CHAPTER I
INTRODUCTION

1.1 The Indian monsoons

The seasonal reversal of meridional temperature and pressure gradients and the associated wind circulations which constitute the summer and winter monsoons is the most outstanding feature of Indian meteorology. As is well known, the Indian monsoons are part of the large planetary scale Asian monsoons which are the most dominant monsoon systems of the world. Complex interactions between the atmosphere, the land and the oceans under the influence of the seasonally changing solar radiation are involved in the development and maintenance of the monsoon circulations. The configuration of the continents and the oceans over the eastern hemisphere is an important geographical feature. About 60% of the northeast quadrant of the globe is covered by continental land mass of Eurasia and north Africa whereas in the other three quadrants about 80% of the area is oceanic. While the Atlantic and Pacific oceans are open to the north and south, the Indian Ocean (including the Arabian sea and Bay of Bengal) is confined to its north by the Asiatic continent and to its west by Africa. These features give rise to large thermal contrasts of opposite sign between the continental and oceanic areas during the northern summer and winter.

Due to the differential response of the land surface and oceanic waters to the incoming solar radiation, the temperatures of land and the overlying atmosphere are higher in summer and lower in winter compared to the oceanic areas to the south and east. These thermal contrasts provide available potential energy for generating and maintaining the seasonal monsoon circulations. In general, higher temperatures at the surface are associated with lower pressures and vice versa. Hence the low level monsoon winds blow from the oceans towards the land in summer (wet season)
and in the reverse direction in winter (dry season). The meridional winds undergo Coriolis deflection in the zonal direction. This is the broad qualitative picture of the low level Asian monsoon circulations.

Figs 1.1 and 1.2 show the sea level pressure distribution over the globe in January and July, typical of the winter and summer monsoon seasons. The lowest surface pressure in July is over northwest India and adjoining Pakistan. In January the highest surface pressure is over the eastern parts of Siberia. The largest annual range of surface pressure is over the Asiatic continent.

The planetary scale changes in the temperature and pressure gradients and wind circulations associated with the monsoons, extend through great depths of the atmosphere. On the basis of the circulation features, the summer monsoon is considered as extending over the four months from June to September, attaining peak intensity in July-August; the winter monsoon conditions prevail from November to April. May and October are regarded as transitional months. The importance of the summer monsoon arises from the fact that it is the main rainfall season for India and other countries of southeast Asia coming under its influence.

1.2 The seasons and rainfall of India

Extending from the tropics (~8°N) to the extratropics (~37°N), both tropical and extra-tropical atmospheric systems affect the weather and climate of India in the course of the year. In Indian meteorology the year is broadly divided into four seasons:

(i) January - February (cold weather season)
(ii) March - May (hot weather season)
(iii) June - September (summer/southwest monsoon season)
(iv) October - December (northeast monsoon season)

The spatial distribution of the annual rainfall of India and the percentage contribution of the four seasons to
Fig 1.1 Monthly mean sea level pressure (hPa) distribution over the globe for January (adapted from Handbook of Aviation Meteorology, Meteorological Office, London, 1971).

Fig 1.2 Monthly mean sea level pressure (hPa) distribution over the globe for July (adapted from Handbook of Aviation Meteorology, Meteorological Office, London, 1971).
the annual rainfall as per the climatological records of the India Meteorological Department (IMD, 1971) are shown in Figs 1.3 and 1.4(a) to (d). The annual rainfall has large spatial variations from high values exceeding 250 cm along the west coast of the peninsula and parts of northeast India to less than 15 cm over the western parts of Rajasthan and northern parts of Kashmir. The southwest monsoon season accounts for 70 to 95% of the rainfall of the year except over the extreme north of the country and the southeastern parts of peninsula. The northeast monsoon (which is essentially the retreating phase of southwest monsoon) is the principal rainy season for the southeastern parts of the peninsular India which receive 50 to 70% of its annual rainfall in this season; it is also the secondary rainfall season for Kerala. Most of the remaining parts of the country receive 5 to 10% of the annual rainfall in these months. In the cold weather season, the extreme northern parts receive 10 to 20% of the annual rainfall under the influence of eastward moving extra-tropical weather systems known as western disturbances in Indian meteorology; the rest of the country receives very little rain. The hot weather season is associated with rising temperatures and increasing convective activity. In these months northeast India and the southern parts of the peninsula receive 10 to 30% of the annual rainfall from thunderstorms; the extreme northern parts of the country also receive similar amount from western disturbances. Precipitation is often in the form of snow over the mountainous terrain of northern India in the months outside the summer monsoon season.

The average rainfall over the plains of India is 925 mm during the southwest monsoon period while it is only 145 mm for the rest of the year (Rao, 1976). This highlights the importance of the summer monsoon in the meteorology of India. Food production, hydel power generation, water supply for domestic and industrial needs etc., are critically depended on the rainfall of this season which has
Fig 1.3 Spatial distribution of annual rainfall of India (adapted from IMD, 1971).
Fig 1.4 Percentage contribution of the four seasons to the annual rainfall (adapted from IMD, 1971).
profound influence on the national economy and social welfare of the country.

1.3 Dates of onset and withdrawal of the monsoon

The criteria used for fixing the dates of onset/withdrawal of the monsoon are increase/decrease in rainfall and changes in the circulation features. These are not exactly repetitive from year to year but by averaging over a sufficiently long period of years one gets a normal picture. Dates of onset/withdrawal of the monsoon at individual stations are identified from long-term 5-day (pentad) rainfall curves of the stations by locating the dates of sharp increase/decrease in rainfall. Some degree of subjectivity is involved in this procedure, which nevertheless gives a consistent overall picture for the country. Diagrams showing isolines of onset/withdrawal of the monsoon prepared in this manner (IMD, 1943) are shown in Figs 1.5 (a), (b).

Fig 1.5(a) shows that the normal date of onset of the southwest monsoon rains is about the third week of May over the Andaman group of islands in the Bay of Bengal and about 1 June over Kerala. The isolines show the manner in which the rains progress north and northwest to cover the entire country by the middle of July.

Fig 1.5(b) shows that the withdrawal of the monsoon rains from western Rajasthan sets in by the beginning of September. The effective duration of the southwest monsoon rains over this area is on the average only about one and half months. By the end of September the monsoon rains are confined approximately to the south of a line joining Pune and Allahabad. The southward retreat of the rains continues at first rapidly till about mid-October and later gradually. By about mid-December the monsoon rains have retreated from the entire country.
Fig 1.5 Normal dates of onset and withdrawal of the monsoon rainfall over India (IMD, 1943).
As stated earlier, the rainfall of the four months June to September is associated with the southwest monsoon, taking into consideration the circulation features. A significant upper tropospheric circulation features associated with the onset of the southwest monsoon is the weakening and northward shift of the sub-tropical westerly jet stream of the winter season over north India and the appearance of the tropical easterly jet stream over the southern latitudes which attains its peak intensity in July/August. By October the upper tropospheric westerlies reappear and progressively strengthen over the northern parts while the tropical easterly jet stream over the southern latitudes weakens and shifts equatorwards. Significant changes also occur in the lower tropospheric circulation features. The onset of the southwest monsoon is associated with the strengthening and deepening of the zonal westerlies over the southern parts of the peninsula which attain maximum development by July-August and begin weakening through September. By October the lower level winds change over to northeasterlies over the southern parts of the peninsula from which the northeast monsoon derives its name. The lower and upper tropospheric circulation changes are connected with the seasonally changing temperature and pressure gradients.

1.4 Vertical variation of zonal and meridional winds across India

To illustrate the progressive changes in the circulation features across India from May to October, vertical variations of the zonal \( u \) and meridional \( v \) components of the monthly mean winds across the country for 1930 are shown in Figs 1.6 (a) to (c). These are based on the rawin data of eight stations: Trivandrum (TRV), Bengaluru (BNG), Hyderabad (HYD), Nagpur (NGP), Gwalior (GWL), New Delhi (DLH), Patiala (PTL) and Srinagar (SRN). In the present context we focus attention on the progressive changes in the zonal winds.
Fig 1.6a Vertical variation of zonal (u) and meridional (v) components of monthly mean winds across India for May and June, 1980.
Fig 1.6b Vertical variation of zonal (u) and meridional (v) components of monthly mean winds across India for July and August, 1980.
Fig 1.6c Vertical variation of zonal (u) and meridional (v) components of monthly mean winds across India for September and October, 1980.
In May westerlies over the south of the peninsula are weak and shallow; the upper easterlies have a maximum strength of about 15 m s\(^{-1}\) near 100 hPa level. The subtropical westerly jet stream in the upper troposphere can be seen a little to the north of Delhi with its core around 200 hPa. With the onset and advance of the monsoon in June the low level westerlies have strengthened and deepened to about 400 hPa over the south where the upper easterlies have also strengthened having a maximum speed of about 25 m s\(^{-1}\) around 150 hPa level. The sub-tropical westerly jet stream over north India has weakened and its core has shifted northwards. In July and August the monsoon circulation has reached the maximum development both in the lower and in the upper troposphere. The tropical easterly jet stream in the upper troposphere can be noticed between 150 and 100 hPa with its axis having an upward slope from Trivandrum to Nagpur. In September the significant changes from August are weakening of both the lower tropospheric westerlies and upper tropospheric easterlies and the strengthening of the sub-tropical westerlies around 200 hPa over north India. By October the sub-tropical westerly jet stream has reappeared over north India. The upper tropospheric easterly circulation has weakened appreciably and easterlies extend up to the surface over the southern parts.

We shall not discuss in detail the changes in the mean meridional winds which are more complex. However, some similarity between the months of May and October and their differences from those for the other 4 months can be noted.

1.5 Studies relating to the summer monsoon

From the early days of Indian meteorology in the last century, there have been numerous studies relating to various facets of the summer monsoon by the meteorologists of the IMD. In recent decades with the availability of global meteorological data over fast telecommunication channels and computer data processing including numerical
weather prediction, interest in tropical meteorology and monsoon meteorology has become global. The tropics, which comprise about half the surface area of the globe, constitute the heat source for generating and maintaining the general circulation of the atmosphere. The interdependence and teleconnections between the weather and climate systems of the tropics and extra-tropics is now well recognised. This has resulted in generating much interest among atmospheric scientists of the extra-tropics in problems relating to tropical and monsoon meteorology.

Beginning from the International Indian Ocean Expedition (IIOE, 1962-1965) there have been several observational studies over the sea areas adjoining India, supported by ships and aircraft, for data collection during different phases of the summer monsoon. A major finding during the IIOE by US aircraft flights was that over large parts of the Arabian Sea the moist air has a depth of only 1 to 1.5 km above the sea surface with lapse rates in excess of saturated adiabatic; a pronounced inversion separates this shallow moist air from extremely dry air aloft of continental origin in which lapse rates close to the dry adiabatic prevail up to mid-tropospheric levels. Vertical build up of moisture leading to formation of convective clouds and rainfall occurs only when the monsoon current approaches the Indian coast due to orographic effect of Western Ghats. Over the sea area, low level convergence caused by synoptic weather systems such as depressions and low pressure areas leads to convective developments and rainfall. Before the IIOE it was believed that the monsoon current over the Arabian sea was a deep moist current after its long traverse over the sea surface.

Since the IIOE there were two collaborative programmes between India and the former USSR for observational studies relating to the summer monsoon over the Arabian Sea, the Bay of Bengal and the equatorial Indian Ocean. The
A comprehensive observational study during different phases of the summer monsoon was undertaken during 1979. Known as MONEX-79 this was an international regional programme within the framework of the First Garp Global Experiment (FGGE) which started on 1 December 1978 and continued for the next 12 months, with the active participation of the global meteorological community.

The large volume of observational data generated during the experiments mentioned above have stimulated several studies related to the summer monsoon by scientists in India and abroad. Numerical modeling and simulation studies have also contributed to the understanding of certain aspects of the development of the monsoon circulation and rainfall distribution.

A number of books, monographs and reviews in tropical meteorology and monsoon meteorology published since the IIOE give survey of existing knowledge and outline the areas where further study and research are needed. Among these are: Ramage (1971); Rao (1976); Riehl (1979); Krishnamurti (1979); Lighthill and Pearce (1981); Das (1986); Fein and Stephens (1987); Chang and Krishnamurti (1987); Hastenrath (1991); Keshavamurty and Sankar Rao (1992); Asnani (1993).

1.6 Some salient features associated with the summer monsoon

We shall briefly consider some of the salient features associated with the summer monsoon during its onset and established phases, in the Indian context.
Fig 1.7 Monthly variation of mean sea level pressure at five stations across India.
(i) Reversal of pressure gradient across India:

As stated earlier, the monsoon circulations are basically associated with the reversal of the north-south temperature and pressure gradients across the country due to the seasonally changing solar radiation. Fig 1.7 shows the variations in the monthly mean sea level pressure at five stations across India based on the climatological records of the IMD. The reversal of the surface pressure gradient across the country occurs around mid-March and mid-October. The decrease of pressure from south to north in July is twice the corresponding increase in January. This shows that the low level circulation over India associated with the summer monsoon is substantially stronger than that of the winter circulation. The diagram also shows that the annual range of surface pressure at Delhi is about six times the corresponding value for Trivandrum. The onset of monsoon over Kerala occurs only about 2 months after the reversal of the surface pressure gradient across the country. Aerological data show that during this period, reversal of the temperature and pressure gradients occurs progressively throughout the troposphere from south to north.

(ii) The surface heat low:

The surface heat low over northwest India-Pakistan is an important feature associated with the summer monsoon. As can be seen from Fig 1.2, this is the central region of an extensive low pressure belt stretching from the deserts of Sahara across Arabia and the deserts of Rajasthan up to Mongolia. Because of the desert terrain and summer convective activity with dust-storms and dust-rising winds, the atmosphere over and around the region of the heat low has high dust content extending to levels above mid-troposphere in the months of May-June. The dust has an important role in the radiative balance over northwest India on which some studies have been made (Das, 1962; Bryson, 1967).
In his well known work relating to the dynamics of deserts and droughts in the Sahel region of Africa, Charney (1975) pointed out that because of the higher albedo, the desert is a radiative sink of heat relative to the surroundings with sinking air motions which enhances the dryness of the air.

During MONEX-79 special radiation measurements were made over the Saudi Arabian desert to investigate the radiative energy budget of the atmosphere and the surface. Radiation budget studies utilising satellite data were also made over the southwest monsoon area during the onset phase of the monsoon. The results of these studies have been discussed in several papers (Ackerman and Cox, 1982; Blake et al., 1983; Krishnamurti, 1985; Smith, 1986a,b etc.).

The heat low during the summer monsoon extends only up to 1.5 km; above this is a well marked ridge extending to the upper troposphere which is part of the sub-tropical high pressure belt (Rao, 1976).

(iii) The monsoon trough:

Extending from the heat low over northwest India to the head of the Bay of Bengal across the Gangetic plains, roughly parallel to the Himalayas, the monsoon trough is an important feature of the summer monsoon. It has a vertical extent up to mid-tropospheric levels with its axis tilting southwards with height. Around 500 hPa the axis of the trough is close to 20°N. The monsoon trough may be regarded as the location of the ITCZ during the northern summer over the Indian region (Riehl, 1979). The trough undergoes fluctuations in its location and intensity which are linked with the distribution of the monsoon rainfall. The northward shift of the trough towards the foot-hills of the Himalayas is associated with "breaks" in the monsoon. During such epochs there is drastic reduction in rainfall over the central parts of the country and increase in rainfall around the foot-hills.
(iv) Tibetan plateau and Tibetan anticyclone:

The warm core anticyclone in the upper troposphere centered over the Tibetan plateau is a prominent feature of the summer monsoon circulation. The Tibetan plateau, at an average elevation of about 5 km, becomes an elevated heat source in the middle troposphere due to solar heating during summer months. Flohn (1960) considered this as a causative mechanism for the onset of the summer monsoon when a critical state of heating of the plateau is reached. The sensible heating of the plateau as well as the latent heat released over the southeastern parts of the plateau during the pre-monsoon and monsoon months are regarded as relevant factors for the development and maintenance of the Tibetan anticyclone (Flohn 1965, 1968). East-west displacements of the Tibetan anticyclone are associated with active/break monsoon situations (Ramaswamy, 1965; Ramamurthy, 1969).

(v) The Tropical easterly jet stream:

The Tibetan anticyclone is the central region of an extended subtropical ridge in the upper troposphere from about 160°E to 15°W around the latitude of 30°N. South of the ridge, the easterly flow concentrates into a jet stream with maximum speed over southern parts of the Indian peninsula. The easterly jet stream begins to make its appearance over the extreme south of the peninsula around the time of the onset of the monsoon. When the monsoon is fully established over the country, the core of the easterly jet stream is around 13-14°N between 150 and 100 hPa with an average speed of about 40 m s⁻¹. The weakening and the reversal of the low level westerly flow with strong easterlies aloft are closely associated with the north-south temperature gradient through the thermal wind relationship. Starting from the early work of Koteswararam (1958) numerous studies exist relating to the various aspects of the easterly jet stream, including its association with fluctuations in monsoon activity (Ananthakrishnan and Ramakrishnan, 1964; Mokashi, 1974; Kanamitsu and Krishnamurti, 1978; Hingane et al., 1985).
(vi) Cross-equatorial flow:

Even before upper air observations became available it was recognised by Simpson (1921) that the southeast trades over the south Indian Ocean cross the equator and become part of the southwest monsoon circulation. A major contribution to the identification of the cross-equatorial flow during summer monsoon was made by Findlater (1969a,b). From the analysis of pilot balloon wind data he showed that a strong flow from the south with an average speed of about 15 m s\(^{-1}\) prevails at the equator over the eastern Africa and adjoining parts of the Indian Ocean below 600 hPa. The orography of east Africa plays an important part in organizing this flow. Starting from about 20°S in a southeasterly direction over the oceanic area, the air current turns southwesterly after crossing the equator. From the coast of Somalia the current flows towards the west coast of peninsular India. Speeds as high as 20 to 40 m s\(^{-1}\) are reached at some points along this current below 3 km level. This is the strongest cross-equatorial flow encountered over any part of the globe. It is known as the low level Findlater jet stream. It is important in the cross-equatorial transport of water vapour (Rao et al., 1981; Van de Boogard and Rao, 1984).

(vii) Effect of orography:

The orographical features of the Indian subcontinent have a profound influence on the development and organisation of the monsoon circulation and the spatial distribution of rainfall. The Himalayas including the Tibetan plateau is by far the most important among the orographical features. In recent years numerical studies have been addressed to understand how the monsoon circulation and rainfall distribution would be in the absence of the Himalayas.

In one such numerical experiment Murakami et al., (1970) used a two-dimensional model in a meridional plane along 80°E extending from equator to pole. Inclusion of the
mountain generated lower tropospheric westerlies and upper easterlies in the model showing speeds of the correct order; excluding the mountain effects, the speeds were considerably reduced. In a subsequent extension of this study, Godbole (1973) made computations with and without the Himalayas and moisture. This study brought out the importance of the Himalayas for the development of the easterly jet stream.

A comprehensive numerical simulation of the summer monsoon including and excluding the mountains was made by Hahn and Manabe (1975) using the GFDL general circulation model. The model with mountains (M-model) simulated the more important circulation and rainfall features of the summer monsoon. The model without the mountains (NM-model) showed large deviations from the observed features. The surface heat low formed over extreme northeast of China in this model with a desert like climate over south Asia. The crucial importance of the Himalayas and the Tibetan plateau is thus brought out. More recently, 5-day prediction experiment using GCM by Zheng and Lou (1986) with and without the inclusion of the mountain and/or diabatic heating effects showed that the predicted temperatures, geopotential heights and wind fields were most realistic when both the mountain and the diabatic heating effects were considered.

(viii) Monsoon depressions

During the monsoon season, depressions form over the north Bay of Bengal and move in a westnorthwesterly direction along the monsoon trough. Many of them can be traced to the westward moving low pressure waves which are the remnants of Pacific typhoons that weaken after crossing the coast of China. On entering the Bay of Bengal they intensify as depressions. On an average 4 to 5 depressions form during the summer monsoon season. They have a typical life cycle of 4 to 5 days. Several studies have shown that the southwest sector of monsoon depressions is the region of heaviest rainfall (Pisharoty and Asnani, 1957; Bedekar and Banerjee, 1969; Dhar and Mahaisker, 1973). Synoptic and
dynamical features of the monsoon depressions have been studied by several research workers (Krishnamurti et al., 1975, 1976; Rajamani and Sikdar, 1989). The cyclonic circulations associated with them generally extends to 400 hPa with winds of 20 m s\(^{-1}\) around 700 hPa. The strongest vertical motions and maximum cloudiness are associated with the sector of maximum rainfall.

(ix) Mid-tropospheric cyclones

These are cyclonic vortices that are prominently noticed at levels close to the middle troposphere. They usually form over the northeast Arabian sea and Gujarat region during epochs of active monsoon. The maximum intensity is generally around 600 hPa. They have a horizontal radius of about 500 km and are quasi-stationary. One such system was studied in great detail by Miller and Keshavamurty (1968) for the period 2 to 10 July 1963 using IIOE data. These systems often cause heavy rains over the northern parts of the west coast and Gujarat. Mid-tropospheric cyclones also sometimes occur over the Bay of Bengal and descend to the surface as monsoon depressions.

1.7 Monsoon rainfall and its variability

Monsoon rainfall and circulation have variability on all time scales — within a season (intra-seasonal), from one year to another (inter-annual) and over periods of several years such as decades, centuries, etc. The description, understanding and prediction of these variations are important aspects of monsoon meteorology.

(i) Intra-seasonal variation

The intra-seasonal variations have been well documented and the synoptic and dynamic features associated with them are fairly well understood. Depressions and lows originating in the north Bay of Bengal and moving westnorth-west and north-south shifts in the location of the monsoon trough are two important synoptic features responsible for
intra-seasonal variations in the monsoon circulation and rainfall. While the depressions give widespread and locally heavy rains over the central parts of the country, the extreme northward shift of the monsoon trough towards the Himalayas is associated with what is known as "break monsoon" situations resulting in drastic reduction of rainfall over the central and north India and increase along the southern slopes of the Himalayas. In a comprehensive study relating to the break monsoon situations, Ramamurthy (1969) has discussed the anomalous features in the pressure and rainfall distributions and the upper-air circulation associated with them. Breaks occur more often in July and August and last for periods from a few days to 2 or 3 weeks. Prolonged breaks in the monsoon result in drought and famine conditions over the regions of suppressed rainfall. Anomalies in the circulation features associated with the active and break monsoon situations have been documented by Alexander et al (1978).

The active/break phases of the Indian summer monsoon have been known for a long time. Recent studies have shown the association between this and the low frequency oscillation of 40-50 day period with eastward propagation in the meteorological features over the equatorial region discovered by Madden and Julian (1971). Observational studies show that along with this there is also a northward propagating mode over the summer monsoon region. Yasunari (1979, 1980) as well as Sikka and Gadgil (1980) found from the analysis of the satellite cloud cover data, northward propagation towards the Himalayas across India of convective cloud bands originating from the equatorial oceanic area, in a period of about 40 days. Such northward propagation of trough-ridge systems in the zonal wind field was noticed in a study by Krishnamurti and Subramanyam (1982). These features have been associated with the active/break phases of the monsoon. The active phase with rains during the movement of the cloud zone across the country ends in the break phase when it has moved up to the Himalayas. A new
system forms near the equator and shows similar progression. There are theoretical and model studies to explain the eastward propagation over the equatorial region and the northward propagation over the Indian region (Webster, 1983; Keshavamurty et al., 1986, 1988; Nanjundiah et al., 1992).

(ii) Inter-annual variability

Inter-annual variability is an important aspect of the summer monsoon rainfall on which a large number of studies exist from the early days of Indian meteorology. It continues to be an active area of current research.

Variations in the monsoon activity and rainfall occur from one year to another. Fig 1.8a,b adapted from the rainfall climatological atlas of India (IMD, 1971) show respectively the spatial distribution of the mean summer monsoon rainfall ($\bar{r}$) and its coefficient of variation (CV) based on long period data of a large number of stations. CV=$(\sigma/\bar{r}) \times 100\%$ where $\sigma$ is the standard deviation of the rainfall series; it is a non-dimensional parameter which gives a measure of the inter-annual rainfall variation over different parts of the country. In general CV is large over areas of low rainfall. The highest value of CV ~60% is found over west Rajasthan and smallest value of ~20% over the west coast and northeast India.

Assuming that the monsoon rainfall is normally distributed (this is very nearly the case), it is of interest to examine the nature of the inter-annual variations over regions with different values of CV. The data in Table 1.1 can be utilised for this purpose. The Table gives the number of years (N) out of 100 in which the actual rainfall ($r$) can be expected to deviate from the long period average $\bar{r}$ by specified percentages ($\pm D\%$) of $\bar{r}$ for different values of CV. According to the convention followed by the IMD, the rainfall is regarded as normal over a meteorological subdivision when the deviation does not exceed $\pm 20\%$. The table shows that over areas where CV=20%, the rainfall can
Fig 1.8a Spatial distribution of the mean summer monsoon rainfall over India (adapted from IMD, 1971).
Fig 1.8b Spatial distribution of coefficient of variation (CV) of the summer monsoon rainfall over India (adapted from IMD, 1971).
be expected to be normal in the above sense in 68 years out of 100. It will be in excess/deficit category with devia-

Table 1.1 Excess/Deficit rainfall years (N) out of 100 year in relation to Coefficient of Variation (CV)

<table>
<thead>
<tr>
<th>CV(%)</th>
<th>±10</th>
<th>±20</th>
<th>±30</th>
<th>±40</th>
<th>±50</th>
<th>±60</th>
<th>±70</th>
<th>±80</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>68</td>
<td>95</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>20</td>
<td>38</td>
<td>68</td>
<td>86</td>
<td>95</td>
<td>99</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>30</td>
<td>26</td>
<td>50</td>
<td>68</td>
<td>82</td>
<td>91</td>
<td>95</td>
<td>98</td>
<td>100</td>
</tr>
<tr>
<td>40</td>
<td>20</td>
<td>38</td>
<td>55</td>
<td>68</td>
<td>79</td>
<td>87</td>
<td>92</td>
<td>95</td>
</tr>
<tr>
<td>50</td>
<td>16</td>
<td>31</td>
<td>45</td>
<td>58</td>
<td>68</td>
<td>77</td>
<td>84</td>
<td>89</td>
</tr>
<tr>
<td>60</td>
<td>14</td>
<td>26</td>
<td>38</td>
<td>50</td>
<td>60</td>
<td>68</td>
<td>76</td>
<td>82</td>
</tr>
<tr>
<td>70</td>
<td>11</td>
<td>22</td>
<td>33</td>
<td>43</td>
<td>52</td>
<td>61</td>
<td>68</td>
<td>75</td>
</tr>
<tr>
<td>80</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>38</td>
<td>47</td>
<td>55</td>
<td>62</td>
<td>68</td>
</tr>
<tr>
<td>90</td>
<td>9</td>
<td>17</td>
<td>26</td>
<td>34</td>
<td>42</td>
<td>50</td>
<td>56</td>
<td>63</td>
</tr>
<tr>
<td>100</td>
<td>8</td>
<td>16</td>
<td>24</td>
<td>31</td>
<td>38</td>
<td>45</td>
<td>52</td>
<td>58</td>
</tr>
</tbody>
</table>

\[ D = \text{Percentage departure of actual rainfall from normal} \]

Table 1.1 shows deviations exceeding 20% for 16 years on either side. There is little chance of deviations beyond ±50%. On the other hand, over west Rajasthan where CV=60%, the rainfall will be in the normal category only in 26 years out of 100. It will be in excess/deficit category for 37 years each. The rainfall can be expected to be within ±60% of normal in 68 years. For 16 years it can be expected to be >160% of \( ar{R} \) and for the same number of years <40% of \( ar{R} \). This shows the large inter-annual variability over regions of low rainfall and high CV.

Because of the profound socio-economic impacts of large deviations in the summer monsoon rainfall from its
normal or long term average, seasonal forecasting of rainfall has engaged the attention of the IMD for more than 100 years. The early forecasts were largely based on the concept that heavy snow accumulation to the north and west of India in the months preceding the summer monsoon has an adverse effect on the monsoon performance. An objective basis for forecasting the seasonal rainfall was provided by Sir Gilbert Walker by introducing the correlation method for testing the relationship between the rainfall and preceding meteorological parameters. Realising that a large scale phenomenon like the summer monsoon should have global teleconnections, he made a world wide survey for the selection of suitable predictors and developed regression formulae for seasonal rainfall prediction. Several improvements have been effected over the years as a result of numerous studies, particularly since 1960's. While the correlation method introduced by Walker is still retained, new predictors not available in the early days have been tested and selected. A recent paper by Parthasarathy et al. (1993) gives a list of about 100 references to studies in the area of inter-annual variability of monsoon rainfall and the prediction of seasonal rainfall.

Walker's (1923,1924) studies on World Weather led to the discovery of what he called the Southern Oscillation (SO). This is a see saw in the atmospheric pressure between the eastern and western parts of the south equatorial Pacific Ocean. Higher pressure in the east and lower pressure in the west corresponds to the high index phase of the SO; the converse situation corresponds to the low index phase. The time scale of the SO varies from 2 to 10 years. The anomaly of the pressure difference between Tahiti (French Polynesia) and Darwin (Australia) has been used as an index of the SO.

The SO is connected with the changes in the SST over the equatorial Pacific arising from the El Niño phenomenon off the Peru coast of South America. This term is used to describe the warm water that appears in some years
over the coastal regions replacing the cold and nutrient-rich waters otherwise prevalent due to upwelling. El Niño has disastrous effect on the Peruvian anchovy fishery industry and hence has been known for a long time. The oceanic warming that begins to appear around December lasts for several months spreading towards the central Pacific and gradually declines (Rassmusson and Carpenter, 1982)

The association between the SO and SST changes in the Pacific was brought out through the studies of Bjerknes (1966,1969). He gave the name "Walker circulation" for the large scale zonal east-west overturning in the equatorial plane over the Pacific arising from the temperature and pressure differences over the eastern and western parts of the ocean. The strength of the Walker circulation undergoes variations with the changing phases of SO. Ocean-atmospheric interactions over the Pacific have a dominant role in the SO and meteorological features associated with it affecting extensive areas. The term ENSO is used for the related phenomena of El Niño and SO considered together.

Studies show that the high index phase of the SO is associated with good Indian summer monsoon rainfall and the low index with sub-normal rainfall and drought conditions (Shukla and Paolino, 1983; Bhalme et al., 1984; Parthasarathy and Pant, 1984; Elliot and Angell, 1987)

Utilising a homogeneous data set for 120-year period 1871-1990, Parthasarathy (1992) has derived the following statistics for the summer monsoon rainfall over the plains of India: Mean ($\bar{r}$) = 852 mm; standard deviation ($\sigma$) = 83 mm; number of years with $(r - \bar{r}) > \sigma$ (excess rainfall years) = 17; number of years with $(r - \bar{r}) < \sigma$ (deficit rainfall years) = 21; highest = 101.7 mm (1961); lowest = 60.4 mm (1877).

All-India summer monsoon rainfall also shows variability on decadal time scales but no long term trend
has been noticed (Mooley and Parthasarathy, 1984). On a smaller space scale increasing/decreasing trends have been found in some studies (Alvi and Koteswaram, 1985; Soman et al., 1988; Rupa Kumar et al., 1992).

1.8 The World Climate Research Programme (WCRP)

Since 1960 the inter-annual variations in climate on regional and global scales have been more than in the previous few decades. This has had adverse effects on the food production in many countries including India. The years 1965, 1966, 1972, 1979, 1982, and 1987 were of sub-normal monsoon rainfall leading to drought and famine conditions in some parts of India.

Regional weather and climate are manifestations of the global climate system which involves the atmosphere, oceans, land surface (including vegetation) and cryosphere all of which interact in complex ways over a vast range of time scales. The World Climate Research Programme (WCRP) was initiated in 1976 under the joint auspices of the World Meteorological Organisation (WMO) and the International Council of Scientific Unions (ICSU). The WCRP is closely linked with the International Geosphere-Biosphere Programme (IGBP) of the ICSU. While the main focus of the WCRP is on the physical processes in the climate system, the thrust of the IGBP is on the chemical and biological aspects. The two programmes supplement each other. These are long term global research programmes involving several countries for data collection of various types, supplemented with theoretical and modeling studies. The ultimate aim is "to provide quantitative understanding of climate and prediction of global and regional climate changes on all time scales."

One of the important conclusions that has emerged in the recent years is that the tropical diabatic heat sources and the tropical oceans play a major role in modulating the general circulation. The large rainfall during
the summer monsoon and the associated latent heat release is a major heat source for the atmosphere over the extensive monsoon area. As discussed in the earlier section, the southern oscillation which has its origin in the atmosphere-ocean interaction over the equatorial Pacific is a major climate signal with global teleconnections. An organized long term programme for the systematic study of various aspects of the interaction between the tropical oceans and the global atmosphere (TOGA) is a major component of the WCRP that is already in operation.