CHAPTER 6

Influence of Moisture over the Northern Indian Ocean on the Climate of Peninsular India

6.1 INTRODUCTION

Joseph and Raman (1966) pointed out the existence of a low-level jet or the Monsoon Low Level Jet stream over peninsular India. The linkage between southwest monsoon wind in the Arabian Sea and India rainfall was studied by Findlater (1969). As expected, large-scale monsoon rainfall accumulation over India and Southeast Asia and wind strength over the Arabian Sea and India are strongly correlated (Ju and Slingo 1995). The cross-equatorial flux entering the Arabian Sea from the southern hemisphere is one of the most important sources of moisture for the Indian subcontinent during the southwest monsoon season. Surface level moisture flux computation showed that the net positive surface-level moisture flux divergence over the Arabian Sea and negative moisture flux divergence over the Bay of Bengal (Kishtawal et al 1991). The evaporation over the Arabian Sea is a variable quantity and forms a significant part of the net moisture budget over the Arabian Sea. The sharp increase between May and June is the combined effect of a sudden increase of the zonal component of the low level wind as well as a sudden increase of atmospheric water vapour over the Arabian Sea during the onset phase of the monsoon (Kishtawal et al 1991). Between April and July, there is a systematic transition of high moisture values from equator to upper latitudes (Kishtawal et al 1994).

During onset of the monsoon over India, the horizontal flux convergence of heat and moisture, as well as diabatic heating, are enhanced over the Arabian
Sea. These subsequently increase with the evolution and advancement of the monsoon over India (Raju et al. 2005). The convection over India is associated with the water vapor amount over the Arabian Sea. The enhancement (suppression) of convection over India during July corresponded to larger (smaller) water vapor amount and to colder (warmer) SST over the Arabian Sea. SST to east of Somalia decrease (increase) with the increase (decrease) of low-level Somali jet. However, the magnitude of SST decrease over the area does not directly correspond to the magnitude of low-level Somali jet (Toshiro, 1997).

The origin and amount of moisture being transported to the Indian subcontinent during the southwest monsoon season was also studied by many investigators. Pisharody (1965) utilizing the data collected during International Indian Ocean Expedition (IIOE), examined the moisture budget and found that evaporation from Arabian Sea to be the main contributor for summer monsoon rainfall. Saba and Baradekar (1973) using additional upper air data concluded that 70% of moisture flux from the south Indian ocean accounts for the bulk of moisture needed for summer monsoon rainfall. The intraseasonal variations of moisture budget have also been examined by several scientists (Ghosh et al. 1978 and Cadet and Reverdin 1981). While the importance of evaporation over the Arabian Sea is suggested by Ghosh et al. (1978) and Murakami et al. (1984), the role of cross equatorial flux has been emphasized by Cadet and Reverdin 1981; Howland and Sikkadar (1983) and Sadburam and Ramesh (1988). Most of these studies suggest that the cross equatorial moisture flux provides an important source of moisture for the Indian Summer Monsoon rainfall though the evaporation from the Arabian Sea is quite significant. The monsoon activity is directly linked to the amount of moisture is transported to the Indian subcontinent during the monsoon period. Active periods of rainfall are characterised by stronger low
level flow directed to Indian subcontinent transporting more moisture in to the Indian subcontinent between latitudes 5°N to 15°N. During break and weak rainfall periods, the low level flow is diverted to equator and hence the moisture is transported south of the Indian peninsula, leading to below normal rainfall over India.

The importance of the Arabian Sea, which acts as a moisture source, and its role in the onset and maintenance of summer monsoon have been studied by Mohanty et al. (1983). Moisture availability and advection by prevailing monsoonal wind are precursors of subsequent rainfalls over the Indian Continent. In a series of studies, Mohanty et al (1983, 1994, 2002) tried to establish the relation of moisture and surface heat budget over the Indian seas to the Indian summer monsoon. It has been found by Cadet and Greco (1987) that the moisture flux entering through the western coast is positively correlated with the coastal rainfall. For June, July, August and September, the amount of moisture crossing the western coast was estimated as (1.5, 2.7, 1.5 and 0.37) × 10^{12} Kg. The volume of water precipitating over the land by estimation from the ISMR normal was (1.95, 3.0, 2.3 and 1.7) × 10^{12} Kg for each of June, July, August and September. This agreement between ISMR and moisture across the continent indicated that a major source of moisture for the ISMR was transported across the western coast (Valsala and Ikeda, 2005). Correlation between the ISMR anomalies and the Arabian Sea moisture convergence anomalies is 0.46, much higher than that between the moisture transport and the moisture convergence (0.25) in their study. The high correlation found between the ISMR and convergence anomaly in the study of Valsala and Ikeda (2003) also indicates that the moisture anomalies arising over the Arabian Sea has a significant contribution to the subsequent rainfall.
A possible reason of the moisture divergence and suppressed convection over the Arabian Sea are speculated to be related to the existence of the high sea level pressure (SLP) anomaly over the Arabian Sea. The usual breaks in ISMR often occur following a propagation of high SLP anomalies from the eastern Indian Ocean to the west as fast moving Rossby waves. From the modeling experiments Krishnan et al (2000) proposed that the life of the high SLP increases as the background westerly winds dominant over the westward propagation of the Rossby waves.

In a diagnosis study of surface wind vector patterns in the Arabian Sea to a degree of great detail, Halpern and W01ceshyn (1999) showed that eastward expansion of the Somali Jet raised the intensity of surface wind convergence and, consequently, increased the amount of integrated cloud liquid water in the eastern Arabian Sea, which, presumably, influence the rainfall of the west coast of India. Shukla (1975) suggested colder SST anomalies over western Arabian Sea tend to reduce monsoon rainfall over India. The important factor in explaining the fluctuations in monsoon circulation and precipitation rate is the air-sea interaction (Saha 1974). SST anomaly may influence Monsoon rainfall through their effects on evaporation and the resultant moisture transport (Meethl 1997; Chang and Li 2000). A large amount of water vapor is carried from over the ocean to the monsoon region by the Asian Summer Monsoon flow. The water vapor transport, therefore, is greatly affected by the monsoon circulation, which in turn has a significant influence on the rainfall in the monsoon region.

The possible effects of the SST anomaly as postulated by several workers (viz. Saha, 1970a, b, 1974) may be qualitatively described as follows: 1) Warmer SST anomalies and stronger winds may cause higher evaporation and the monsoon current may be more moist and unstable. Colder SST anomalies may cause
higher surface pressures and less evaporation over the Arabian Sea and this may reduce the cross-equatorial moisture flux and thus reduce the rainfall over India.

3) Higher pressures over the western Arabian Sea and lower pressures over the eastern Indian Ocean may set up east-west circulation.

Moisture availability and advection by prevailing monsoonal wind are precursors of subsequent rainfalls over the Indian Continent. In a series of studies, Mohanty et al (1983, 1994, 2002) tried to establish the relation of moisture and surface heat budget over the Indian seas to the Indian summer monsoon. A contrast is made on meteorological fields over the Indian seas between the extreme monsoon years (WET vs. DRY) based on monthly reanalysis data sets of the last 42 years (Mohanty et al 2002). They reported a statistically significant region between air sea fluxes and wind over the Arabian Sea in the pre and summer monsoon epochs. For a last few decades, relative contributions of moisture from the Arabian Sea and cross-equatorial flow to the Indian summer monsoon have provided a controversial topic (Hastenrath and Lamb 1980). The importance of the Arabian Sea, which acts as a moisture source, and its role in the onset and maintenance of summer monsoon have been studied by Mohanty et al (1983).

During the summer monsoon epochs, large scale moisture convergence usually occurs below 800 hPa, and moisture turns into clouds above 800 hPa as explored by Mohanty et al (1983). Thus, the surface moisture convergence yields accumulation of water in the low level of the atmosphere.

The physical processes by which the Indian Ocean responds to intraseasonal forcing are the same as those of the Pacific, but differences in the background conditions have a large influence on the oceanic effect. The shape of the Indian Ocean basin has an important effect because it is closed in the northern
subtropics. In the Pacific (or Atlantic) equatorial Kelvin waves reflect along the eastern boundary to coastal signals that propagate poleward; as a result intraseasonal wind forcing is lost to the tropics in those basins. In the Indian Ocean, by contrast, coastal waves are directed into the Bay of Bengal (and from the Bay around the southern tip of India into the Arabian Sea), providing an important source of remote forcing to the off-equatorial tropics originating in equatorial winds (Potemra et al. 1991; McCreary et al. 1993; Schott et al. 1994; Somayajulu et al. 2003; Yu 2003).

From the earlier studies it has been shown that the role of moisture, surface temperature and the geographic coastal boundaries of the northern Indian Ocean in modulating the climate of the Indian region during monsoon. This necessitates investigating the role of Arabian Sea rather the remotely brought moisture in distributing and modulating the climatic features over Indian Region.

In this study, a regional climate model RegCM3 has been used to study how the water vapour flux through the southern and western boundaries (as defined in the following section) to the Arabian Sea affects the climate of Peninsular India. The moisture through the western and southern boundary of the model domain were shut down in two different sensitivity experiments while keeping the evaporative flux from the Arabian Sea surface unaltered. Thus the difference in the control experiment and sensitivity experiments give an indication whether the moisture flux from the Arabian Sea surface can compensate, to an extend, the moisture reduction in the monsoon flow through lateral boundaries at the south and west. The parameters such as Vertically integrated moisture, moisture transport, precipitation and surface air temperature, which is having a direct
effect from moisture in the atmosphere has been studied for three contrasting years.

6.2 MODEL DESCRIPTIONS

The Regional Climate Model RegCM3 used in the present study is originally developed by Giorgi et al. (1993 a, b) and then augmented and described by Giorgi and Mearns (1999) and Pal et al. (2000). The model includes cumulus parameterization schemes, large-scale precipitation scheme, planetary boundary layer (PBL) parameterization, surface vegetation soil hydrology package, the Biosphere-Atmosphere Transfer Scheme (BATS), Ocean flux parameterization, pressure gradient scheme, explicit moisture scheme, the radiative transfer scheme and the ocean-atmosphere flux scheme.

The model was set up as in the previous chapter. So details are not mentioned in this section.

![Fig. 6.1 the model domain for the experiment and control run.](image)
6.3 OBJECTIVES

During the period of the Asian summer monsoon (ASM), a large amount of water vapor is brought to the Asian continent by the monsoonal flows. However, the origin of the water vapor carried by the streams is uncertain, and there are two possible kinds of source. One is the contribution from some distant sources outside the monsoon region due to the large-scale flows. Some literature (Li 1999; Ding 2004) suggest that the water vapor source of the ASM is in the oceanic regions of the Southern Hemisphere or the Arabian Sea, as most of the monsoon region in summer is a moisture sink (i.e., evaporation is less than precipitation). The second kind of water vapor source is the evaporation of water vapor when the low-level monsoonal flows pass over the oceans.

The objective of this study is to determine whether the monsoon rainfall over India during boreal summer is mainly associated with the distant sources due to the long-distance transport of water vapor by the low-level monsoonal streams, or with the water vapor provided by the adjacent oceans.
6.4 DATA AND METHODOLOGY

In this study, RegCM3 has been used for simulating the Indian summer monsoon circulation and associated rainfall for three characteristic years with and without moisture advection through the Western and Southern boundaries of the model domain. The lateral boundary conditions for wind, temperature, surface pressure and water vapor are interpolated from 6 hourly NCEP reanalysis. The terrain height and land-use data for the given domain are generated from the United States Geographical Survey (USGS) global 5 min resolution terrain and land-use data. The original weekly averaged optimum interpolated Sea Surface Temperature (OISST) available from the National Oceanic and Atmospheric Administration (NOAA) for the whole year is horizontally interpolated into the specified domain and also in each time step for the model integration. The model domain covers the area approximately 50° E to 110° E and 5° S to 40° N with a horizontal grid distance of 60 km. The grid is defined on a Normal Mercator Projection. The CONTROL Run results are compared with GPCP precipitation and NCEP winds (shown in the previous chapter; Fig. 5.3 & 5.4). The difference in wind vectors and precipitation for the CONTROL Run and the Experiments (EXP_WB-CTL and EXP_SB-CTL) are analyzed to get a spatial perspective of the results. In this study, a control simulation is made over the domain and topography as shown in Fig. 6.1 & 6.2

6.4.1 CONTROL EXPERIMENT
In the control Run the model was integrated for five months from May to September for three years 1996, 1997 and 2002, which are considered as the three recent typical years designated as wet, normal and dry for peninsular Indian rainfall. The lateral boundary conditions are updated and supplied every 6 hours into the model and the time step of the integration has been kept at 150 seconds. The model resolution is 60 km.

6.4.2 SENSITIVITY EXPERIMENT

In this study we design the sensitivity experiments such that the moisture advection through the lateral boundaries through which the monsoon flow fetches moisture to the subcontinent are cut down for successive experiments. Since during the summer monsoon season, the zonal flow is southwesterly, moisture advection through south and west lateral boundaries of the model domain are closed for different experiments. They are termed as EXP-SB and EXP-WB respectively. In the third experiment the moisture through West, East and South boundaries were shut down (EXP-AB). Despite letting moisture though the boundary, the values at the model domain boundary are relaxed through a buffer zone of eight model grids. All the experiments are conducted for three years. The model is integrated from May to September for each of these experiments. The first month is taken as the spin up time for the model. The rest four months averaged to get the seasonal averaged values of Vertically Integrated moisture, precipitation and air temperature.

6.5 RESULTS

Fig. 6.3a indicates while shutting down the moisture over the southern boundary, that the vertically integrated moisture over peninsular India still increases. This means that the Arabian Sea acts as a source region for the
moisture. But while the western boundary has been closed, there is a decrease in the total column moisture over the entire peninsular India and Arabian Sea. But over Bay of Bengal, the compensation of moisture by evaporation is higher in both the experiments. The anomaly of peninsular Indian and west coastal precipitation for the EXP-SB is positive (Fig. 6.4a). But for EXP-WB, there is a large decrease in the western coastal region and Arabian Sea (Fig. 6.4b). Similarly the southeastern coastal region and Bay of Bengal also experiences a reduction in the precipitation. The rainfall which has an orographic component over the west coast of India suffers a reduction when the western boundary moisture has been shut down. For the EXP-AB, similar results are observed for moisture except a redistribution of the anomalies over the Bay of Bengal.

Fig. 6.5. shows the surface air temperature difference for the three experiments for the year 1996. The air temperature over the landmass has been reduced for EXP-SB, while for EXP-WB the air temperature over the pathway over the Indian subcontinent has reduced. Similarly for EXP-AB also there is a sharp decrease (1.5°C) in the temperature over Peninsular India and Bay of Bengal.
Fig. 6.3. The difference (EXP-CTRL) in the vertically integrated moisture seasonally averaged for June to September 1996 for (a) EXP-SB, (b) EXP-WB and (c) EXP-AB

Fig. 6.4. Difference (EXP-CTRL) in the seasonal mean precipitation (mm/day) for June to September 1996 for (a) EXP-SB, (b) EXP-WB and (c) EXP-AB
Fig. 6.5. Difference (EXP-CTRL) in the seasonal mean surface temperature for June to September 1996 for (a) EXP-SB, (b) EXP-WB and (c) EXP-AB.

Fig. 6.6. The difference (EXP-CTRL) in the vertically integrated moisture seasonally averaged for June to September 1997 for (a) EXP-SB, (b) EXP-WB and (c) EXP-AB.
As in the case of 1996, for 1997 also shows increase of Total Column moisture for EXP-SB (Fig. 6.6). A supporting feature could also be seen in precipitation (Fig. 6.7a, 6.7b and 6.7c). Though there is spatially a large reduction in precipitation, the southern Peninsular India south of 12° N experiences an increased rainfall in the two experiments. This has an implication that the southern peninsular India is fed significantly by the moisture flux over the Arabian Sea and Bay of Bengal. A reduction in the moisture field is associated with more evaporation from the Oceanic region in the experiment domain and eventually a decrease in the surface air temperature (Fig. 6.8). In the three experiments conducted for the year 2002, the vertically integrated moisture is having similar patterns as that of the other years, with an increase in the moisture over peninsular Indian region for the EXP-SB (Fig. 6.9a) and increase over Bay of Bengal and adjoining coastal regions for EXP-WB and EXP-AB (Fig. 6.9b and 6.9c). But the excess in the peninsular Indian rainfall has decreased over western coast and oceanic region (Fig. 6.10). A simultaneous reduction in the air temperature also is noted (Fig. 6.11).

The vertically integrated moisture transport has also been analysed for the three years. In all the three cases, the western boundary experiment and southern boundary experiment showed divergent anomalies over peninsular India and the western coastal region. For the EXP-AB, the anomalies are even stronger and the convergent pattern over Bay of Bengal and Arabian Sea has weakened too. Over the southern Peninsular India, for the EXP-AB, weak anomalies shows that the moisture transport over this region is compensated by evaporative moisture from the adjacent oceanic regions (Fig. 6.12c). The main difference in these three sets of experiments is that the EXP-WB and EXP-AB moisture transport anomaly vectors with almost double the magnitude than the southern
Fig. 6.7. Difference (EXP-CTRL) in the seasonal mean precipitation (mm/day) for June to September 1997 for (a) EXP-SB, (b) EXP-WB and (c) EXP-AB

Fig. 6.8. Difference (EXP-CTRL) in the seasonal mean surface temperature for June to September 1997 for (a) EXP-SB, (b) EXP-WB and (c) EXP-AB
Fig. 6.9. The difference (EXP-CTRL) in the vertically integrated moisture seasonally averaged for June to September 2002 for (a) EXP-SB, (b) EXP-WB and (c) EXP-AB

Fig. 6.10. Difference (EXP-CTRL) in the seasonal mean precipitation (mm/day) for June to September 2002 for (a) EXP-SB and (b) EXP-WB and (c) EXP-AB
Fig. 6.11. Difference (EXP-CTRL) in the seasonal mean surface temperature for June to September 2002 for (a) EXP-SB, (b) EXP-WB and (c) EXP-AB.

Fig. 6.12. Difference (EXP-CTRL) in the horizontal moisture transport for June to September 1996 for (a) EXP-SB, (b) EXP-WB and (c) EXP-AB.
Fig. 6.13. Difference (EXP-CTRL) in the horizontal moisture transport for June to September 1997 for (a) EXP-SB, (b) EXP-WB and (c) EXP-AB.

Fig. 6.14. Difference (EXP-CTRL) in the horizontal moisture transport for June to September 2002 for (a) EXP-SB, (b) EXP-WB and (c) EXP-AB.
boundary experiment (Fig. 6.12-6.14). Another feature that is to be pointed out from the analysis is that over the southern peninsular India, the moisture transport anomalies are relatively low. The moisture divergent anomalies over the western coastal and Arabian Sea region are marked with highly reduced values of precipitation, especially in the EXP-WB and EXP-AB.

In order to analyze the intraseasonal variations in the precipitation due to this experiments, longitudinally averaged (70-85° E) precipitation for the monsoon
season is represented in Hovmöller plots (Fig. 6.15-6.17). There is a clear indication that the intraseasonal variation in the peninsular Indian rainfall is sensitive to the moisture advection through the western and southern boundary of the model domain. The analysis shows that for a WET year 1996, the reduced moisture in all the experiments has redefined the spatial (meridional) and intraseasonal distributions in the rainfall over peninsular India during active months (June and July, see Fig. 6.15). For the EXP-AB, for the WET year 1996, the southern peninsular rainfall has increased (6.15d) while for the normal and DRY years the precipitation has decreased (Fig. 6.16d and 6.17d).

For normal year 1997, the distribution of rainfall has not varied much in time or region, but obviously the amount has decreased considerably. Here also, during June and July, there is a sharp decrease in the precipitation. For the year 2002 which is typically a dry year, the western boundary experiment shows a large decrease in the precipitation during the first half of the season (Fig. 6.15 and 6.17). This has an implication that during the first half of the monsoon season (during June and July), the rainfall depends heavily on the moisture advected through the boundaries of the domain and later depends on local moisture sources from the adjacent oceanic regions.
Fig. 6.16. The Hovmöller diagrams of daily Precipitation longitudinally averaged for 70°-85°E for a period of June to September 1997 for (a) Control Run, (b) EXP-SB, (c) EXP-WB and (d) EXP-AB.
Fig. 6.17. The Hovmöller diagrams of daily Precipitation longitudinally averaged for 70°-85°F; for a period of June to September 2002 for (a) Control Run, (b) EXP-SB, (c) EXP-WB and (d) EXP-AB.

6.5 CONCLUSION

In the study using the Regional Climate model RegCM3, the effect of absence of moisture in the low-level monsoon flow through the western and southern lateral boundary of the model domain on the Vertically Integrated moisture, precipitation, surface air temperature and integrated moisture transport are
studied. The southern boundary experiment EXP_SB showed that when the moisture influx to the domain through the southern boundary was shut down, still there is an increase in the vertically integrated moisture over the peninsular India for the wet year 1996, normal year 1997 and dry year 2002. But for the western boundary experiment, EXP_WB, the integrated moisture has substantially reduced implying that the total column moisture is mainly fed by the western boundary stream rather the compensation by evaporation from the Arabian Sea or the meridional transport through the southern boundary. The greatest decrease in moisture fields is for the wet year 1996 and the lowest change is for the dry year. There is sharp decrease in moisture over the Arabian Sea also. For precipitation also greatest decrease is seen for the wet year. Over the Western Ghats and the Adjoining Arabian Sea there is negative anomaly for precipitation for all the three years. Surface temperature anomaly patterns observe a decrease in temperature where the moisture was anomalously low. This could be due to the fact that the dry air allows for greater evaporation and thus facilitating cooling in surface temperature. The Vertically Integrated moisture transport anomaly vectors for EXP_WB are double the order of magnitude larger than the EXP_SB implying a more significant role of moisture through western Arabian Sea than moisture advected meridionally through southern boundary.

The intraseasonal variability in the zonally averaged precipitation over Peninsular India shows that the precipitation pattern and its distribution in time have been mostly modified for the wet year. In all the experiments the EXP_WB showed reduction in precipitation for the first half of the season owing to the reduced moisture.