Chapter II

SUBJECT OVERVIEW
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2.1 Introduction

The monsoon is actually an extremely complex and intricate combination of physical processes that operate not only in the atmosphere, but involve land and ocean as well. From a meteorological point of view, the monsoon is essentially an annual oscillation of the state of the atmosphere in response of the relative position of the sun, as it moves between the tropic of Cancer in the northern hemispheric summer and the tropic of Capricorn in the southern hemisphere summer. It has attracted the curiosity of many scientists from around the world, and of course India, but their understanding of the monsoon is yet far from complete, and the phenomenon is such that it has eluded even a precise and unique definition.

The first scientific explanation of the monsoon was postulated by Sir Edmund Halley (1686). According to him, the monsoon was caused by the differential heating between the Asian landmass and the Indian Ocean. In other words, the monsoon has the character of a giant land-sea breeze that reverses its direction twice during a year. Later, it was Ramage (1971) who made the first attempt to delineate the monsoon regions on the basis of some objectively prescribed criteria. He postulated that a geographical region could qualify for being called as a monsoon region only if the wind patterns in January and July were distinctly different and satisfied certain basic criteria. The area between 35°N and 25°S and 30°W and 170°E satisfies this definition and India and the surrounding seas fall within this area. Although Ramage’s criteria were objective, they were still arbitrary to a certain extent, and they restricted the monsoons to south and Southeast Asia, northern Australia and tropical Africa. These came to be regarded as the traditional or classical monsoon domains.

Asnani (1993) gave the most inclusive definition of the monsoon in which the role of the Inter-Tropical Convergence Zone (ITCZ) was brought into consideration. Asnani’s definition was simple: ‘the monsoon is where the ITCZ is’, but it paved the way for what could be called as the globalization of the monsoon. As the ITCZ migrates north-south in association with the march of the sun, the whole area of the global tropics and adjoining subtropics can be include
in the monsoon regime (Fig. 2.1). Therefore, our present day perspective of the monsoons is not in terms of the amplitude of the seasonal reversal of winds as such, but more in terms of the amplitude of the seasonal change, which is larger over the monsoon region than elsewhere in the tropics.

2.2 The Asian Summer Monsoon

The Asian monsoon is notable in its broad extent and strength, its domination of weather over large regions, and its influence on the fate of their human populations. Nowhere else on the globe is the amplitude of the seasonal change in wind and rainfall patterns as spectacular as in the North Indian Ocean and the adjoining land areas in summer. Asia is the largest continent on the earth and its tropical zone has the right conditions for the circulation to develop with predominant winds of one direction in winter and of the opposite direction in summer. Asnani (2005h) describes the Indian southwest monsoon as the most intense among all the monsoons of the world. In summer, the Himalayan mountain range and the Tibetan plateau act as an intense and extensive heat source that supplies heat directly to the middle troposphere. In winter, they act as a heat sink. The resulting annual oscillation in pressure, temperature and wind accentuate a vigorous monsoon activity over South Asia practically all through the summer.

Fig. 2.1: The monsoon regions of the world (after Kelkar, 2008)
Heat low, Monsoon trough, Tibetan high, Low level jet, Mascarene high, Tropical easterly jet, Monsoon depressions, Mid-tropospheric cyclones, Off-shore trough and Western disturbances are factors that exert their influence over Indian monsoon. Their effects on Indian monsoon are explained in foregoing paragraphs.

2.2.1 Factors exerting influence on Indian monsoon

The Indian Summer Monsoon is a unique feature of the tropical circulation. The thermal contrast owing to the peculiar distribution of land and oceans, coupled with the effect of Coriolis force, results into characteristic patterns of meteorological parameters which show distinct seasonal reversal. These characteristic patterns are obviously inter-related and are also related to tropical circulation pattern. Some of these patterns are semi-permanent in nature. They are observed throughout the summer monsoon season, though with variations in positions and intensity, on interannual and intra-seasonal scale. Such variations are closely linked with the intensity of monsoon circulation and rainfall distribution, both spatial and temporal, over India. The major semi-permanent features associated with the Indian Summer Monsoon are discussed in the following section.

2.2.1.1 Heat Low

The deepest low-pressure area over Pakistan and adjoining NW India is known as the Heat Low. It is generally linked to the regions of maximum heating which are out of reach of the maritime air mass. The heat low is shallow, extending up to about 1.5 km and is overlain by a well-marked ridge extending to the upper troposphere, which is part of the subtropical high pressure belt. The tapering shape of peninsular India, the Himalayan barrier to the north and the Assam hills to the northeast displace the centre of the low to the extreme northwest of the continent. Blocking of cold air incursions from the north by the Himalaya also makes the heat low more intense in this region. The intensity of heat low is a good indicator of the continental heating and land-sea contrast, which drives the monsoon. Ramage (1971) has shown that surface pressure at Jacobabad is inversely related to the intensity of monsoon rains over a strip of subcontinent between 18º N and 27º N.
2.2.1.2 Monsoon trough

During the summer monsoon season, the most conspicuous signature of the monsoon circulation at the surface is a trough extending from the heat low southeastwards up to Gangetic West Bengal, termed as the monsoon trough. The monsoon trough is regarded as a part of the equatorial trough of the northern summer in the Indian longitudes and indicates the separation between air of northern and southern hemispheric origin. The trough axis experiences considerable day-to-day variation in its position, which has a vital bearing upon the monsoon rainfall distribution in the region. No other semi-permanent feature has such a control on monsoon activity. During active monsoon conditions, the monsoon trough lie south of its normal position and cyclonic whirls form all across the trough (though mostly over North Bay of Bengal). They move across its length and breadth, spreading rains along their tracks. During the break monsoon, the monsoon trough hugs the sub-Himalayan region or even disappears north of it and cyclonic whirls more or less remain absent over central parts of India and across the Indo-Gangetic Plain and rains also remain suppressed over most of India except the foot-hills of Himalayas. It is observed that the trough line tilts southwards with height. According to Ramakrishnan (1972), when the tilt of the trough is large and it is at 15° N at 500 mb, west coast gets moderate to heavy falls, but when the trough at that level is along 20° N, west coast rain witnesses scantly rains.

2.2.1.3 Tibetan High

The Tibetan plateau, located more than 4500 m above sea level with a length of about 2000 km and width of about 600 km in the west and about 1000 km in the east, is considered to be one of the key factors in the development of monsoon circulation in the region. The atmospheric pressure on the surface of the plateau varies between 700 and 500 hPa. The Tibetan plateau exerts its influence as a mechanical barrier in the atmospheric flow as well as a high-level heat source (Murakami, 1987). An anticyclone appears in the upper troposphere over Tibet during the Indian summer monsoon season, primarily due to latent and sensible heating over the plateau. The variations in the intensity and position of this high and its orientation are closely related to the monsoon circulation over South Asia.
Ramaswamy (1965) points out that well-distributed rainfall over India is associated with well-pronounced and east-to-west oriented anticyclone over Tibet at 500 and 300 hPa levels. It has also been observed that the shifting of the Tibetan anticyclone eastwards to southern China and northern Myanmar allows extra-tropical westerlies to penetrate into the monsoon regime of South Asia. Such situations, leading to increased meridional flow, usually result in the so-called ‘break monsoon’ conditions with an abrupt weakening of the monsoon activity over most of India.

2.2.1.4 Low Level Jet

A strong cross-equatorial low level jet stream (LLJ) with its core at an altitude of about 1.5 km and wind speeds of 80-100 km/h exists over the Indian Ocean and South Asia during the southwest monsoon. It is conduit carrying moisture generated by the trade winds over the vast expanses of the south Indian Ocean and also the moisture evaporated over the Arabian Sea to areas of monsoon rainfall production over South Asia.

It was Findlater (1966a and b), who analysed the wind observations taken from aircraft and pilot balloons, and discovered the existence of the cross-equatorial East African low-level jet (also known as low-level cross-equatorial jet, Findlater’s jet or Somali jet). This jet has subsequently been recognized as a major feature of the lower-tropospheric circulation over the western Indian Ocean during the Indian summer monsoon season. It is estimated that this jet stream, situated near the western periphery of the monsoon regime, could account for about 50% of the total cross-equatorial transport of air in the lower troposphere in the month of July (Pant and Rupa Kumar, 1997). This jet, thus, is one of the strongest and most sustained low-level wind systems on earth. It is normally strongest in July and August during which its core attains maximum speeds up to 100 kt. The axis of the low-level jet is observed to be quite stable over the western Indian Ocean. However, it is subjected to north-south oscillations over India and eastern Indian Ocean. The displacements of convective heating zones are responsible for the latitudinal oscillations of the low-level jet and the associated active/break spells in the monsoon circulation and rainfall (Sikka and Gadgil, 1980). Joseph and Simon (2005) found that during the phase of active monsoon,
the low-level jet passes through the peninsular India and this region receives higher rainfall as compared to the rest of India. However, during the break monsoon phase, the low-level jet shows a branching out over eastern Arabian Sea; one heading towards north-east (into the monsoon trough) and the other turning towards south-east, into another convective zone formed in the equatorial region.

2.2.1.5 Mascarene High

The Mascarene high is one of the important features of the tropical general circulation which has profound influence on South Asian climate and weather. This is the high pressure area at sea level south of the equator in the Indian Ocean near Mascarene Island, with its centre located near 30° S and 50° E. The position and the intensity of this high are considered to be closely linked to the summer monsoon activity.

The Mascarene high undergoes short-period fluctuations in its intensity owing to the passage of extra-tropical westerly waves of the southern hemisphere. The intensification of the Mascarene high strengthens the East African low-level jet and the corresponding monsoon current over the Arabian Sea (Sikka and Gray, 1981). The intensity of the Mascarene high is also found to be associated with the onset of the monsoon over India as well as the subsequent fluctuations in its activity (Okoola and Asnani, 1981).

2.2.1.6 Tropical Easterly Jet

The Tropical Easterly Jet (TEJ) is the meteorological term which refers to an upper level easterly wind that starts in late June and continues until early September. It is an important upper tropospheric feature of summer monsoon circulation over south Asia, indicative of horizontal temperature gradient in the troposphere. This strong flow of air that develops in the upper atmosphere during the Asian monsoon is centered around 15° N, 50-80 °E and extends from South-East Asia to Africa. The strongest development of the jet is at about 15 km above the earth's surface with wind speeds of exceeding 40 m/s over the Indian Ocean. The position and speed of the jet have appreciable spatial and temporal fluctuations. The north-south movement as well as the structure of the Tropical Easterly Jet is observed to be closely linked to the monsoon activity. The
strongest portion of the jet stream is over Indian peninsular region, with a maximum speed of about 75 m/s (Koteswaram, 1958a and b). The rainfall distribution related to the tropical easterly jet system is indicative of the vertical motion patterns in the lower troposphere in its association. In the entrance region of the jet over Asia, abundant rainfall is found to the north of the jet axis, and in the exit region over West Africa reverse pattern is observed (Koteswaram 1958a and b).

2.2.1.7 Monsoon lows and Depressions

Monsoon depressions are the synoptic features that cause most of the monsoon rains. These are low pressure areas with two or three closed isobars (at 2 mb intervals) covering an area of about five degrees square. They generally form in the Bay of Bengal north of 18° N, move west-northwest at least up to the central parts of the country before weakening or filling up, and give widespread rains in the southwest quadrant with many heavy falls. These low pressure systems are referred to as depressions when surface winds are up to 33 kt (while over the sea) and cyclonic storms when higher speeds prevail. Weaker systems with only one closed isobar and wind speeds less than 17 kt, are called lows. In addition to providing beneficial rainfall along and near their tracks, these systems transport heat and moisture upwards and maintain the activity of the monsoon trough. Bhalme and Mooley (1980) and Mooley and Parthasarasthy (1983) have shown that the monsoon depressions have greater westward penetration during years of excess monsoon rainfall over the Indian region than during years of deficient monsoon rainfall.

2.2.1.8 Mid-tropospheric cyclones

The name ‘Mid-tropospheric cyclones (MTCs)’ is given to those synoptic systems found over South Asia during the summer monsoon months whose cyclonic vorticity has a maximum between 700 and 500 hPa, with much smaller values at the surface. These systems are quasi-stationary and generally occur over the northern parts of the west coast of India and occasionally over the northern Bay of Bengal. They are not as frequent as monsoon depressions and are usually observed during the first half of the monsoon season. They help to accentuate the
monsoon activity over the region and sometimes help in the early shift of the monsoon current to the drier western parts of the Indian subcontinent.

A detailed study on MTCs over the northeast Arabian Sea was carried out by Miller and Keshavamuthy (1968), who observed that the area of convergence and cyclonic circulation was well-marked between the 600 and 500 hPa levels.

2.2.1.9 Off-shore trough along west coast of India

During the summer monsoon season, particularly in the onset and advance phase, the existence of a weak sea level trough off and along the west coast of India is a common feature seen in the daily weather charts. Small vortices develop within this trough, known as off-shore vortices (George, 1956), which are shallow zones of convergence causing enhanced rainfall activity along the coastal belt. The off-shore troughs form more often near coastal Karnataka and move northward along the coast, with associated northward movement of the belt of heavy rainfall. Nearly half of the active to vigorous monsoon situations in Konkan and three-quarters of such events in coastal Karnataka are associated with the off-shore trough (Rao, 1976).

2.2.1.10 Western disturbances

Western disturbances are the surface level frontal characteristic systems that form over the western parts of the globe near Mediterranean Sea and pass through all the countries at extra-tropical latitudes. The middle latitudes are characterized by migratory low-pressure systems forming at the polar front, which oscillates north and south with the march of the season. These cyclonic systems have a well-developed frontal structure, with a warm front, a cold front, and a warm sector in between. These western disturbances, originating in the mid-latitudinal cyclones over western Asia, travel eastwards across Iran, Pakistan and India. They affect the southern region, north of 30° N, giving rise to cloudiness and precipitation. They enter India via north or northwest parts and exit in north-northeastward or northeastward direction.

The western disturbances reach the subcontinent as irregular or weak disturbances over northwestern India and Pakistan, which stagnate and intensify with the moisture feed from the Arabian Sea and even from the Bay of Bengal.
Heavy precipitation associated with these western disturbances, is usually caused during winter. The areas, which receive widespread rainfall, due to these western disturbances, are Kashmir, Punjab, Haryana, Northwestern Uttar Pradesh, Himachal Pradesh and adjoining parts of Pakistan.

2.3. The Indian monsoon and its variability

The Indian summer monsoon rainfall shows variability on different time and spatial scales, varying from intra-seasonal to interannual scales. The components discussed in the earlier section influence intra-seasonal variability of monsoon. Studies have shown that the nature of the intra-seasonal variability is not different during the years of major droughts or major floods. This suggests that a simple conceptual model to explain the interannual variability of the Indian monsoon rainfall should consist of a linear combination of a large-scale persistent seasonal mean component and a statistical average of intra-seasonal variations (Krishnamurthy and Shukla, 2000). Thus, the present study has tried to analyse only the interannual variability of the summer monsoon rainfall. The interannual variability of the seasonal monsoon is nonperiodic, and may result from the inherent atmospheric dynamics that is nonlinear. The variability of a nonlinear system can be nonperiodic even if the forcing is constant. This increases the complexity in the prediction of Indian summer monsoon rainfall.

The interannual variability of the monsoon can be further influenced by the slowly varying forcings such as SST, soil moisture, sea ice and snow at the surface (Charney and Shukla 1981). These global boundary forcings can modify the location and intensity of heat sources and circulation such as Hadley and Walker circulations in the tropics. Understanding the influences of these boundary forcings is important to establish the relation between the monsoon variability and other global climate variability. It is also known that the monsoon may have teleconnections with the climate of remote locations such as Africa and the Atlantic Ocean. The strength of the seasonal monsoon in a particular year may depend on the relative contributions from the internal dynamics and external forcings. (Krishnamurthy and Kinter, 2002). The factors responsible for monsoon variability are discussed in the following section. The mechanisms include
internal dynamics, the influences of land and ocean variability and teleconnections to climate variability in other regions.

2.3.1 Influence of Sea Surface Temperature

A substantial fraction of the large-scale rainfall over the Indian region occurs in association with the propagation of synoptic scale systems from the surrounding seas onto the region. Not surprisingly, the variability of the monsoon is linked to facets of the oceans and events in the atmosphere over the oceans. The influences of the world oceans are discussed in the following section.

2.3.1.1 Influence of Indian Ocean

Gradients of SST within the oceans are important in determining the location of precipitation over the monsoon region (Lindzen and Nigam, 1987). As a ballpark figure, it might be supposed that the distribution of SST in the Indian Ocean plays a role in determining monsoon rainfall variability. Shukla (1975) found that the monsoon rainfall over India was significantly reduced with cold SST over the Arabian Sea.

Using a longer SST record over a larger region of the Arabian Sea, Shukla (1987) showed that above-normal (below-normal) monsoon rainfall followed warm (cold) SST anomalies. His analysis obtained a more robust relation that excess (deficient) monsoon rainfall is followed by large negative (positive) SST anomalies in the Arabian Sea with peak values during October-November. In a more recent GCM study, Shukla and Fennessy (1994) showed that the annual cycle of SST in the Indian Ocean plays an important role in establishing the rainfall and circulation over the Indian monsoon region.

Clark et al. (2000) tried to find a long-lead predictive relation between the Indian Ocean SST and the monsoon rainfall. They reported that significant positive correlation (0.53) was found between the winter (DJF) SST in the north Arabian Sea (around 66° E, 20° N) and the subsequent summer (JJAS) monsoon rainfall over India (IMR index). They also found a strong positive correlation (0.87) between the summer monsoon rainfall index and the SST in the central Indian Ocean (around 86° E, 4° N) during the preceding September-November period. Recently, the Indian Ocean Dipole (IOD) phenomenon has been catalogued as another important manifestation of the tropical air-sea interaction.
(Saji et al., 1999; Webster et al., 1999; Behera et al., 1999; Vinayachandran et al., 1999; Murtugudde et al., 2000; Rao et al., 2002; Vinayachandran et al., 2002).

2.3.1.1 IOD – EQUINOX – Monsoon Connections

Indian Ocean Dipole is an ocean-atmosphere coupled phenomenon in the equatorial Indian Ocean, which has come to light in recent years. (Webster et al., 1997; Saji et al., 1999; Murtugudde et al., 2000). IOD occurs in a rather narrow equatorial channel between the eastern equatorial Indian Ocean and equatorial west Arabian Sea, characterized by irregular oscillations of sea-surface temperatures between the two regions. During the positive phase of IOD, lower SSTs are found over the eastern equatorial Indian Ocean as compared to its western counterpart due to the upwelling of cold waters off the eastern Malaysian coast. The negative phase of IOD brings about the opposite conditions. The phenomenon begins to evolve in March-April and peaks in October-November and hence lasts for only 6 months. In some respect it is similar to El-Niño-LaNina variability in the equatorial Pacific Ocean but the amplitude of the SST variations in IOD is much less than in the ENSO. EQUINOX is the atmospheric component of the coupled Indian Ocean Dipole mode (Gadgil et al., 2004). IOD - EQUINOX connections with the SW monsoon has been investigated in several studies and also linked with the amplification of ENSO phenomenon (Ashok et al 2004, Yamagata et al 2003, Annamalai et al 2003, Behra et al 2003, Oh et al 2005 and others). Gadgil et al (2004) have shown that monsoon droughts have much better coherence if the incidence of warm ENSO and EQUINOX occur in phase such that the reduced convection over India due to both phenomena may enhance the effect of large-scale subsidence over main land India. The connections between the ENSO, IOD and Asian Monsoon are very intriguing and Indian researchers may devote more attention to this branch of monsoon research.

2.3.1.2 Influence of Pacific Ocean

Early studies had identified monsoons as a regional physical entity and, naturally, attempts to understand its structure and variability were focused on local effects. As global observations became more readily available to researchers, indications emerged that the monsoon was a macro-scale phenomena
which was intertwined and interactive with other global-scale circulations (Kutzbach, 1987). Out of the many global relationships of the monsoon, the El Niño/ Southern Oscillation (ENSO) – monsoon relationship is one that has been the most investigated, and naturally most favoured for use as a predictor.

El Niño is an anomalous warming of the eastern tropical Pacific Ocean that occurs at 2 to 10 year intervals and is frequently associated with far-reaching climatic and economic impacts around the world. It is typically associated with geographically extensive sea surface temperature anomalies of one standard deviation or more for extended periods of many months to more than a year (Enfield, 1989). On the other hand, the occurrence of unusually cold anomalies in the sea surface temperature in the El Niño region is generally referred to as ‘La Nina’. The southern oscillation is an accentuation of the surface air pressure difference between the tropical eastern and the western Pacific Ocean waters. The strength of this oscillation is measured by the Southern Oscillation Index (SOI). The SOI is computed from fluctuations in the surface air pressure difference between Tahiti and Darwin. In his search for precursors to the Indian monsoon rainfall, Walker (1923, 1924) uncovered a tendency, particularly south of the equator, for a variation in pressure between eastern and western Pacific over a period of years, an alteration he called the Southern Oscillation. However, much later it was established that El Niño and Southern Oscillation are the oceanic and atmospheric manifestations of the same phenomenon (Bjerknes, 1969). The oceanic and atmospheric processes associated with El Niño and the southern oscillation is highly interactive, so that the sea surface temperature and the SOI anomalies reach their peak phases almost simultaneously. Thus the El Niño/Southern Oscillation (ENSO) system has been established, providing a new framework on research on inter-annual climatic fluctuations over large areas in the tropics.

Sikka (1980), and, later Pant and Parthasarathy (1981) and Rasmusson and Carpenter (1982), for the first time associated monsoon droughts over India with warm phase of ENSO. Subsequently several investigators worldwide have worked on the ENSO-monsoon connections.

However, in the recent period, Torrence and Webster (1999) have shown that the El Niño–Southern Oscillation (ENSO) and Indian monsoon have
undergone significant inter-decadal changes in variance and coherency over the last 125 years. Significantly, though, the relationship between ENSO and the monsoon is not stationary and has been rather weak since the mid- to late 1970s.

The weakening of the ENSO- monsoon relationship after the incorrect prediction for 1997 – 98 has led to upsurge of many studies. Krishna Kumar, et al., (1999); Gadgil S. et al., (2005) showed that in addition to ENSO, there exists other meteorological parameters, which has a profound influence on the Indian monsoon system.

2.3.1.3 Influence of Atlantic Ocean

The North Atlantic oscillation (NAO) phenomenon describes the varying strength of two atmospheric pressure systems lying over the subpolar and the subtropical region of the North Atlantic. In general, there is a high pressure system over the subtropical region near the Azores, and a low pressure situation over the subpolar region near Iceland. The variability in the strength of this pressure gradient can be expressed by the NAO Index, which gets positive if the pressure systems are well established and negative when the pressure gradient between them is weaker. The positive phase of the NAO is associated with more and stronger winter storms that enter Eurasia at higher latitudes than normal, producing substantially more snow than normal. While with a weaker winter meridional pressure gradient, western Eurasia experiences fewer and weaker storms from the North Atlantic whose trajectory is more zonally oriented than normal. This results in less than normal snow depth across western Eurasia.

The response of the atmosphere and ocean to the NAO is given in a series of papers by Walker (1924), van Loon and Rogers (1978), Rogers and van Loon (1979) and Meehl and van Loon (1979). Some of the studies have shown that the variations in monsoon rainfall are connected with the widespread and long-lasting changes in the pressure distribution over a large portion of the earth’s surface. Through extensive correlation analysis, Walker (1924), Ramage (1983), and Raman and Maliekal (1983) studied a northern oscillation relating northern hemispheric pressure anomalies with the Indian summer monsoon. Dugam et al. (1996) studied the interannual and long-term variability in the NAO and ISMR and found that the NAO of the preceding year in January has a statistically
significant inverse relationship with the summer monsoon rainfall for the whole of India and Peninsular India.

Recently, Liu and Yanai (2001) suggested that Indian monsoon rainfall is strongly modulated by tropospheric temperature over Eurasia which is, in turn, strongly affected by the North Atlantic Oscillation (NAO). Chang et al. (2001) noted that the relationship between surface air temperature over western Eurasia and the Indian monsoon rainfall has become stronger in recent years, over about the same period that the relationship between the monsoon and ENSO has diminished. They suggested that, as the ENSO-monsoon relationship has weakened, the possibility for the NAO to influence the monsoon through the above mechanism has increased.

It is clear from the above discussion that the monsoon system is governed by both regional as well as global meteorological factors. An evaluation of these factors, along with their changing inter-relationships, is of utmost importance in the recent decade. The following chapters are thus devoted to assess the role played by some of the important regional and global factors in determining the crucial monsoon rainfall over India.