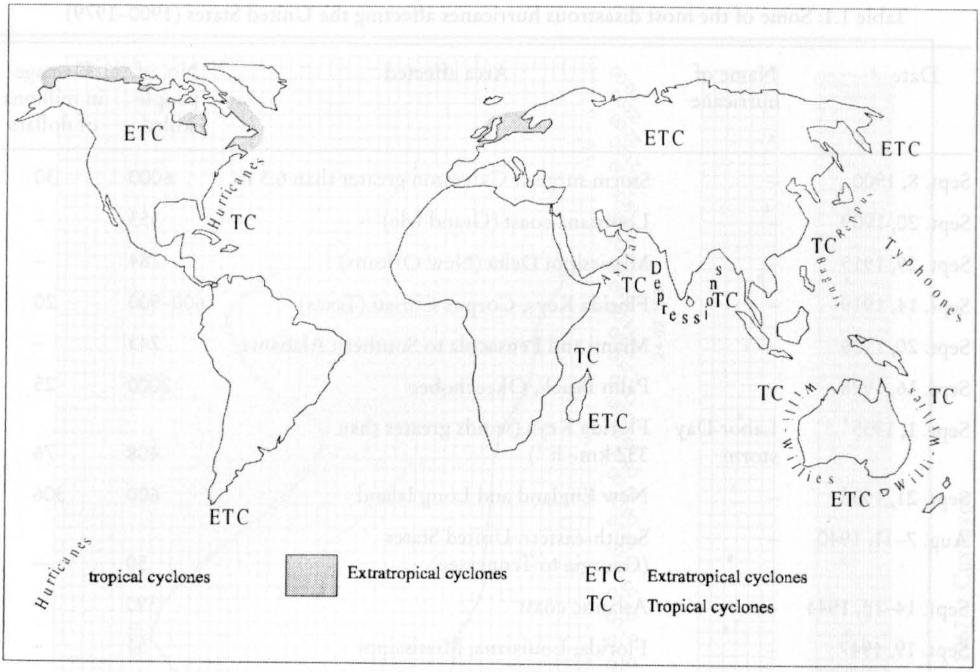

Fig. 1.8: Global Storm Surges due to Tropical Cyclones (TC) and Extratropical Cyclones (ETC)

1.2 Global Weather Systems

In order to understand global weather systems, it is convenient to begin with the so-called "general circulation of the atmosphere," which refers to the motion of the atmosphere around the globe in an average sense, both in space and time. Before discussing the general circulation, it is appropriate to introduce certain nomenclature. There are two important characteristics of the atmosphere, which can be seen in Fig. 1.9:

- the pressure decrease with height above the earth surface
- the change of temperature with height above the earth surface.

The pressure decreases with height in a monotonic fashion, as can be seen from the ordinate on the right side of Fig. 1.9. The units of pressure are millibars (another internationally used unit is the kilopascal, 1 kPa = 10 mb). On average, the atmospheric pressure at sea level is 1013.2 mb. The height scale (kilometres) is shown on the left hand side of the graph. For general interest, the maximum heights of three mountain peaks, namely, Mount Everest, Mount Blanc, and Ben Nevis, are included. The heights of different cloud types are also indicated.

The second important characteristic is the change of temperature with height, indicated by the curve in Fig. 1.9. Temperature inversions occur several times with increasing height, and this gives rise to three warm and two cold regions. The warm regions are near the earth's surface, at a height between 40 and 60 km, and above 150 km (i.e. more or less the top of the atmosphere). The first cold region extends from about 10 to 35 km and the second cold region from about 80 to 90 km. The exact distribution of temperature with height depends on latitude and, to a certain extent, on the season.

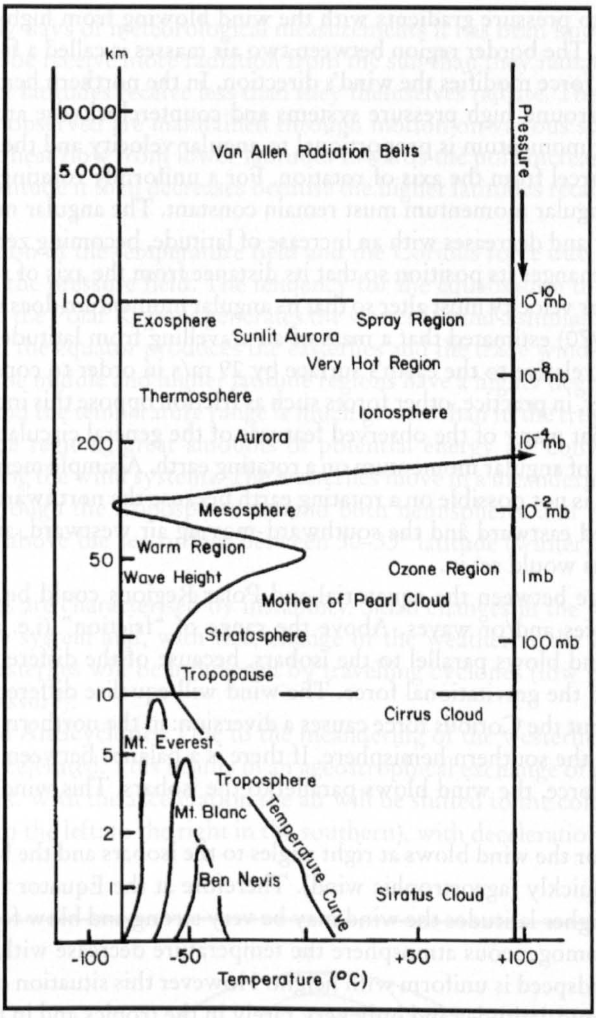

Fig. 1.9: Vertical structure of the atmosphere (DOBSON, 1963)

It can be seen that the temperature decreases from the earth's surface as far as the tropopause. The atmosphere below the tropopause is called the troposphere, and the region immediately above the troposphere is referred to as the stratosphere. The electrical conductivity of air above the 80-km level is much greater than that at lower levels, especially during sunlight hours. This region of the atmosphere, called the ionosphere, allows radio waves to propagate great distances.

The knowledge obtained from the observations of troposphere and stratosphere led to a more definitive theory concerning the general circulation of the atmosphere. The foundation among the general circulation is the interdependence of the three-dimensional fields of temperature, pressure and wind (FLOHN, 1971). There are three possible movements of an air mass: 1) vertical, 2) horizontal and 3) partly vertical and partly horizontal. The vertical movements means that wind blows at the height from warm to cold regions and near the ground from cold to warm areas, which is thermally induced. The horizontal movement of an air mass occurs due to pressure gradients with the wind blowing from high pressure area to a low pressure area. The border region between two air masses is called a frontal zone.

The Coriolis force modifies the wind's direction. In the northern hemisphere, the wind blows clockwise around high pressure systems and counterclockwise around areas of low pressure. Angular momentum is proportional to angular velocity and the square of the distance of the air parcel from the axis of rotation. For a uniformly rotating earth and atmosphere, the total angular momentum must remain constant. The angular momentum is greatest at the equator and decreases with an increase of latitude, becoming zero at the poles. If a large mass of air changes its position so that its distance from the axis of rotation also changes, then its angular velocity must alter so that its angular momentum does not change. BARRY and CHORLEY (1970) estimated that a mass of air travelling from latitude 42° to 46° would increase its speed relative to the earth's surface by 29 m/s in order to conserve angular momentum. However, in practice, other forces such as friction oppose this increase, but it is important to note that many of the observed features of the general circulation are due to the poleward transfer of angular momentum on a rotating earth. A simple meridional (i.e. north-south) circulation is not possible on a rotating earth because the northward-moving air mass would be deflected eastward and the southward-moving air westward, and thus zonal (i.e. east-west) motions would set in.

Heat exchange between the equatorial and Polar Regions could be achieved through a system of vortices and/or waves. Above the range of "friction" (i.e. above a height of >1–2 km), the wind blows parallel to the isobars, because of the different direction of the Coriolis force and the gravitational force. The wind will equalise differences in pressure at the frontal zone, but the Coriolis force causes a diversion: in the northern hemisphere to the left, to he right in the southern hemisphere. If there is a balance between the gradient force and the Coriolis force, the wind blows parallel to the isobars. This wind is called the geostrophic wind.

At the Equator the wind blows at right angles to the isobars and the balance of pressure is regained very quickly (ageostrophic wind). Therefore at the Equator the winds are very light whereas at higher latitudes the wind may be very strong and blow for a long duration.

In an ideal homogeneous atmosphere the temperature decrease with high is about 10° C/km and the windspeed is uniform with height. However this situation of an ideal air mass never happens in mid-latitudes and only very rarely in the tropics and in the Polar Regions. The horizontal exchange of air is carried out (geostrophically) by travelling weather systems such as cyclones and anticyclones; the ageostrophic wind of the vertical circulation is proportionally much smaller, but cannot be ignored. Furthermore the horizontal component of the movement can either be stable or not unstable. If the horizontal gradient of the wind exceeds a threshold value – which may occur in the frontal zone – the situation of the wind and pressure fields will be changed on a large scale. That will result in the development of new cyclones (low pressure) and anticyclones (high pressure).

In a frontal zone the windspeed is much greater in the upper layers. These strong winds at a high of about 8 to 12 km above sea level are referred to as the Jet stream. There are at least two types of Jet streams, one in the polar front and the other in the subtropics.

For weather and climate purposes, as well as for the atmospheric forcing of storm surges, interest here is primarily in the troposphere and, to a lesser extent, in the lower part of the stratosphere. Earlier, the term "general circulation of the atmosphere" was introduced. In practice, this term is used to describe the more or less permanent wind and pressure systems of the troposphere and the lower stratosphere. To explain the dynamics of the climate system, initially we will omit orographical effects (FLOHN, 1971, BARRY and CHORLEY, 1992)

Since the early days of meteorological measurements it has been known that the tropical areas of the globe receive more radiation from the sun than they radiate back into space, whereas the higher latitudes receive less than they themselves radiate. The average temperature distributions observed are maintained through motion on various scales in the atmosphere. The rate of heat flow from lower latitudes towards the pole increases from the equator to about 35° latitude it then decreases because the higher latitudes retain some of this imported heat.

The distribution of the temperature field and the Coriolis force due to earth's rotation largely determine the pressure field. The tendency for the equalisation of pressure between the subtropics and the Polar Regions generates the westerlies and a similar tendency between the subtropics and the equator produces the easterlies and the trade winds.

Westerlies: The middle and higher latitude regions have a higher degree of baroclinicity than the tropics, and the temperature range is much greater than in the tropics. In the middle and higher latitude regions, great amounts of potential energy are converted into kinetic energy, thus creating the wind systems. The westerlies move in a meandering path (Fig. 1.10). They meander through the troposphere around both hemispheres and reach their highest speed at 9–11 km above the sea surface between 30–35° latitude (winter) and in summer at 40–45° latitude.

The westerlies are characterised by instability. Small changes in the Jet stream result in disturbance to the system and, with this, change of the weather at the earth's surface. At the surface the westerlies will be influenced by travelling cyclones (low pressure) and anticyclones (high pressure).

Cyclones and Anticyclones: Due to the meandering of the westerlies the wind is both accelerated and decelerated. This results in an ageostrophical exchange of air mass perpendicular to the isobars. With the acceleration the air will be shifted to the cold side (in the northern hemisphere to the left; to the right in the southern), with deceleration on the warm side

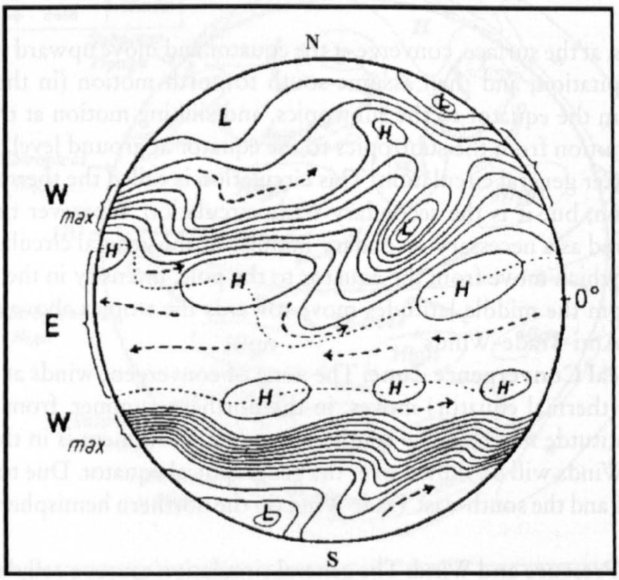

Fig. 1.10: Schematic repesentation of general circulation (4–10 km; line = isobars; winds = broken line; trade = dotted line) (FLOHN, 1971)

(in the northern to the right; to the left in the southern). This results in cells of low and high pressure: cyclones and anticyclones.

Due to the Coriolis force, the cyclones move with their winds rotating around them in an anticlockwise sense in the Northern Hemisphere.

Secondary Trade Circulation: The subtropical high pressure cells at 30° latitude north and south indicate a drop in pressure from the subtropics to the equator, which is due to the ageostrophical east wind, the Trade Winds (Fig. 1.11). This Trade Wind may reach a level of 10 km above the sea surface and also have an effect at ground level. Frictional effects mean that the wind at the surface moves to the southeast in the northern hemisphere/northeast in the southern hemisphere.

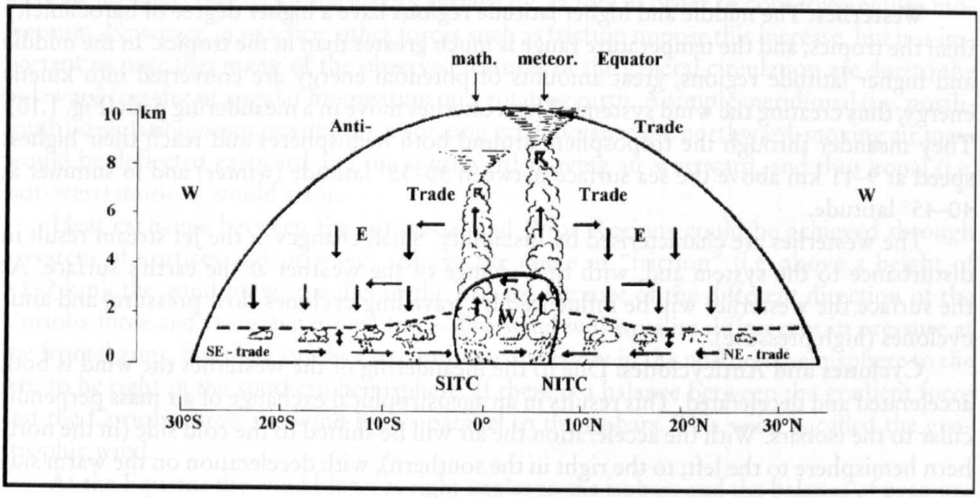

Fig. 1.11: Trade winds with ITCZ and equatorial westerlies (FLOHN, 1971)

These winds, at the surface, converge at the equator and move upward to the tropopause, producing precipitation, and then assume south to north motion (in the northern hemisphere) aloft from the equator to the subtropics, and sinking motion at the subtropics and south to north motion from the subtropics to the equator at ground level, referred to as the thermal motor after general circulation. This circulation is called the thermical motor of the general circulation, but it is the secondary trade circulation. However the thermic motor must be considered as a necessary secondary impulse of the general circulation.

The winds, which move from the equator to the pole, intensify in the westerlies. When the westerlies from the middle latitudes move towards the tropics above the Trade Winds, they are called "Anti-Trade-Winds".

Inter-Tropical Convergence Zone: The zone of convergent winds at ground level and lowest pressure (thermal equator) moves, in the northern summer, from the geographical equator to 20° latitude north, in the southern summer, movement is in the opposite direction. The Trade Winds will be shifted over the geographical equator. Due to this the pressure situation changes and the south-east Trade Wind (in the northern hemisphere) becomes equatorial westerlies.

Patterns of Pressure and Wind: The general circulation causes a cellular pattern of pressure and wind at the surface (level of 0–2 km). This structure changes with the season, because of the inclination of the earth and, with this, the changing solar radiation.

It must be considered that the "only true zonal distribution of pressure exists in the region of the subpolar low in the southern hemisphere where the ocean is continuous. To a lesser extent, the equatorial low is zonal. At other latitudes, particularly in the northern Hemisphere, where the bulk of the land exists, large seasonal temperature differences disrupt the idealised zonal patterns." (LUTGENS and TARBUCK, 1986).

The sea level pressure distribution for the month of July (representative of summer in the northern hemisphere) and January (representative of winter) is shown in Fig. 12. It can be seen that the observed pressure regimes are cellular. The high pressure centres are over the eastern side of the Atlantic and Pacific oceans (this affects the west coast climates of adjacent continents), north and south of the equator, South Indian Ocean, Arctic Ocean, and Antarctica. Occasionally, names are given to these centres. For example the one over the eastern Pacific is called the "Hawaiian High" and the one over the eastern Atlantic is called the "Azores High". The low pressure centres are the "Iceland Low" (over the North Atlantic), the "Aleutian Low" (over the North Pacific), and one each over the South Atlantic, South Pacific and Indian oceans in a shifting zone along the equator, and one in the Southern Ocean near Antarctica. The two semipermanent cells, the Iceland Low and the Aleutian Low "represent the great number of cyclonic storms that migrate eastward across the globe and converge in these areas." (LUTGENS and TARBUCK, 1986).

With reference to Fig. 1.13, the following remarks may be made. Pressure is higher and the gradients are steeper in the winter hemisphere (i.e. the hemisphere that has winter at that time), and the pressure centres shift northward in July and southward in January (TREWARTHA, 1968). The pressure belts in the subtropics are more or less continuous in the winter hemisphere, whereas in the summer hemisphere, the heated continents break the continuity. Between the subtropical high and the subpolar lows lies the main zone of travelling

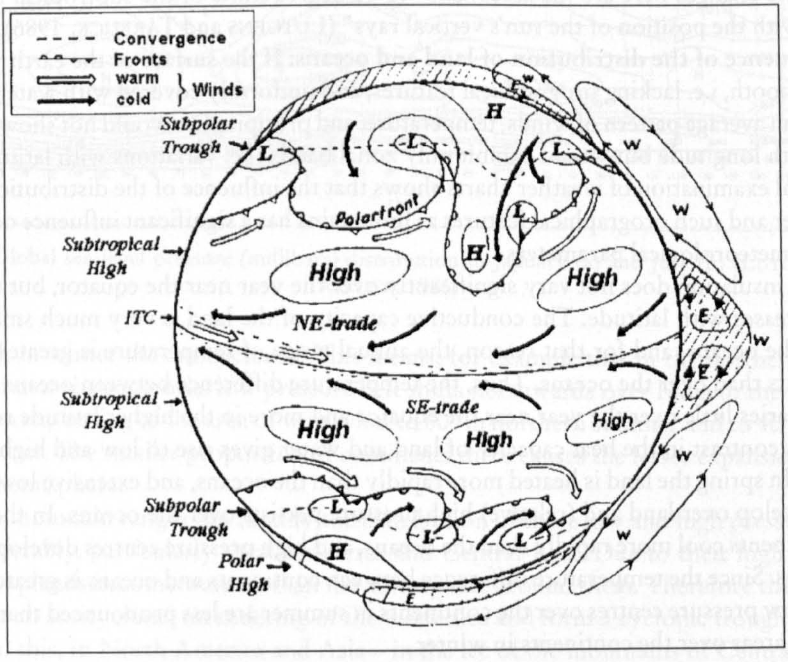

Fig. 1.12: Schematic representation of atmospheric circulation between 0–2 km eight and vertical circulation to 15 km height (FLOHN, 1971)

Table 1.2: Planetary Pressure and vertical Wind Belts

Pressure belt	latitude	Wind belt (0–3 km)	Wind belt (> 3 km)	
Polar High	80–90°	Polar Easterlies (0–3 km)		Sinking air dominates, with evaporation of clouds and dryness.
Subpolar Trough	55–65°	extratropical (mid-latitude) westerlies	westerlies 18–30 km; during winter more than 50 km	Cyclonic disturbance with clouds and precipitation moving from west to east.
Subtropical High Pressure Area	25–30°	Tropical Easterlies (Trade; 0–10 km)		Sinking air dominates, with evaporation of clouds and dryness.
Equatorial Trough	0–10°	Tropical Easterlies and equatorial westerlies		Cyclonic disturbance with clouds and precipitation moving from west to east.

cyclones and anticyclones (westerlies). The high and low pressure areas are called centres of action, because their strength over a given period (e.g. week, month or season) as compared with long term averages, is an indication of the departure of the weather from its average.

"Relatively little pressure variation occurs from midsummer to midwinter in the southern hemisphere, a fact we attribute to the dominance of water in that hemisphere. The most noticeable changes here are the seasonal 5- to 10 degree shifts of the subtropical highs that moves with the position of the sun's vertical rays" (LUTGENS and TARBUCK, 1986).

Influence of the distribution of land and oceans: If the surface of the earth were perfectly smooth, i.e. lacking orographical features, and uniformly covered with water, then the long-term average pattern of winds, temperature, and precipitation would not show any variation with longitude but would exhibit only zonal bands (i.e. variations with latitude only). A general examination of weather charts shows that the influence of the distribution of land and water and such orographical features as mountains has a significant influence on the patterns of meteorological parameters.

The insulation does not vary significantly over the year near the equator, but the variation increases with latitude. The conductive capacity of the land is very much smaller than that of the oceans, and for that reason, the annual range of temperature is greater over the continents than over the oceans. Thus, the temperature difference between oceans and continents varies little over the year near the equator and more in the higher latitude regions.

This contrast in the heat capacity of land and water gives rise to low and high pressure centres. In spring the land is heated more rapidly than the oceans, and extensive low pressure areas develop over land and (relative) high pressure persists over the oceans. In the autumn the continents cool more rapidly than the oceans, and high pressure centres develop over the land areas. Since the temperature difference between continents and oceans is greater in winter, the low pressure centres over the continents in summer are less pronounced than the high pressure areas over the continents in winter.

The different heat capacity of land and water results in the following significant consequences: in summer the planetary low pressure belts will be taken over the continents and

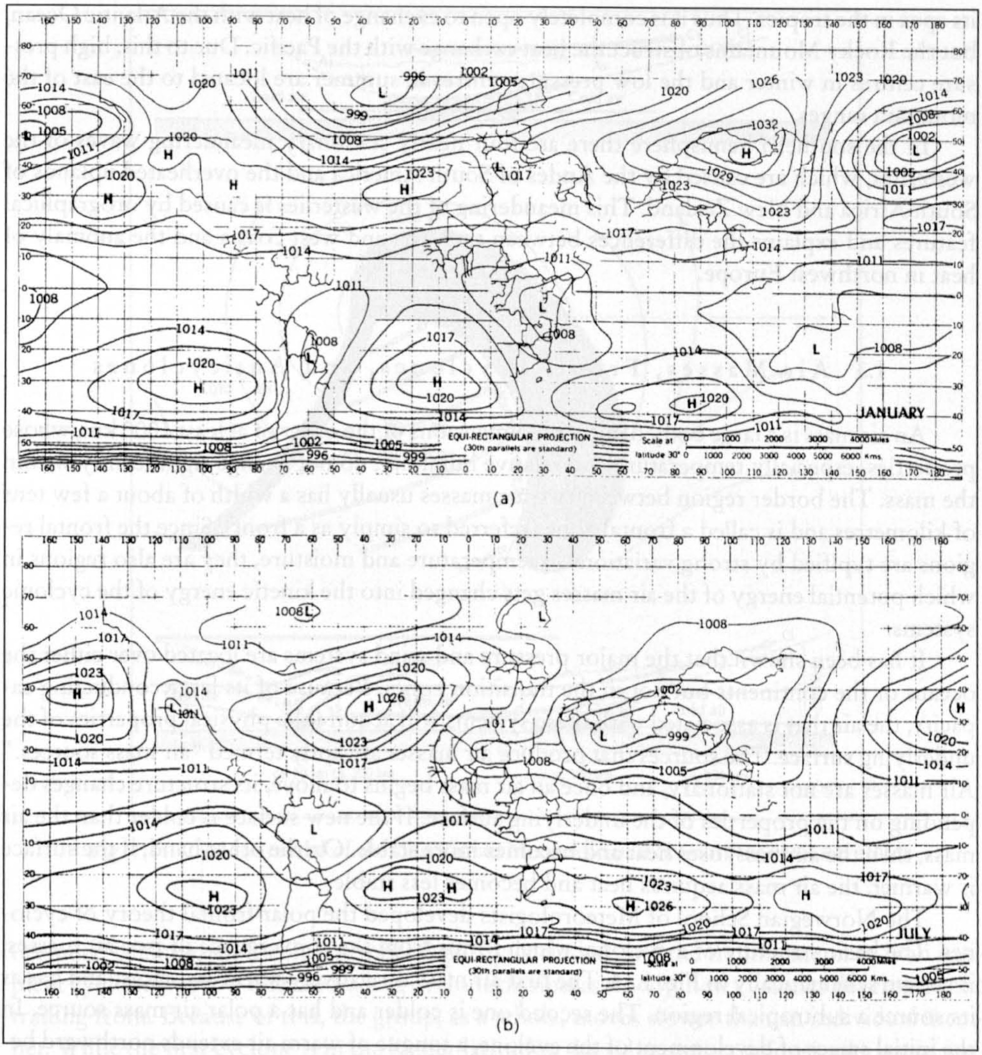

Fig. 1.13: Global sea-level pressure (millibars) distribution in January (a) and July (b) (LUTGENS and TARBUCK, 1986)

reinforced, in winter the anticyclones. This means, for example that in the northern hemisphere summer the equatorial low pressure belt shifts northwards over India to the 30° latitude and an expanding of the area of west wind to 60° in northern summer and to 40° in southern summer. The smaller proportion of continents there causes the lesser expansion in the southern hemisphere.

Large mountain ranges can modify the distribution of these low and high pressure centres considerably, particularly the Cordilleras and Central Asia. Due to their high heating area these uplands become warmer than the atmosphere around them. Therefore the mountains cause an anticyclonal meandering of the westerlies and form a cyclonic trough in their lee. Due to this, in North America and Asia – in the lee of the mountains of Central Asia – there is a high trough with cold air on the eastern side and warm air on the western side (FLOHN, 1971). North America may be considered as a triangle with its base in the Arctic and its apex in the tropics. Thus it is completely open to exchange of heat with the Atlantic Ocean, but the Rocky Mountains obstruct the heat exchange with the Pacific. Due to this, high pressure centres in winter and the low pressure centres in summer are located to the east of the mountain ranges.

In the southern hemisphere there are four nearly stationary meandering waves of the westerlies, which are caused by the Andes of South America and the overheated uplands of South Africa and New Zealand. This meandering of the westerlies is caused by orographical features and explains the differences between the east- and west coasts and the anomaly of heat in northwest Europe.

1.3 Air Masses, Fronts, Cyclones, and Anticyclones

An air mass is a large body of air with dimensions of the order of at least 1000 km, whose properties, especially temperature and relative humidity, do not change significantly within the mass. The border region between two air masses usually has a width of about a few tens of kilometres and is called a frontal zone (referred to simply as a front). Since the frontal regions are typified by strong variations in temperature and moisture, they are also regions in which potential energy of the air masses gets changed into the kinetic energy of the cyclonic systems.

It has been shown that the major pressure and wind systems are located over either the oceans or the continents but not in the transition zones. Because of its large conducting capacity, the air that is associated with these systems will acquire the physical properties of the underlying surface. The sources that produce air masses are aptly termed "air mass sources." Air masses are not stationary, and once an air mass begins to move, its structure changes depending on the properties of the underlying surface. If the new surface is colder than the air mass, then the air mass loses heat and becomes more stable. On the other hand, if the surface is warmer, the air mass acquires heat and becomes less stable.

The Norwegian School of Meteorologists developed the polar frontal theory of cyclones. The basic structure of a cyclone, which forms from the convergence of two air masses, is shown schematically in Fig. 1.14. The first air mass is relatively warm and moist and has as its source a subtropical region. The second one is colder and has a polar air mass source. In the initial stages of development of the cyclone, a tongue of warm air extends northward between these two air masses. The narrow region separating the air masses its the front and is referred to as the polar front, since it represents the southern edge of the polar air mass.

A warm front is one along which cold air is displaced by warm air, and a cold front is one in which the reverse is true; a stationary front is one that does not move.

In the frontal theory of cyclones, the initial stage is characterised by a quasi-stationary front separating a warm and a cold air mass. The next stage involves the development of wave motion on the front, with the subsequent development of a low pressure center. At this stage of cyclogenesis, the cyclone is referred to as nascent. In the next stage, the cold front overtakes the warm front, and this process is called occlusion. With the progress of the occlusion process, the warm air is lifted to higher levels and becomes replaced at the lower levels by colder and heavier air. Because of this, the center of gravity of the air mass is lowered, and large amounts of potential energy are released. This potential energy is converted into kinetic energy of the wind systems that surround the cyclone center.

PETTERSSEN (1969) stated that an extratropical cyclone is usually accompanied by three or four similar cyclones to form a series, or a family. The first member of this family is an

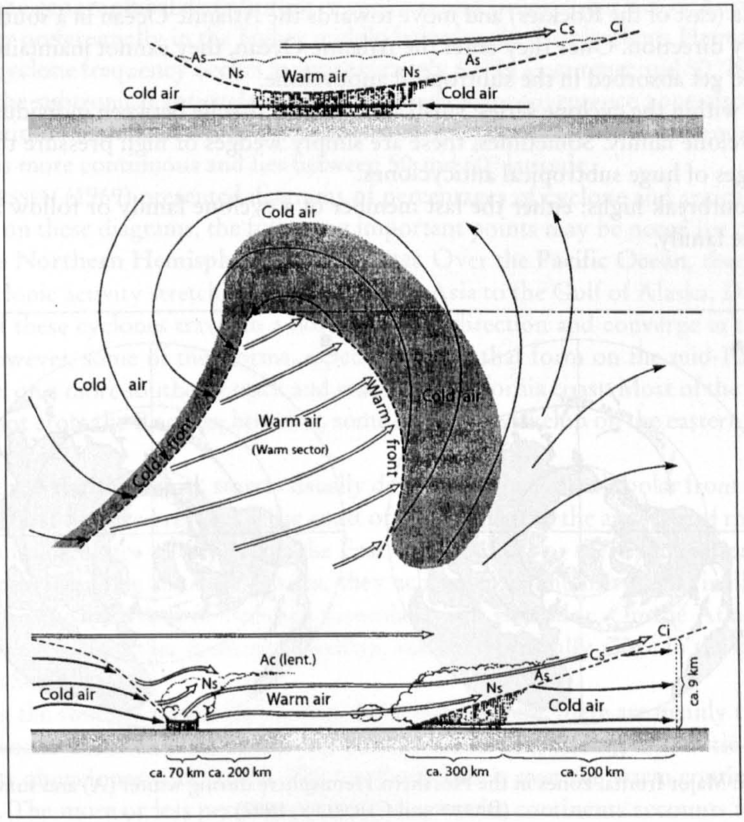

Fig. 1.14: Cyclone model of the Norwegian Meteorological School (WARNECKE, 1997)

occluded cyclone, the second member is partly occluded, and the trailing member is an incipient cyclone wave. While the leading cyclone dissipates slowly, new cyclones develop on the trailing front. Because of this, the group, as a whole, moves slower than an individual member. While the first cyclone is in the higher latitudes, the subsequent cyclones take more southerly paths, and in the rear of the frontal member, cold air moves southward into the subtropics. This phenomenon is called a polar outbreak and will lead to the development of an arctic cyclone. At times, on the surface weather charts, it is difficult to recognise a coherent cyclone family. This is especially true in North America because of the influence of the Rockies. Coherent cyclone families, with three to six members, travel eastward over the northern oceans with a period of 3–8 d.

Anticyclones, as the name implies, are opposite to cyclones, i.e. they are centers of high pressure. Their intensities are lower than those of cyclones, they exhibit a more irregular behaviour than cyclones, an as a rule, they move slower. PETTERSSEN (1969) gave the following classification for anticyclones.

(1) Subtropical highs: vast, elongated, and deep (in height) anticyclones located in the subtropics. These are highly persistent, are either stationary or slowly moving, and can be seen on practically any weather chart.

(2) Polar continental highs: anticyclones that develop predominantly over northern continents during winter. In North America, they develop mainly in Alaska and western

Canada (east of the Rockies) and move towards the Atlantic Ocean in a southeasterly to easterly direction. Once they enter the Atlantic Ocean, they cannot maintain their identity and get absorbed in the subtropical anticyclone.

(3) Highs within the cyclone series: small anticyclones that lie between individual members of a cyclone family. Sometimes, these are simply wedges of high pressure that travel at the edges of huge subtropical anticyclones.

(4) Polar-outbreak highs: either the last member of a cyclone family or follow any intense cyclone family.

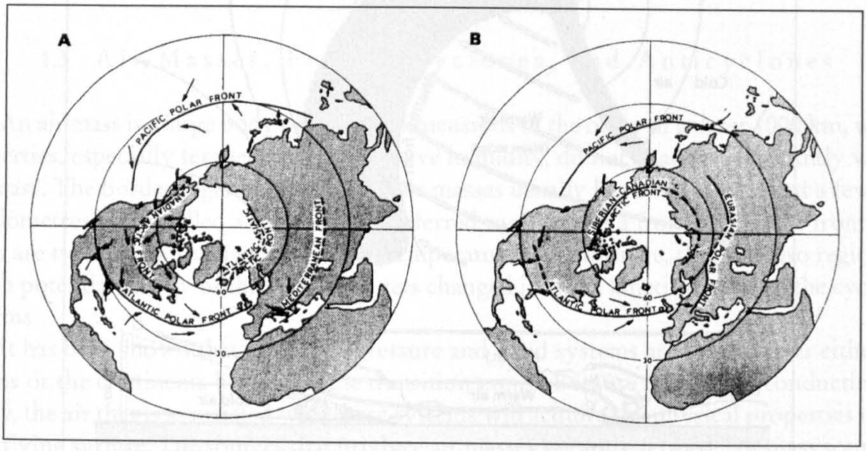

Fig. 1.15: Major frontal zones in the Northern Hemisphere during winter (A) and summer (B) (BARRY and CHORLEY, 1992)

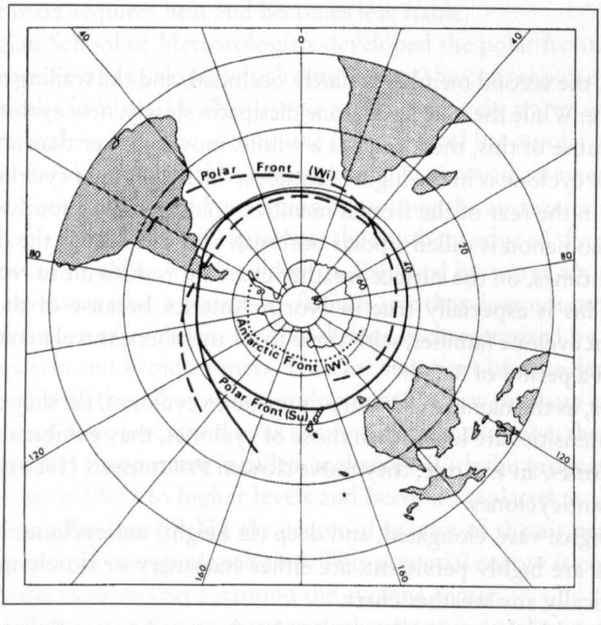

Fig. 1.16: Major frontal zones in the Southern Hemisphere during summer (Su) and winter (Wi) (BARRY and CHORLEY, 1992)

Next, the **geographical distribution** of cyclones and anticyclones will be discussed. Cyclones occur preferentially in the higher middle latitudes. In the Northern Hemisphere, the maximum cyclone frequency occurs at approximately 60 °N in summer and 50 °N in winter. Note that the subtropical anticyclones and the equatorial convergence zone also have a similar 10° latitude seasonal shift. In the Southern Hemisphere, the belt of maximum cyclone frequency is more continuous and lies between 50 and 60° latitude.

PETTERSSEN (1969) presented diagrams of percentages of cyclone and anticyclone centers. Based on these diagrams, the following important points may be noted for cyclone activity in the **Northern Hemisphere** during winter. Over the **Pacific Ocean**, there is a wide zone of cyclonic activity stretching from Southeast Asia to the Gulf of Alaska. During winter, most of these cyclones travel in a northeastward direction and converge in the Gulf of Alaska. However, some of the storms, especially those that form on the mid-Pacific polar front, travel on a more southerly track and reach the California coast. Most of the Pacific cyclones cannot cross the Rockies; however, some of them redevelop on the eastern side of the Rockies.

Over the **Atlantic Ocean**, storms usually develop on the Atlantic polar front (Fig. 1.15). One of the most favoured regions is the coast of Virginia and to the area east of the southern Appalachians. These are referred to as the East Coast Storms or the Cape Hatteras Storms, and while moving along the Gulf Stream, they achieve great intensity, and finally they become stagnant near Iceland or between Greenland and Labrador. On the Atlantic-Arctic front, many cyclones either form or redevelop, and they generally move in the direction of the Barents Sea.

During the summer period for the Northern Hemisphere, there are mainly two belts of high frequencies of storm occurrence. The northern belt surrounding the Arctic is irregular and consists of cyclones with fronts. The southerly belt is over the warm continents of the subtropics. The more or less permanent heat low over the continents accounts for the high frequencies found over southern California, Nevada, Arizona, and northern Mexico. At the higher levels, there is an anticyclone with strong subsidence, and because of this, clouds and weather systems are absent in the second belt.

The principal tracks of the depressions in the Northern Hemisphere for the winter period are shown in Fig. 1.17. Note that these tracks basically reflect the influence of the major frontal zones.

Next, the geographical distribution of the anticyclones in the Northern Hemisphere will be briefly discussed. There is a belt over the oceans with a maximum occurrence frequency off the subtropical west coast. In the eastern North Pacific, strong frequencies occur. Regarding the distribution of the anticyclonic centres in the Northern Hemisphere during summer, note that the belt of subtropical anticyclones is now farther north than in winter. The occurrence frequency is again significant in the eastern Pacific but is low in the western Pacific because of the summer monsoon.

Earlier, a front was defined as a sloping zone of transition between two air masses of different density. Although a front is several kilometres wide, it is narrow compared with the horizontal dimensions of the air masses. On weather charts, fronts appear as lines of discontinuity in wind and temperature. At the front, there is a kink in the isobars (i.e. lines of equal pressure) directed from low to high pressures.

Next, the **principal frontal zones on the globe** will be identified. Although fronts are not usually stationary, certain regions nevertheless consistently show high frequency of fronts, these regions being the areas of confluence between the main air mass sources discussed earlier. Fig. 1.17 shows the major frontal zones in the Northern Hemisphere during

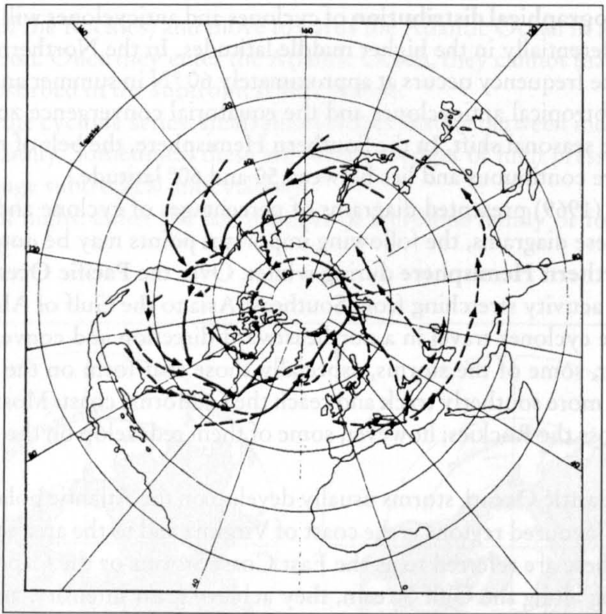

Fig. 1.17: Principal Northern Hemisphere depression tracks in January. Tracks represented by broken lines are less certain than those represented by solid lines (KLEIN, 1957)

winter. In the Atlantic Ocean region, one has the Atlantic polar front, which is the confluence region between the polar continental and the tropical maritime air mass sources, and the opposing currents indicated maintain the front. Quite often, the Atlantic polar front extends eastward over Europe. Its position varies quite drastically in the meridional direction; i.e. it can be anywhere from the West Indies to Portugal in the south to the Great Lakes and Iceland in the north (PETTERSSEN, 1969). This frontal zone is responsible for the cyclones that bring precipitation over a wide belt from the eastern part of the North American continent to northwest Europe.

In the southern hemisphere the Polar Front has more cyclonic activity in summer than the northern hemisphere in its summer. The Polar Front is located in January about 45° S with branches spiralling poleward towards eastern South America and from 30° S in the South Pacific (150° W) (Fig. 1.16). In winter of the southern hemisphere there are two Frontal zones spiralling towards Antarctica from about 20° (BARRY and CHORLEY, 1992).

A second important frontal zone is formed by the Atlantic-Arctic fronts, which are in the confluence region between the arctic source region and the polar maritime air. The storms that form on this frontal zone usually travel from Iceland along the northern part of Norway to the Barents Sea. A third important frontal zone is the Mediterranean front, which forms at the confluence of the cold air from Europe and the mild air from North Africa and Mediterranean Sea area. The cyclones that develop here usually travel in northeasterly direction to southern parts of central Asia. However, some travel eastward to northwest India.

Over the North Pacific Ocean, there are usually two polar fronts, the one nearest the Arctic coast being the more pronounced. Most of the North Pacific storms form along this frontal zone and travel towards the Gulf of Alaska, but some of them take a southerly route to California and northern Mexico. The Pacific-Arctic front usually extends towards the Great Lakes, and many of the storms between the Great Lakes and the Rockies develop on this front. Cold air from the Arctic may reach as far south as Texas, or even northern Mexico, in the rear of these storms.

A second weak polar front is found in winter in the southern hemisphere at 65°–70 °S. Zones of airstream confluence in the southern hemisphere are less numerous and more persistent, paricularly in coastal regions, than in the northern hemisphere.

The frontal zone distribution during the summer period for the Northern Hemisphere is shown in Fig. 1.15. Since, in summer, the differences in the properties of the various air masses are not as pronounced as in winter, one can find permanent frontal zones only in the Arctic region. The polar fronts over the western Atlantic and Pacific are usually 10° farther north in summer as compared with their winter positions. There is now a frontal zone over Eurasia and over the middle part of North America. These new zones reflect the prevailing meridional temperature gradient and the large scale orographical influences. The Arctic front, in summer, is formed along the Arctic coasts of Siberia and North America and is associated with the snow (and ice) boundaries of the higher latitudes.

1.4 Regional Weather System

In this section, the regional weather systems of North America, South America, Europe, Africa, Asia, Australia, and the ocean region will be briefly considered. The detailed meteorological problems associated with storm surges will be considered in Chapter 5.

1.4.1 Weather Systems of North America

The climate of North America is determined by its location in the Northern Hemisphere and its great range from 9° N (Isthmus of Panama) to 71° N (Point Barrow) and to 84° N if the Arctic Archipelago is included. Furthermore it is influenced by its great Landmass with its greatest breadth (4250 km along 40° N) in the temperate zone, the long meridional barrier of the Western Cordilleras, the cold Hudson Bay in the North and the warm Gulf of Mexico from the south, the surrounding oceans and their currents with the warm Gulf Stream, cold Labrador Current, the warm Alaska Current and the cool California Current. The region, where the currents meet – for example the region of Newfoundland where the Gulf stream meets the Labrador Current – its one of cyclogenesis and fog formation.

The atmospheric circulation develops from the interaction of the stationary Hawaiian, Azores, Arctic and Greenland Highs and of the Aleutian and Icelandic Lows, which are semipermanent, are seasonable and variable in intensity (MARTYN, 1992).

During both winter and summer, the mean pressure field at the midtropospheric level shows a prominent trough over the eastern part of North America. The origin of this can be traced to the influence of the Rockies on the upper westerlies, but in winter, the strongly baroclinic zone along the east coast of North America is also responsible. Over the midwestern states, cyclones generally move in a southeast direction, bringing continental polar air southward, whereas along the Atlantic coast the cyclones travel northeastward. If the upper air trough is far to the west of is average position, then depressions form ahead of it over the South Central States (PETTERSSEN, 1969) and move in a north-easterly direction towards the lower St. Lawrence.

Considering January as a typical month for the winter period, the surface pressure chart shows an extension of the subtropical high over the southwest part of the United States (this high being referred to as the "Great Basin High") and a polar anticyclone over the Mackenzie River area. On both the Atlantic and Pacific coasts, the pressure is low because of the Icelandic and Aleutian lows. Because of heating over the land, the Icelandic low is split and a secondary low appears over the northeastern part of Canada. The cyclone frequency is maximum on the Pacific coast and in the Great Lakes area during winter, whereas in the Great Plains, the maximum frequency is in spring and early summer. On the average, in the month of December, the Gulf of Alaska has the maximum frequency of lows and the Great Basin region has the maximum frequency of highs, as compared with any other region in the Northern Hemisphere.

In winter, there are three main depression tracks across North America

(1) Depressions from the west move eastward between 45 and 50° N.

(2) Some depressions first travel southeastward as far as the Central States and then travel northeastward towards New England and the Gulf of St. Lawrence. Depressions developing over the Pacific cross the western mountains as upper troughs and redevelop in the lee of the mountains in Alberta and Colorado.

(3) Depressions form on the polar front off the east coast of the United States and move northeastward towards Newfoundland.

In the summer period, the frequency of depressions originating in the east coast is less, and the tracks of depressions from the west are somewhat northward as compared with their winter positions. The tracks pass over Hudson Bay, Ungava Bay, Labrador, or the Gulf of St. Lawrence. The maritime frontal zone that gives rise to these depressions is not pronounced.

In early April, the Aleutian low (which is located approximately at 55° N, 165° W during September to March) splits into two; one centre is over the Gulf of Alaska and the other is over northern Manchuria. Cyclogenesis increases in Alberta and Colorado. By the end of June, the subtropical high pressure cells in the Northern Hemisphere are displaced northward, and because of this, the depression tracks also move northward.

The essential features of the sea level circulation in the eastern and central parts of the United States and Canada can be determined from sea level pressure maps. However, due to the presence of mountains and rugged orographical features in the west, sea level pressure gradients do not accurately reflect the wind distribution. Because of the presence of high coastal mountains, the Aleutian low pressure system does not extend far inland. HAURWITZ AUSTIN (1944) stated that because the inland pressures are reduced to sea level, they appear quite high compared with those over the surrounding ocean, and this sea level correction gives rise to steep fictitious pressure gradients in northern British Columbia and southern Alaska. Due to the presence of several fjords and the banking effect produced by the coastal mountains, the average surface winds do not agree with the mean isobaric pattern.

1.4.2 Weather Systems of Mexico and Central America

Central America includes the continental strip joining North to South America (between 18 and 8° N) and the West Indies, a string of islands from Florida (25° N) to Venezuela (10° N) separating the Caribbean Sea from the Atlantic (MARTYN, 1992).

The main mountain range in Central America is the Sierra Madre in Mexico. This region generally lies between the subtropical belt of high pressure and the equatorial belt of low pressure, whose boundary changes with the ITCZ. The Hawaiian High and the Azores influence it. The prevailing winds are trade wind (easterly) and the migratory low pressure centers generally move from east to west. Thus, these secondary circulations are significantly different from those of middle and high latitudes.

Central America is exposed to tropical cyclones, which spring up from June to November over the Gulf of Mexico, the Caribbean Sea and in the vicinity of the Bahamas and over the tropical part of eastern Pacific. These affect the coast of Central America, and all the way to Newfoundland (MARTYN, 1992). The number varies from 1 (1890) to 21 (1933) a year (DUNN AND MILLER, 1960).

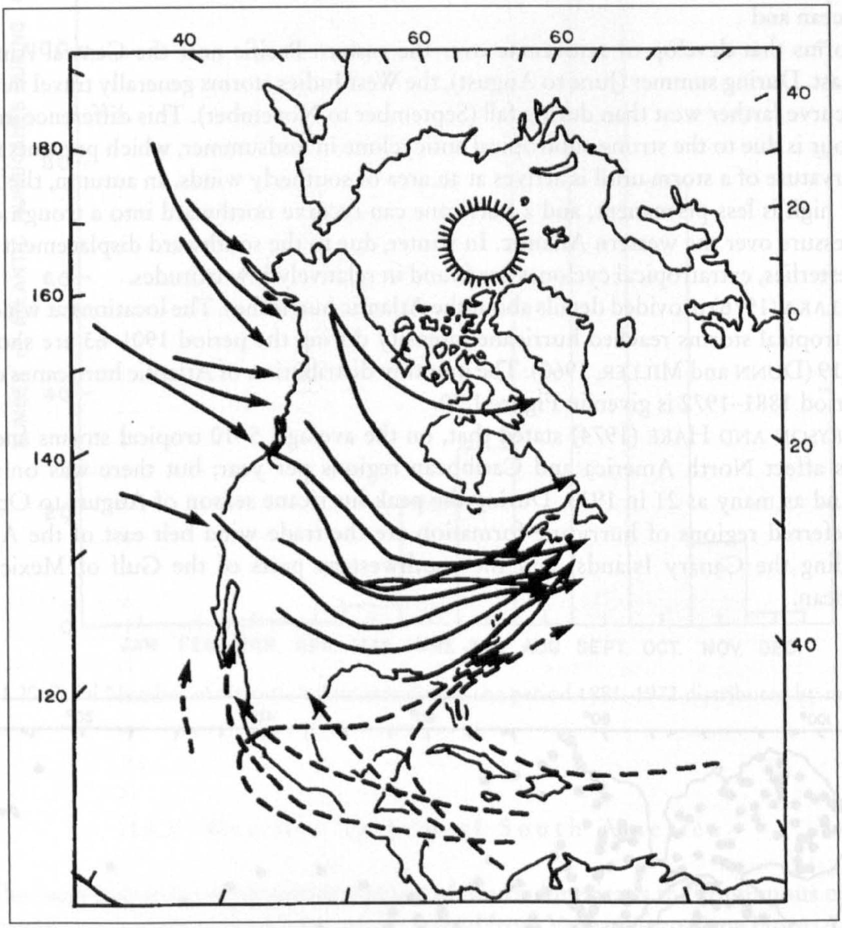

Fig. 1.18: Cyclone tracks of North and Central America. Solid lines represent extratropical cyclones and broken lines represent tropical cyclones. (HAURWITZ and AUSTIN, 1944)

The tracks of the hurricanes are shown in Fig. 1.18. The following is a summary of the average conditions associated with these tracks in Mexico and Central America:

(a) The Antillean hurricanes recurve in the eastern part of the Gulf of Mexico, and the hurricane season is August to October. During August, the recurvature occurs farther north than during October.

(b) A frequently observed track is over the Caribbean Sea, the Yucatan Peninsula, and then over the northeast coast of Mexico or along the coast of Texas.
(c) Occasionally, the hurricanes, after crossing the Yucatan Peninsula, travel over Central Mexico and arrive at the Pacific coast and then travel northwestward.
(d) Similar to across Central America, and then the track is towards the north-west, parallel to the Pacific coast and passing over the Gulf of California.
(e) These storms develop over the southeast Pacific and travel towards the Gulf of Mexico. Some tropical cyclones also form south of the Revillagigedo Islands.

Thus, two main classes of cyclones can be noted:
(1) hurricanes that develop over the warm waters of the Caribbean Sea and the Atlantic Ocean and
(2) storms that develop or rejuvenate over the eastern Pacific near the Central American coast. During summer (June to August), the West Indies storms generally travel inland or recurve farther west than during fall (September to November). This difference in behaviour is due to the strong subtropical anticyclone in midsummer, which prevents the recurvature of a storm until is arrives at an area of southerly winds. In autumn, the Atlantic high is less permanent, and a hurricane can recurve northward into a trough of low pressure over the western Atlantic. In winter, due to the southward displacement of the westerlies, extratropical cyclones are found in relatively low latitudes.

ALAKA (1976) provided details about the Atlantic hurricanes. The locations at which Atlantic tropical storms reached hurricane intensity during the period 1901–63 are shown in Fig. 1.19 (DUNN and MILLER, 1960). The monthly distribution of Atlantic hurricanes during the period 1881–1972 is given in Figure 1.20.

BRYSON AND HARE (1974) stated that, on the average, 5–10 tropical storms and hurricanes affect North America and Caribbean regions per year; but there was only 1 in 1914 and as many as 21 in 1933. During the peak hurricane season of August to October, the preferred regions of hurricane formation are the trade wind belt east of the Antilles (including the Canary Islands) and the southwestern parts of the Gulf of Mexico and Caribbean.

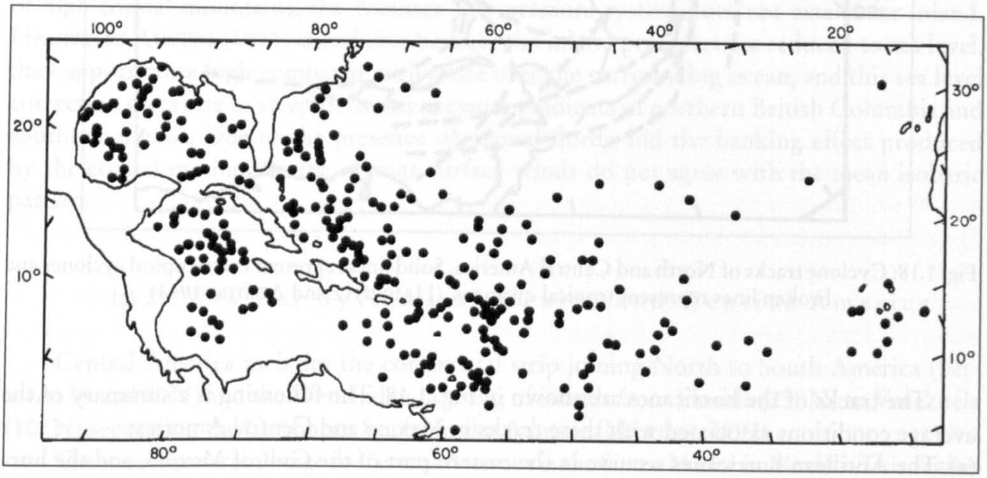

Fig. 1.19: Locations at which Atlantic tropical storms reached hurricane intensity during the period 1901–63. (DUNN and MILLER, 1960)

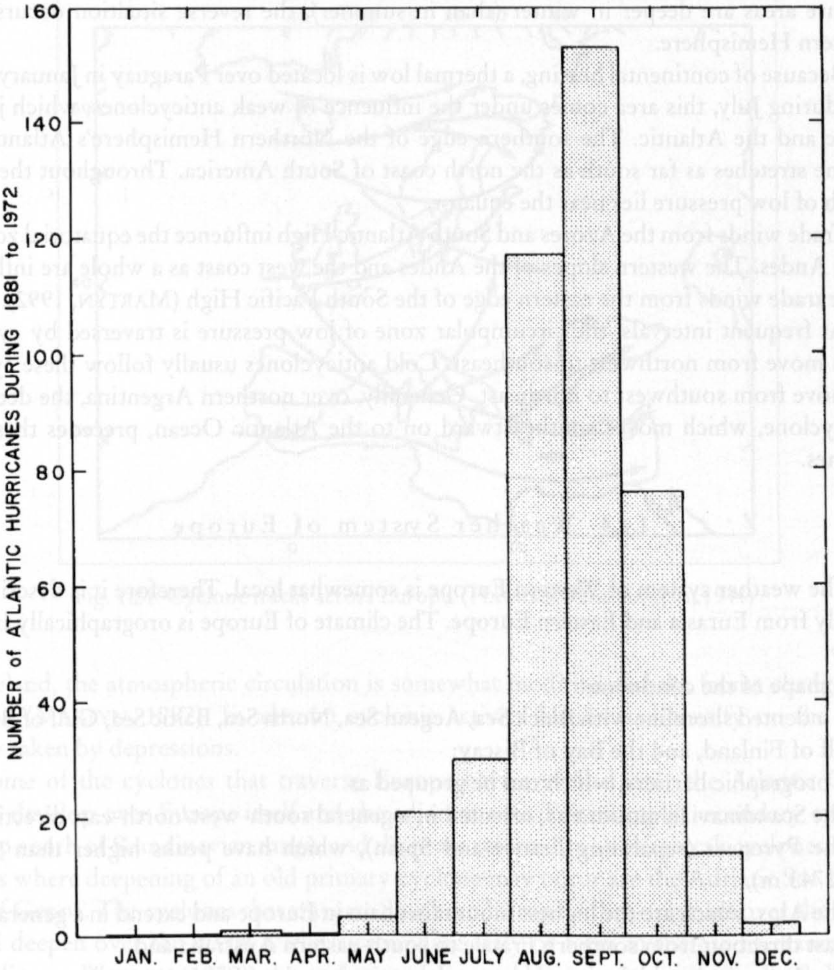

Fig. 1.20: Total Number of Atlantic hurricanes during the period 1881–1972 distributed by month

1.4.3 Weather System of South America

The most important orographical feature of South America is the continuous chain of high mountains, known as the Andes, which extend from Venezuela to Cape Horn. Another topographical feature is that South America does not have prominent coastal indentations (such as Hudson Bay, Gulf of St. Lawrence, and Gulf of Mexico in North America) or large inland lakes.

A more or less persistent feature is the presence of two semipermanent anticyclones, one over the Atlantic and the other over the Pacific, near the east and west coasts, respectively. The southern end of South America is affected by the zone of polar front depressions, which in July reach as far north as 35–45° S (MARTYN, 1992). South of Cape Horn, there are deep semipermanent cyclones of the Weddel and Belgique seas. One main difference between the Northern and Southern hemispheres is that, whereas in the Northern Hemisphere the low pressure areas are deeper in winter (than in summer), the reverse situation occurs in the Southern Hemisphere.

Because of continental heating, a thermal low is located over Paraguay in January. However, during July, this area comes under the influence of weak anticyclones, which join the Pacific and the Atlantic. The southern edge of the Northern Hemisphere's Atlantic anticyclone stretches as far south as the north coast of South America. Throughout the year, a trough of low pressure lies near the equator.

Trade winds from the Azores and South Atlantic High influence the equatorial zone east of the Andes. The western slopes of the Andes and the west coast as a whole are influenced by the trade winds from the eastern edge of the South Pacific High (MARTYN, 1992).

At frequent intervals, the circumpolar zone of low pressure is traversed by cyclones, which move from northwest to southeast. Cold anticyclones usually follow these cyclones and move from southwest to northeast. Generally, over northern Argentina, the deepening of a cyclone, which moves southeastward on to the Atlantic Ocean, precedes these anticyclones.

1.4.4 Weather System of Europe

The weather system of Western Europe is somewhat local. Therefore it is described separately from Eurasia and Eastern Europe. The climate of Europe is orographically influenced by

1. the shape of the continent;
2. the indented shoreline with Black Sea, Aegean Sea, North Sea, Baltic Sea, Gulf of Bothnia, Gulf of Finland, and the Bay of Biscay;
3. the orographic barriers, which can be grouped as
   - the Scandinavian mountains, oriented in a general south-west/north-east direction
   - the Pyrenees (separating France and Spain), which have peaks higher than 9000 ft (2743 m),
   - the Alps, which are the highest mountain chain in Europe and extend in a general west-east direction from southern France to south-eastern Australia and
   - the Apennines, which extend almost the entire length of Italy;
4. the huge continental mass to the east and
5. the extensive ocean to the west.

MARTYN (1992) summarised that the climate of Europe is influenced by the permanent Icelandic Low stationed over the North Atlantic and the Azores High. While the Icelandic Low is deeper in winter, the Azores High reinforces in summer. The seasonal Asian High influences Europe in winter. Summer is characterised by the presence of the Arctic High in the Spitzbergen region and the South Asian Low. This pressure system gives rise to prevailing south-westerlies over northern, western and central Europe, and north-westerlies and westerlies in southern Europe (MARTYN, 1992). The westerly airstream changes in easterly or northeasterly, when high pressure develops over eastern or northeastern Europe.

In winter, the cyclones that travel across North America, or those that develop on the Atlantic Front, travel south of Iceland in a general northeasterly direction towards Norway. The latitudinal variation of cyclones that approach the west coast of Europe for the different seasons of the year is listed in Table 1.3. The cyclone tracks across Europe are shown in Fig. 1.21. This difference in frequency is more pronounced in summer than in winter.

„In summer, when the Azores High becomes stronger and extend in a ridge across western Europe, the Iceland Low weakens and the Arctic High lies across eastern Greenland

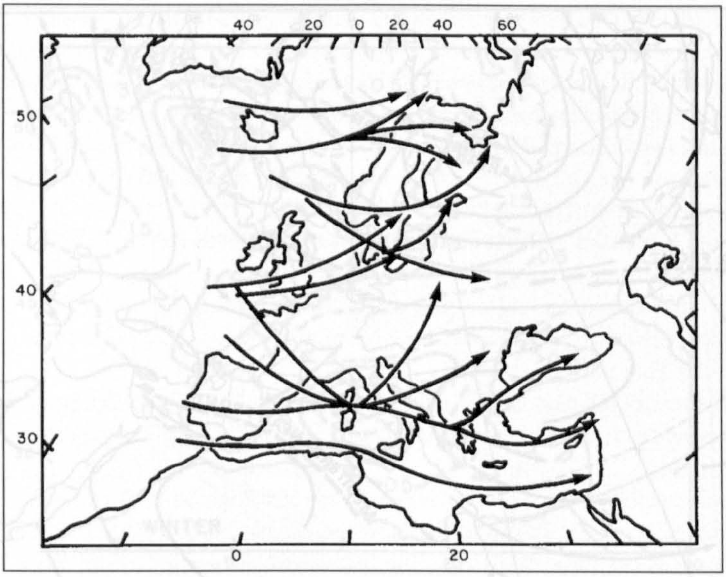

Fig. 1.21: Cyclone tracks across Europe. (Haurwitz and Austin, 1944)

and Iceland, the atmospheric circulation is somewhat modified and the fronts change their position (Martyn, 1992). In autumn cyclonic activity begins to intensify on the tracks usually taken by depressions.

Some of the cyclones that traverse Europe have travelled over the Atlantic Ocean. Others develop over Europe itself and the adjacent seas. For example, secondary cyclones develop south of Scandinavian range, and these are referred to as Skagerrak cyclones. Other regions where deepening of an old primary cyclone may occur are the Adriatic Sea and the Gulf of Genoa. The cyclones that traverse Southern Europe either originate over the Atlantic and deepen over the warm water surrounding Italy or form in the Mediterranean Sea. According to Wallen (1970), the cyclones of Europe have duration of usually 8 d but at times up to 17 d. Fig. 1.23 shows the frequency of cyclones in winter and summer for Europe.

Table1.3: Cyclone frequency (% of the total annual occurrence) at 15° W longitude (Atlantic Ocean). (Haurwitz and Austin, 1944).

Latitude	Winter	Spring	Summer	Autumn	Year
30–35 ° N	1.7	2.0	0.4	2.0	6.1
35–40 ° N	3.0	3.9	1.1	3.8	11.8
40–45 ° N	3.3	4.2	2.3	3.1	12.9
45–50 ° N	2.1	3.0	3.7	2.7	11.5
50–55 ° N	2.3	3.7	4.5	2.4	12.9
55–60 ° N	3.0	4.5	6.0	4.1	17.6
60–65 ° N	3.2	5.1	5.0	5.4	18.7
65–70 ° N	1.9	2.1	2.2	2.3	8.5
30–70 ° N	20.5	28.5	25.2	25.8	100.0

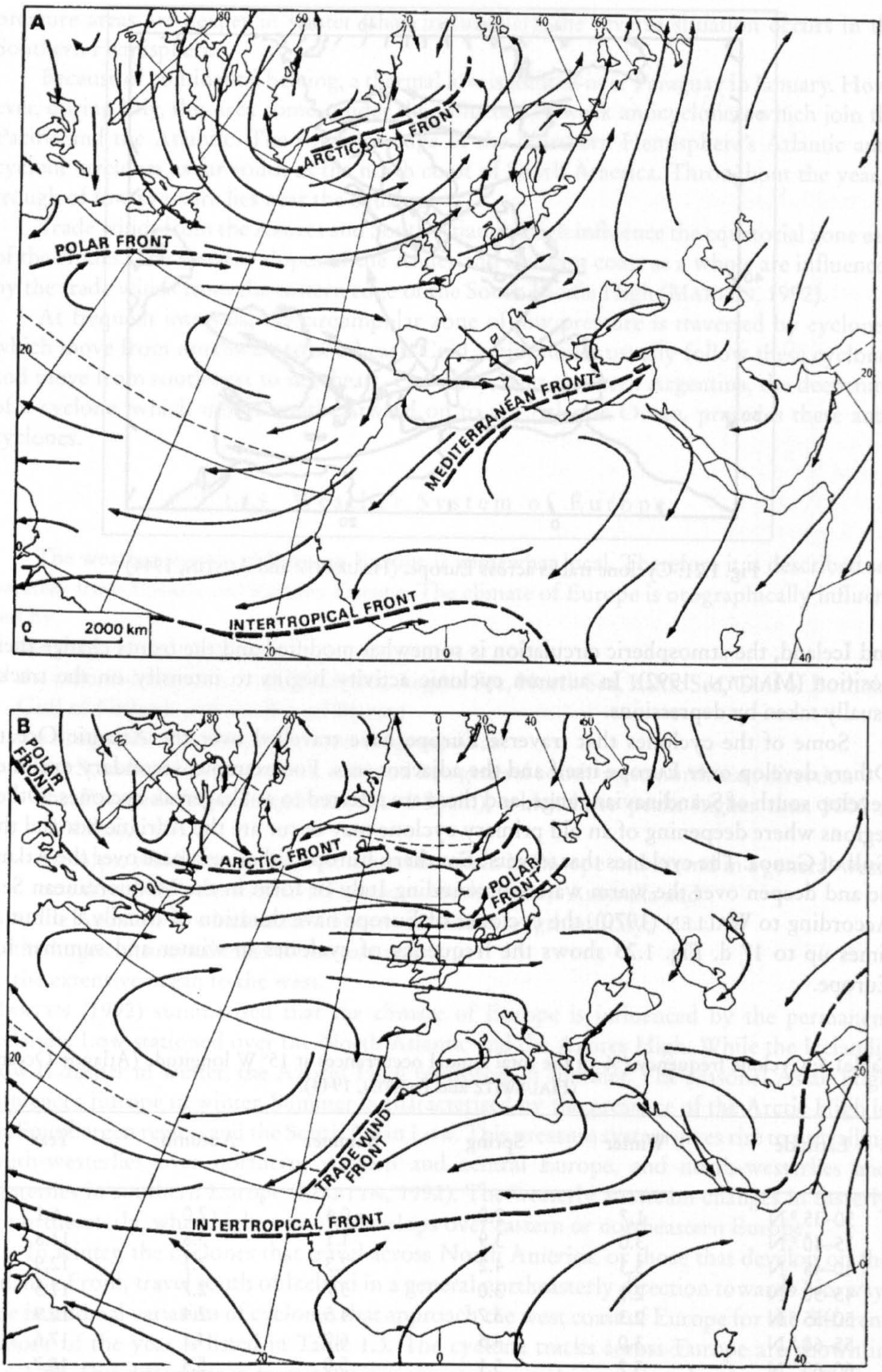

Fig. 1.22: Prevailing wind directions and atmospheric fronts over Europe and the North Atlantic. January (A) July (B) (MARTYN, 1992)

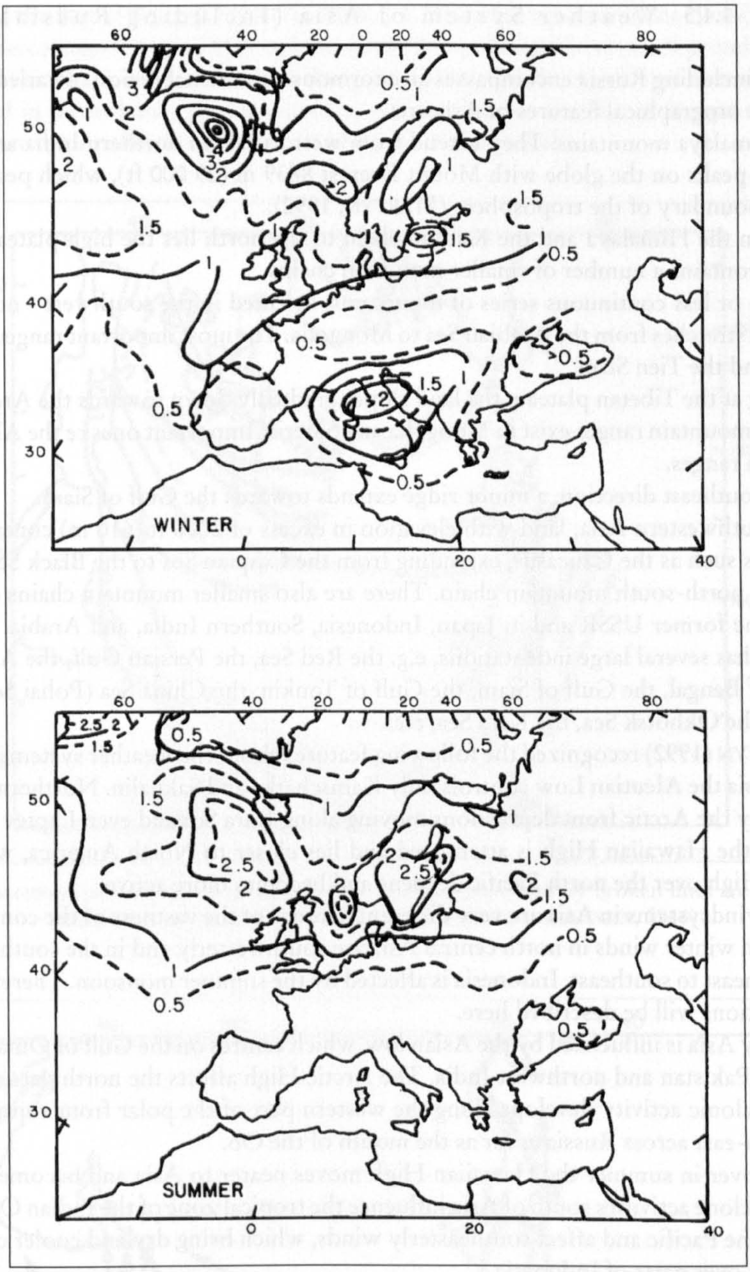

Fig. 1.23: Average Frequency of cyclones with central pressure less than 1000 MB during a winter season (top) and a summer season (bottom) (HAURWITZ and AUSTIN, 1944)

1.4.5 Weather System of Asia (Including Russia)

Asia including Russia encompasses an enormous continental region of varied relief. The important orographical features of Asia are:

1. The Himalaya mountains: They extend from west to east in northern India and have the highest peaks on the globe with Mount Everest 8839 m (29 000 ft), which penetrates the upper boundary of the troposphere (MARTYN, 1992).
2. Between the Himalaya and the Kunlun chain to the north lies the high plateau of Tibet, which contains a number of smaller mountain chains.
3. A more or less continuous series of mountains, oriented in the southwest - northeast direction, stretches from the Arabian Sea to Mongolia. The most important ranges are Hindu Kush and the Tien Shan.
4. Starting at the Tibetan plateau, the land slopes gradually down towards the Arctic Ocean. Several mountain ranges exist in Mongolia and Siberia. Important ones re the Altai and Yablonova ranges.
5. In the southeast direction, a minor ridge extends towards the Gulf of Siam.

In southwestern Asia, land with elevation in excess of 2000 ft (610 m) contains mountain ranges such as the Caucasus, extending from the Caspian Sea to the Black Sea. The Urals form a north-south mountain chain. There are also smaller mountain chains on the east coast of the former USSR and in Japan, Indonesia, Southern India, and Arabia. The Asian continent has several large indentations, e.g. the Red Sea, the Persian Gulf, the Arabian Sea, the Bay of Bengal, the Gulf of Siam, the Gulf of Tonkin, the China Sea (Pohai Sea), the Sea of Japan, the Okhotsk Sea, the Kara Sea, etc.

MARTYN (1992) recognized the following features about the weather systems in Asia. In Eastern Asia the Aleutian Low controls only Kamschatka and Sakhalin. Northern Asia is influenced by the Arctic front depressions moving along Kara Sea and even Laptev Sea coasts. In winter the Hawaiian High is attenuated and lies closer to North America, whereas the Aleutian High over the north Pacific deepens and becomes more active.

The windsystems in Asia are very different because of the vastness of the continent. For example, in winter winds in north central Asia are southwesterly and in the south they blow from northeast to southeast. Indonesia is affected by the summer monsoon. Therefore not all winddirections will be described here.

In July Asia is influenced by the Asian low, which centres on the Gulf of Oman, the Persian Gulf, Pakistan and northwest India. The Arctic High affects the north part of the continent. Cyclonic activity develops along the western part of the polar front running southwest-north-east across Russia as far as the mouth of the Ob.

Moreover in summer the Hawaiian High moves nearer to Asia and becomes stronger. The anticyclone activities south of Asia influence the tropical zone of the Indian Ocean, Australia and the Pacific and affect southeasterly winds, which bring dry and cooler continental tropical air over parts of Indonesia.

South-east and east Asia, the coasts of the Seas of Okhotsk and Japan, the Amur, Sakhalin and Kamchatka regions, the Philippines and Indonesia are dominated by a monsoon circulation. In winter the wind blows opposite its direction in summer. Then cyclonic activities increase rapidly over very warm seas and oceans and, though the affected area is limited, it is extremely violent and can be disastrous owing to the exceptional heights of waves, and the torrential rain (tropical cyclones known as typhoons).

The tracks of extratropical and tropical cyclones across Asia are shown in Fig. 1.24 and 1.25, respectively. The approximate percentage distribution of tropical cyclones in the Arabian Sea and the Bay of Bengal is given in Table 1.4. Note that whereas in the Arabian Sea the maximum percentage is during May to June, in the Bay of Bengal it is from September to October. Later the Arabian Sea and Bay of Bengal cyclones and the resulting storm surges will be discussed in more detail. Special attention will be given to the Bay of Bengal surges because they are responsible for almost half of the lives lost globally.

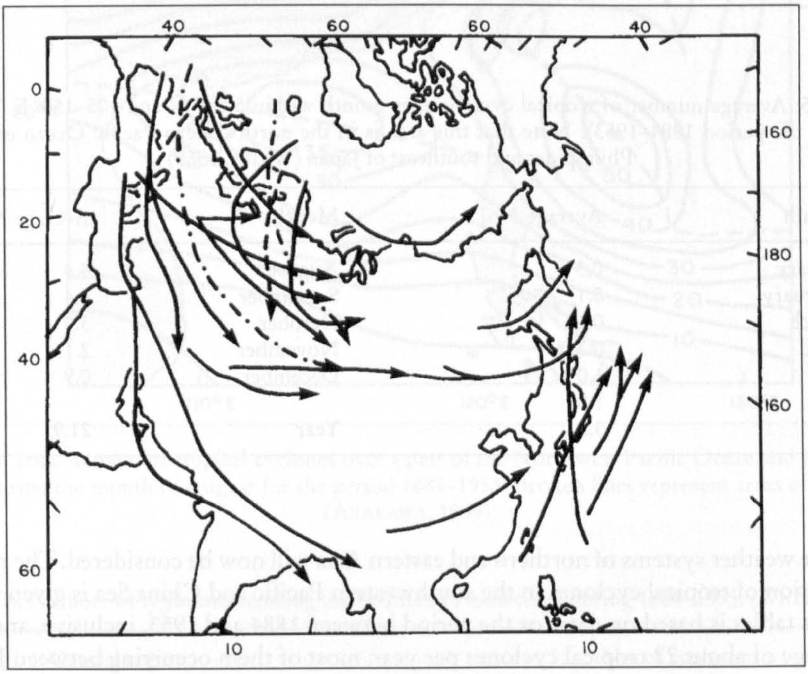

Fig. 1.24: Extratropical cyclone tracks across Asia. Tracks represented by broken lines are less certain than those represented by solid lines. (HAURWITZ and AUSTIN, 1944)

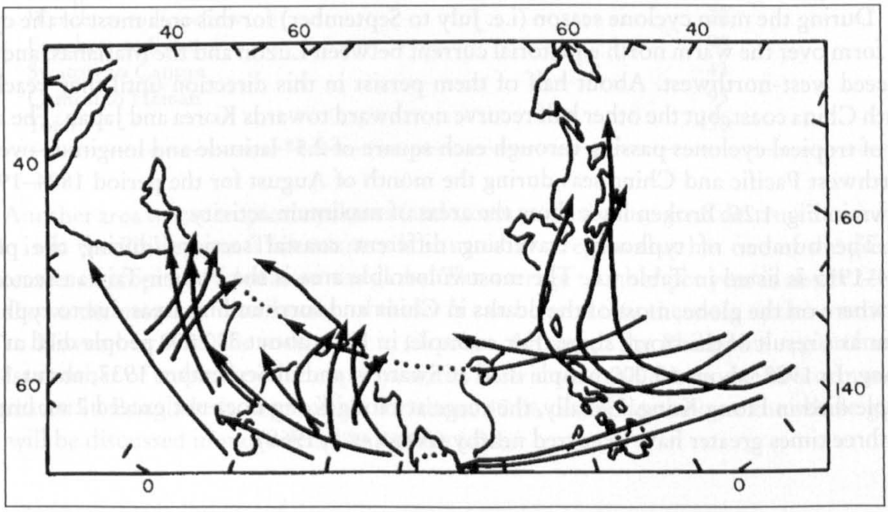

Fig. 1.25: Tropical cyclone tracks across Asia. (HAURWITZ and AUSTIN, 1944)

Table 1.4: Bimonthly distribution (approximate %) of tropical cyclones in the Arabian Sea and the Bay of Bengal (HAURWITZ and AUSTIN, 1944)

Water body	Jan.–Feb.	Mar.–Apr.	May–June	July–Aug.	Sept.–Oct.	Nov.–Dec.
Arabian Sea	1	11	50	1	11	26
Bay of Bengal	1	2	17	29	34	17

Table 1.5: Average number of tropical cyclones per month within 5–30° N and 105–150° E (based on data for the period 1884–1953). Note that this area is in the northwestern Pacific Ocean east of the Philippines and southeast of Japan (WATTS, 1969)

Month	Average No.	Month	Average No.
January	0.3	August	4.4
February	0.1	September	4.4
March	0.1	October	3.0
April	0.3	November	2.1
May	1.0	December	0.9
June	1.5		
July	3.8	**Year**	**21.9**

The weather systems of northern and eastern Asia will now be considered. The monthly distribution of tropical cyclones in the southwestern Pacific and China Sea is given in Table 1.5. This tables is based on data for the period between 1884 and 1953, inclusive, and shows an average of about 22 tropical cyclones per year, most of them occurring between July and October (ARAKAWA, 1969). During July to September, tropical cyclones frequently travel over the coasts of China and Korea; however, the southern parts of China experience them sometimes as early as May and as late as mid-November. Between mid-November and April, tropical cyclones rarely traverse the mainland of China.

During the main cyclone season (i.e. July to September) for this area most of the cyclones form over the warm north equatorial current between Luzon and the Marianas, and they proceed west-northwest. About half of them persist in this direction until they reach the South China coast, but the other half recurve northward towards Korea and Japan. The number of tropical cyclones passing through each square of 2.5° latitude and longitude over the Northwest Pacific and China seas during the month of August for the period 1884–1953 is shown in Fig. 1.26. Broken lines show the areas of maximum activity.

The number of typhoons traversing different coastal sections during the period 1884–1955 is listed in Table 1.6. The most vulnerable area is the Fukien-Taiwan sector. As elsewhere on the globe, most of the deaths in China and surrounding areas due to typhoons occur as a result of the storm surge. For example, in 1881, about 300 000 people died at Haiphong. In 1922, about 60 000 people died at Swatow, and in September 1937, about 11 000 people died in Hong Kong. Usually, the surge at Hong Kong does not exceed 2 m, but surges three times greater have occurred nearby (ARAKAWA, 1969).

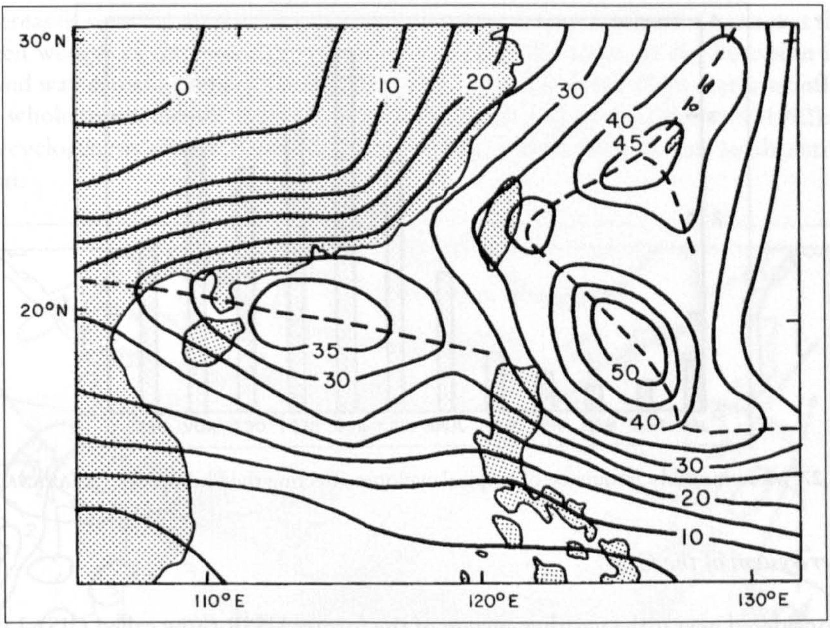

Fig. 1.26: Total number of tropical cyclones over a part of the Northwest Pacific Ocean and the Sea of China during the month of August for the period 1884–1953. Broken lines represent areas of maxima. (ARAKAWA, 1969)

Table 1.6: Number of typhoons crossing the Southeast Asian coast during 1884–1955. (WATTS, 1969)

Coastal region	No. of typhoons
Korea and further east	87
Liaoning to Shantung Peninsula	39
Shantung Peninsula to Shanghai	22
Shanghai to Wenchow	34
Wenchow to Foochow	30
Foochow to Swatow	90
Swatow to Canton	43
Canton to Hainan	93
Total	438

Another area where tropical cyclones (and storm surges) cause great destruction and loss of life is in the Philippines. This country is situated in a region that has one of the greatest frequencies of tropical cyclones on the globe. The average number per year is about 22. Fig. 1.27 shows the monthly distribution of these. It can be seen that the main cyclone season is July to November, with the maximum in October. Although the Philippine region has the highest number of tropical cyclones per year, the destruction and deaths due to storm surges are greatest in Bangladesh, responsible for about 40 % of the deaths over the whole globe. This will be discussed in more detail in section 6.3.1.

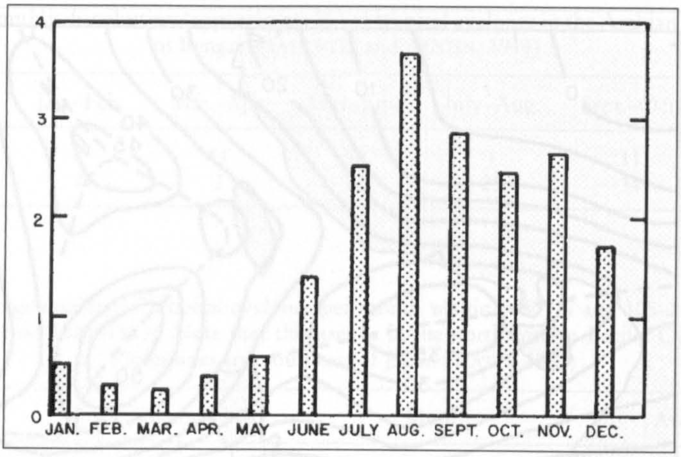

Fig. 1.27: Mean monthly frequency of tropical cyclones affecting the Philippines. (ARAKAWA, 1969)

Weather System of the CIS

Considered next is the weather system of the former USSR (now called CIS). LYDOLPH (1977) mentioned that during winter, the strong dominance of a high pressure cell over Eurasia causes the majority of fronts and cyclone tracks to be located along the edges of the land mass. In winter, the polar front generally lies south of the former CIS. This front has two branches: the western branch lies in the Mediterranean – Asia Minor – Middle East area, and an eastern segment lies off the coast of China and across Japan, stretching into the Aleutians. Many cyclones that affect the weather over the CIS develop on the western segment. The cyclones forming in the eastern Mediterranean usually move northeastward across the Black Sea, the Caucasus, Ukraine, the lower Volga, and western Siberia. Cyclones developing in the Middle East travel into Soviet Central Asia. Cyclones forming along the eastern branch of the polar front in winter travel north of the CIS.

Thus, many of the cyclones affecting the CIS in winter either originate in the Icelandic low area or in the Mediterranean Sea. The Barents Sea also acts as a region of cyclogenesis and redevelopment. The Black Sea and the Caspian Sea also act as areas of cyclogenesis during winter. Other areas of cyclogenesis are western Siberia, the Baltic Sea, and southern Finland. In the Far East, cyclogenesis occurs over the northern part of the Okhotsk Sea (sea level pressures as low as 970 mb occur). However, in the Far East, most of the cyclogenesis occurs over Japan and the Sea of Japan. These cyclones affect southern portions of the Kamchatka Peninsula, Sakhalin Island, and Kuril Islands.

In winter, one of the stormiest areas in the CIS is the Ob Estuary region where cyclones travelling from the west along the Arctic coast meet those from the southwest travelling along the Black and Caspian seas. During spring, the center of maximum cyclone frequency shifts eastward from the Barents Sea to the Ob Gulf. In summer, the location of maximum cyclone frequency shifts southeastward into central Siberia south of the Taymyr Peninsula. In summer, the frequency of cyclones over the Black and Caspian seas diminishes considerably. In the Far East, the Aleutian low becomes weak, and the Amur Valley becomes a region of strong cyclogenesis.

Generally speaking, cyclones are more evenly distributed across the CIS landmass in summer. In winter, most of the cyclones affecting the former CIS originate outside the country, whereas in summer, most of the cyclogenesis occurs in the CIS itself. Summer is the season when wedges of the Azores High can stretch over the centre of the European former USSR and way across as far as Lake Baykal. In the north the Arctic High exerts its influence, but the whole south, mostly Turestan, is covered by the Asian Low (MARTYN, 1992). Areas of high cyclogenesis are the Amur Valley, the Urals, western Siberia, and northcentral Kazakhstan.

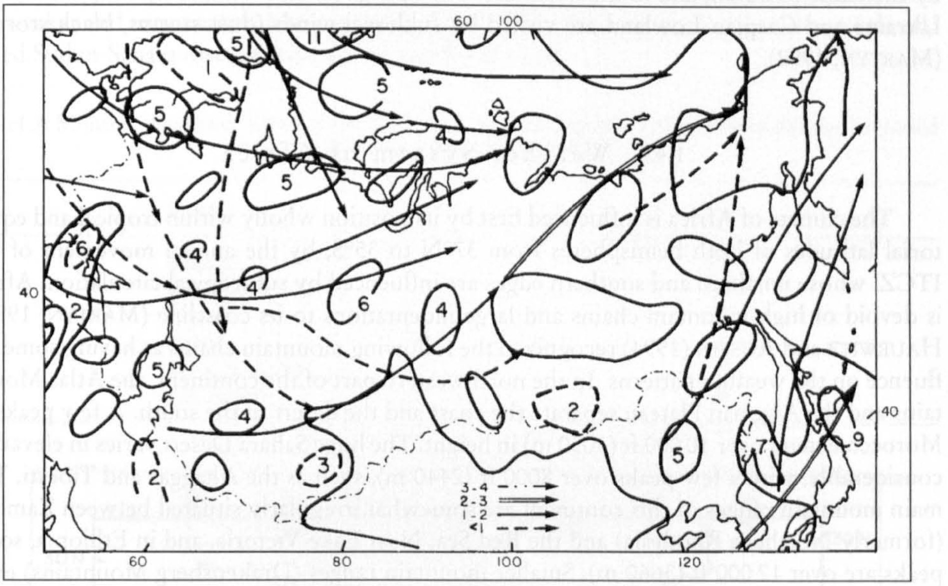

Fig. 1.28: Total number of cyclones during a 20-yr-period over the Soviet Union during the month of January. The principal tracks of cyclones are also shown. (LYDOLPH, 1977)

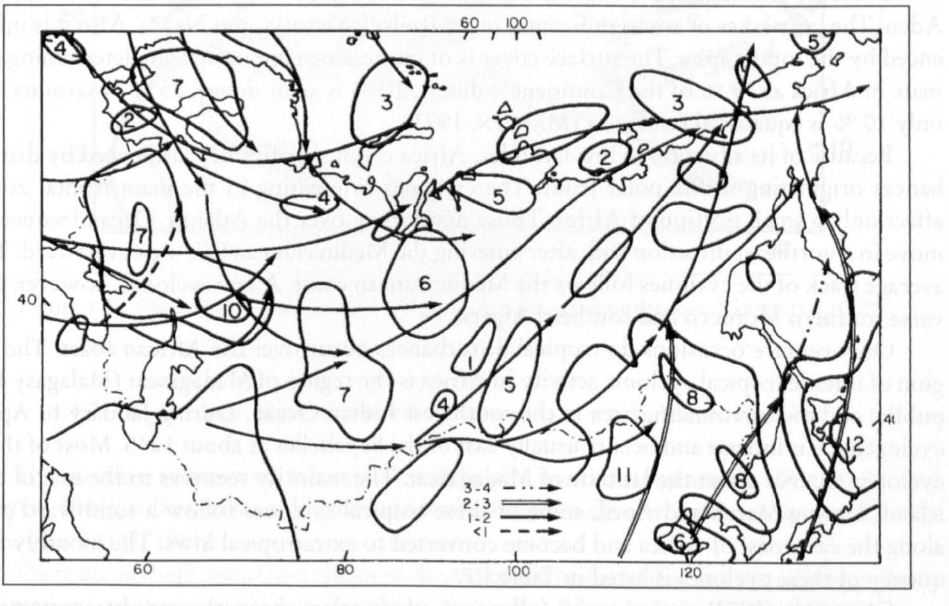

Fig. 1.29: Total number of cyclones during a 20-yr-period over the Soviet Union during the month of July. The principal tracks of cyclones are also shown. (LYDOLPH, 1977)

Generally, the movement of cyclones and fronts over the former CIS is slower than over the eastern part of North America. Also, there is frequent stagnation for a day or more. On the average, about 32 cyclones per year affect central Asia. The frequencies of cyclogenesis and the main routes of cyclones in January and July are shown in Fig. 1.28 and 1.29, respectively.

In winter, strong winds causing blizzards in the steppes and deserts of central Asia go by the name of buran, and in the north are called purga. In the summer months the eastern Ukraine and Caspian Lowland are visited by sukhovei winds (dust storms, black storms) (MARTYN, 1992).

1.4.6 Weather System of Africa

The climate of Africa is influenced first by its position wholly within tropical and equatorial latitudes of both hemispheres from 37°N to 35°S, by the annual movement of the ITCZ, whose northern and southern edges are influenced by subtropical circulation. Africa is devoid of high mountain chains and large indentations to its coastline (MARTYN, 1992). HAURWITZ and AUSTIN (1994) recognized the following mountain chains as having some influence on the weather patterns. In the northwestern part of the continent, the Atlas Mountains and the Algerian Plateau separate the coast and the desert to the south. A few peaks in Morocco extend over 10 000 ft (3050 m) in height. The huge Sahara Desert varies in elevation considerably, with a few peaks over 8000 ft (2440 m), such as the Ahaggar and Tibesti. The main mountain ranges of this continent are somewhat irregularly situated between Zamibia (formerly Northern Rhodesia) and the Red Sea. Near Lake Victoria, and in Ethiopia, some peaks are over 12 000 ft (3660 m). Smaller mountain ranges (Drakensberg Mountains) exist in the southeast; the Auaz Mountains in the southwest, the Cameroon Mountains in Cameroon, and the Ankaratra Mountains in Madagascar (Malagasy Republic) are other examples.

The only indentations along the coastline are the gulfs of Guinea, Gabès, Sidra, and Aden. The only lakes of any significant size are Rudolf, Victoria, and Nyasa. Also it is influenced by the topography. The surface cover is of tremendous importance in determining climate in Africa as 39 % of the Continent is desert, 10 % is semi-desert, 35 % is savanna and only 10 % is equatorial rainforest (MARTYN, 1992).

Because of its situation in low latitudes, Africa is not significantly influenced by disturbances originating in the polar front. The cyclones originating in the main frontal zones affect only a small portion of Africa. Those developing over the Atlantic Ocean frequently move in a northeast direction and, after entering the Mediterranean Sea, move eastward. The average track of the cyclones follows the Mediterranean coast. A few cyclones, however, traverse southern Morocco and southern Algeria.

Only on rare occasions do tropical disturbances occur over the African coast. The region of intense tropical cyclonic activity in Africa is the region of Madagascar (Malagasy Republic) and the surrounding area in the southwest Indian Ocean. During January to April, cyclogenesis is intense and occurs usually east of the Seychelles at about 10° S. Most of these cyclones recurve about the latitude of Madagascar. The majority recurves to the east of this island. During March and April, some of these tropical cyclones follow a southward path along the east coast of Africa and become converted to extratropical lows. The monthly frequency of these cyclones is listed in Table 1.7.

GRIFFITHS (1972) provides the following information about the weather systems of Africa, with particular reference to those of Egypt. During winter, the Mediterranean Sea is a center of cyclogenesis. These Mediterranean depressions mainly affect northern parts of Egypt. During spring (March to May), the tracks of the Mediterranean depressions shift southward, and during this season, these are referred to as the „desert“ or „Khamsin“ depressions. The frequency of these varies from two to six per month. Also, these depressions, in spring, are smaller in size than the winter depressions.

During summer, the depressions do not traverse Egypt. In fall (October to November), Khamsin-type depressions move across Egypt. Compared with the spring depressions, these are weaker and move more slowly towards the east. The most frequent trajectories of the so-called Sudan-Sahara disturbances are shown in Fig. 1.30.

Table1.7: Monthly distribution (totals) of cyclones in the Mozambique Channel area during the period 1848–1966. (GRIFFITHS, 1972)

Month	No.
January	28
February	30
March	18
April	6
May–November	3
December	15

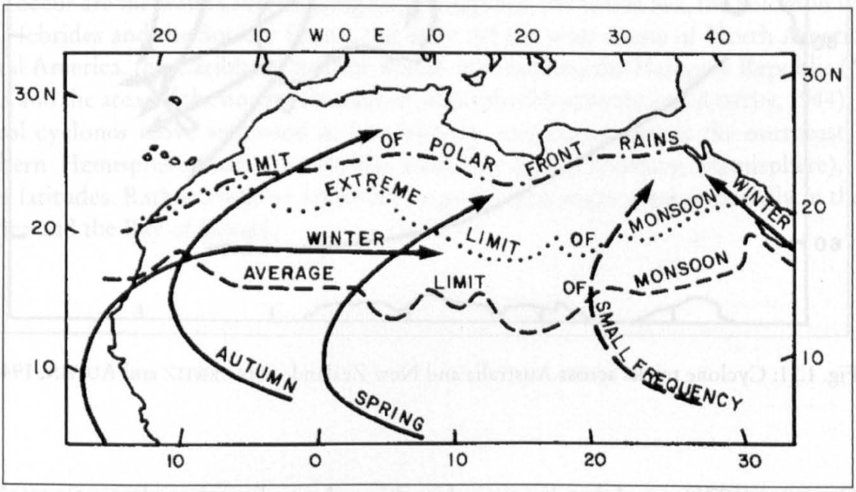

Figure 1.30: Most frequent trajectories of the Sudan-Sahara disturbances. (GRIFFITHS, 1972)

1.4.7 Weather Systems of Australia and New Zealand

The weather systems of this region will be discussed first generally (HAURWITZ and AUSTIN, 1944), followed by a consideration of certain details of the Australian weather systems (GENTILLI, 1971).

There are no high mountain chains in the mainland of Australia, and the only significant indentations to the coastline are the Great Australian Bight and the Gulf of Carpentaria. However, Tasmania is mountainous. New Zealand is also relatively mountainous. The continent is small and no other continents are in its vicinity. Therefore the two neighbouring oceans, the Indian and the Pacific, have a very great influence. In January low pressure centre forms over northern Australia. The ITCZ is lying at around 20° S, north of it there are north-westerly winds, south are south-east trade winds. In July an anticyclonic centre comes into existence over central Australia and joins up along an axis over 30° S with permanent tropical highs over the adjacent oceans.

The tracks of cyclones across Australia and New Zealand are shown in Fig. 1.31 Cyclones developing along the polar front off South Africa usually move south-eastward to the south of New Zealand. Also, stationary cold fronts over Queensland lead to cyclones that move in a general south-easterly direction, either to the north of New Zealand or across North Island of New Zealand. Cyclones developing over New South Wales travel across South Island of New Zealand. Sometimes, cyclones develop along the south coast of Australia.

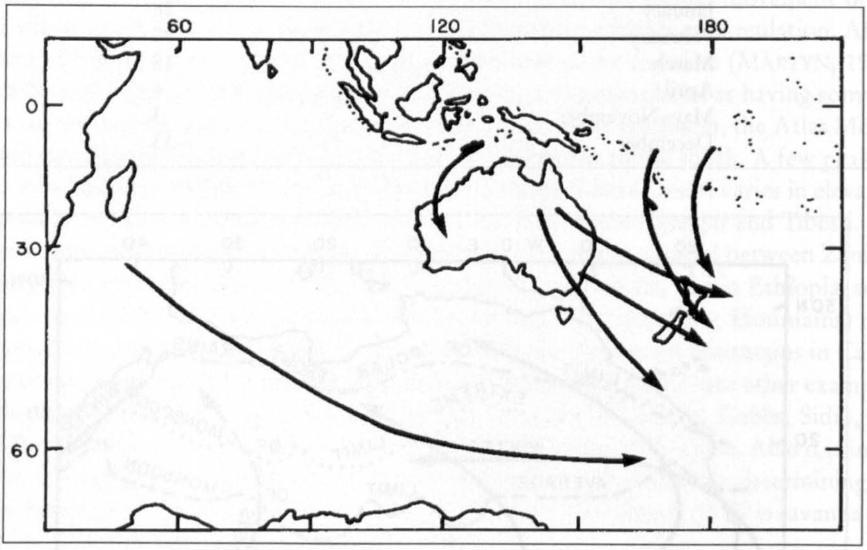

Fig. 1.31: Cyclone tracks across Australia and New Zealand. (HAURWITZ and AUSTIN, 1944)

GENTILLI (1971) stated that, because of its shape, Australia is the only continent that has roughly the same frequency of tropical cyclones on both the east and west coasts. Data for the period 1870–1955 show that, on the average, Northern Territories and Queensland together experience about 3.3 tropical cyclones per year, whereas the west coast average is 2.1. As far as the monthly distribution is concerned, western Australia experiences the highest frequency during December to April.

Generally, in the Australian region, tropical cyclones originate in the belt of 4–20° latitude (north and south). One significant feature of tropical cyclones in the region of Australia are their relatively short tracks. Those originating in the Timor Sea travel in a southwest direction with a speed ranging from 8 to 24 km s^{-1}.

1.4.8 Weather Systems of the Oceanic Regions

Since tropical and extratropical cyclogenesis depends on the positions of the various frontal zones, the positions of these will be briefly summarized. The intertropical front lies in the low pressure belt between the large anticyclones of both hemispheres, whereas the polar fronts are mainly located off the east coasts of the continents, and the Arctic and Antarctic fronts lie in the troughs that extend from the high latitude deep cyclones (HAURWITZ and AUSTIN, 1944).

The cyclones of the middle and high latitudes generally develop as wave disturbances on the polar front. Since the position of the front varies considerably, the positions of cyclogenesis also vary with the season. In the Northern Hemisphere, most of these cyclones move in a north-easterly direction towards the Aleutian and Icelandic lows, whereas in the Southern Hemisphere, they move southeastward toward the circumpolar low. The seasonal variation is more pronounced in the Northern Hemisphere. In summer, cyclogenesis usually occurs farther north; the cyclones move slower and they are shallower than the winter cyclones.

Tropical cyclones develop in the intertropical front beyond 5° latitude in the summer hemisphere. Tropical cyclones are a rare phenomenon in the South Atlantic and eastern part of the South Pacific. Their frequency in the North Indian Ocean is quite different from elsewhere. In the Arabian Sea and the Bay of Bengal, they occur mainly in the periods between the southwest and the northeast monsoon seasons. Other water bodies where tropical cyclones occur are the waters surrounding the Philippines, the China Sea, the Solomon Islands, New Hebrides and the Society Island, the areas off the west coasts of North America and Central America, the Caribbean Sea, the waters surrounding the Malagasy Republic (Madagascar, and the area off the northwest coast of Australia (HAURWITZ and AUSTIN, 1944). These tropical cyclones move westward in low latitudes and then towards the northeast in the Northern Hemisphere (and towards the southeast in the Southern Hemisphere), in the higher latitudes. Rather irregular trajectories can occur in many areas, especially in the Arabian Sea and the Bay of Bengal.