Anomalous behaviour of the Indian summer monsoon 2009

B Preethi*, J V Revadekar and R H Kripalani

Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pune 411 008, India.
**Corresponding author. e-mail: preethi@tropmet.res.in*

The Indian subcontinent witnessed a severe monsoon drought in the year 2009. India as a whole received 77% of its long period average during summer monsoon season (1 June to 30 September) of 2009, which is the third highest deficient all India monsoon season rainfall year during the period 1901–2009. Therefore, an attempt is made in this paper to study the characteristic features of summer monsoon rainfall of 2009 over the country and to investigate some of the possible causes behind the anomalous behaviour of the monsoon.

Presence of El Niño like conditions in the Pacific and warming over the equatorial Indian Ocean altered the circulation patterns and produced an anomalous low level convergence and ascending motion over the Indian Ocean region and large scale subsidence over the Indian landmass. Furthermore, the cross-equatorial flow was weak, the monsoon was dominated by the slower 30–60 day mode, and the synoptic systems, which formed over the Bay of Bengal and the Arabian Sea, did not move inland. All the above features resulted in less moisture supply over the Indian landmass, resulting in subdued rainfall activity leading to a severe monsoon drought during 2009.

1. Introduction

India is a tropical country dominated by the monsoons, with the annual march of climate punctuated by the winter, pre-monsoon, monsoon and post-monsoon seasons. India's climate is mainly affected by summer or southwest monsoon season (1 June to 30 September). It accounts for about 75–90% of the annual rainfall for most parts of India (Parthasarathy *et al* 1987). Though all the monsoons have some common characteristic features, each monsoon is unique in nature. The summer monsoon rainfall over India exhibits large inter-annual variability, some years with excess rainfall and some years with a large deficiency in rainfall throughout the country. The inter-annual variability of the Indian summer monsoon rainfall has profound impact on agricultural production, economy and human lives (Parthasarathy and Pant 1985; Parthasarathy *et al* 1992; Gadgil *et al* 1999). Recently, the Indian subcontinent witnessed a severe monsoon drought during the year 2009. India as a whole received 77% of its long period average during summer monsoon season of 2009, which is the third highest deficient all India monsoon rainfall year during the period 1901–2009.

The spatial and temporal variation of Indian summer monsoon rainfall (ISMR) is linked to the internal dynamics associated with intra-seasonal oscillations and also to the external factors like air–sea interaction processes in the equatorial Pacific (El Niño Southern Oscillation, ENSO), processes in the Indian Ocean (Indian Ocean Dipole mode), changes in Eurasian snow cover, north Atlantic oscillation, etc. The two oscillations such as northward propagation of the inter-tropical convergence zone (ITCZ) or zonally oriented belt of precipitation from its equatorial position to continental

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position (Sikka and Gadgil 1980) with a periodicity of 30–60 days and the westward propagation of synoptic scale convective systems that originates over the warm waters of Bay of Bengal (Gadgil 2000), with a periodicity of 10–20 days contributes equally to the intra-seasonal active and break cycles of the monsoon rainfall. Heavy rainfall events are generally associated with cyclonic disturbances such as depressions or cyclonic storms moving across the country. These disturbances form over the warm waters surrounding the country and are usually having a life period of about 3–4 days. Active phase of monsoon is characterized by the clustering of the low pressure systems over the warm waters surrounded by the subcontinent whereas relatively very few systems form during the break phase. Studies reveal that the strength of monsoon activity has inverse (direct) relationship with slower 30–60 (faster 10–20) day mode (e.g., Kripalani *et al* 2004 and references therein).

Numerous studies have shown that the warm phase of ENSO (El Niño) is associated with weakening of the Indian monsoon with a reduction in rainfall, while the cold phase (La Niña) is associated with strengthening of the monsoon and enhancement of rainfall (Sikka 1980; Rasmussen and Carpenter 1983). Although the El Niño related droughts were severe, India has experienced an equal number of droughts and floods which are not related to ENSO (Kripalani and Kulkarni 1996, 1999). The air–sea interaction process in the Indian Ocean also plays an important role as a modulator of the Indian monsoon rainfall and also influences the relationship between the ISMR and ENSO (Behera *et al* 1999; Saji *et al* 1999; Ashok *et al* 2001; Gadgil *et al* 2003, 2004). The presence of positive Indian Ocean Dipole (IOD) mode during the years 1994 and 1997 reduced the impact of ENSO on ISMR (Ashok *et al* 2001). Studying the individual and combined effect of EQUINOO (Equatorial Indian Ocean Oscillation, the atmospheric component of IOD) and ENSO, Gadgil *et al* (2004) established that large deficit or excess in ISMR occurs when the amplitude of these two modes are large and they act in phase and reinforce one another.

Processes happening in upper tropospheric and mid-latitude regions can also affect the monsoon. The tropical easterly jet (TEJ) having its core near 15°N latitude located around 150–200 hPa and the formation of Tibetan anticyclone in the upper troposphere (Krishnamurti 1973) are characteristic features of summer monsoon season (Koteswaram 1958). Tibetan Plateau acts as an elevated heat source that maintains the upper-tropospheric anticyclone during the summer monsoon (Koteswaram 1958; Krishnamurti 1973; Yanai and Wu 2006). Association of Indian summer monsoon with the northern hemisphere mid-latitudes has been studied by several researchers (Joseph 1976a, 1976b; Kripalani *et al* 1997; Krishnan *et al* 2009). Greater equatorward penetration of upper troposphere westerlies from the northern hemisphere mid-latitudes over India is favourable for large scale failure of the monsoon (Joseph 1976a, 1976b). Intrusion of large-amplitude westerly troughs from mid-latitudes to Indo-Pakistan region in the middle and upper troposphere influences monsoon breaks (Ramaswamy 1962). Understanding the internal dynamics of monsoon–midlatitude interactions revealed that the sustenance of monsoon breaks through monsoon mid-latitude feedbacks can generate drought like conditions over India (Krishnan *et al* 2009). Studying the linkage of monsoon 2002 drought with the convective activity over northwest Pacific, Mujumdar *et al* (2007) reported that the ENSO induced circulation response produced an anomalous pattern comprising of alternating highs and lows which extend meridionally from the equatorial region into the sub-tropic and mid-latitude regions of west-central Pacific. This meridional pattern which is associated with anomalous circulation pattern over NW Pacific induced subsidence and rainfall deficiency over Indian landmass through anomalous east-west circulation. These studies show that the dependence of monsoon rainfall on the internal dynamics and the external forcings is complex. The complexity of monsoon makes it difficult to predict.

Most of the state-of-the-art models of the atmosphere or the coupled atmosphere–ocean system failed to predict the deficit rainfall over the Indian region in June–July–August (JJA) 2009 (Nanjundiah 2009). Examination of skill of six general circulation models in simulating 2009 monsoon shows that neither the models simulate the observed interannual variability nor their multi-model ensemble significantly improves the skill of monsoon rainfall predictions (Acharya *et al* 2011). Also, except for one model, the real-time predictions with longer lead (2- and 1-month lead) made for the 2009 monsoon season did not provide any indication of a highly anomalous monsoon. But, with less lead time (zero lead), most of the models as well as the multi-model ensemble had provided estimation of below normal rainfall for the monsoon season (Acharya *et al* 2011). The inability of the accurate prediction of monsoon using recent general circulation models point towards further improvements of the models and also better understanding of the forcing mechanisms which causes the failure of monsoon.

The massive deficit in Indian summer monsoon rainfall of 2009 have been studied by Francis and Gadgil (2009, 2010). Their study (Francis and Gadgil 2009, 2010) suggested that in addition to the unfavourable phase of ENSO and EQUINOO, reversal of SST gradient between Bay of Bengal and eastern equatorial Indian Ocean (with warmer sea surface temperatures over eastern equatorial Indian Ocean (EEIO) than the Bay) played a critical role in the aberrant behaviour of rainfall during June. The revival of monsoon during July 2009 was due to the positive phase of EQUINOO which occurred due to suppression of convection over EEIO in association with the El Niño (Francis and Gadgil 2010). They attributed the large deficit in rainfall during August and the associated negative phase of EQUINOO to El Niño (Francis and Gadgil 2010). To understand the teleconnections associated with the abnormal El Niño like conditions during 2009 with warm sea surface temperature anomalies throughout the tropical Pacific and subtropical north-west Pacific, Ratnam *et al* (2010) carried out sensitivity experiments and demonstrated that the warming in the central Pacific modified the regional Walker circulation over the tropical and subtropical Pacific to cause subsidence over the Indian subcontinent. Recent study by Neena *et al* (2011) reveals that the two long breaks, which made the 2009 monsoon a drought, was primarily driven by internal dynamics processes, the interaction between monsoon intraseasonal oscillation (MISO) and the westward propagating connectively coupled planetary scale equatorial Rossby wave (PSER), in the atmosphere. The arrival of the divergent phase of PSER mode over the Indian domain reinforced and extended the break condition initiated by the northward propagating MISO and created the long break of July–August 2009 (Neena *et al* 2011). Another factor for the dry spells during 2009 monsoon was the intrusion of western Asian desert air towards central India and the formation of a blocking high over western Asia, which advects descending very dry air towards central India (Krishnamurti *et al* 2010). In addition to these studies, India Meteorological Department published a detailed report on the synoptic conditions of monsoon 2009 and also the circulation, thermal and convective features associated with the monsoon to understand the possible reasons for the deficit monsoon rainfall (Pai and Sreejith 2010). They attributed the deficiency of rainfall in June to the formation of severe cyclonic storm (*Aila*) over Bay of Bengal, the incursion of dry and cold midlatitude air to Indian region and also to the weak cross equatorial flow. The large rainfall deficiency in August was attributed to the active oceanic convergence zone along with the basin wide warming of Indian Ocean with maximum along equator and the deficiency during September is attributed to the influence of moderate El Niño that evolved during the later part of the monsoon season. Most of the analysis done by Pai and Sreejith (2010) used outgoing long wave radiation (OLR) data as a proxy for convection. However, the present analysis is based on actual rainfall data. Moreover, additional analysis are required using the rainfall data to find out the propagation characteristics and dominant periodicities persisted during the monsoon period. These are examined with the help of wavelet analysis and Hovmoller diagram. Therefore, in this study, an attempt is made to document some additional possible causes for its failure.

2. Data and methodology

2.1 *Rainfall data*

India is divided into 36 meteorological subdivisions and 6 homogeneous monsoon regions based on the rainfall characteristics. Spatial extent of these meteorological subdivisions and homogeneous monsoon regions can be obtained from the website of Indian Institute of Tropical Meteorology, Pune (www.tropmet.res.in). IMD publishes weekly mean rainfall data and long-term mean rainfall for the corresponding week for all the 36 meteorological subdivisions of India. Basic rainfall characteristics of Indian summer monsoon rainfall during 2009 are studied using the weekly mean rainfall data for the 36 meteorological subdivisions of India, published in the *Weekly Weather Reports* issued by IMD. Rainfall anomalies are computed for each subdivision for all the monsoon weeks in terms of percentage departures from the long-term mean for the corresponding week of that particular subdivision. All-India area-weighted index for the summer monsoon rainfall activity over the Indian region is computed weekly.

In addition to the weekly subdivisional rainfall data, daily data for 53 stations are available from all-India weather summary published by IMD. The 53 stations cover all land area of the country. Broadly the eastern and the northern parts are covered by 13 well distributed stations each, and the south peninsular region is covered by 18 stations. Remaining small area over central India is represented by six stations. There are three stations over the Indian Islands. Location of the stations is shown in figure 1. Though the data is available only for 53 stations, the network of these stations are well distributed over the Indian region and the data is consistently available for the entire monsoon period. Present study utilizes the daily rainfall data for the period from 1 June to 30 September 2009. Kripalani *et al* (2004) used data for these stations to study the intra-seasonal oscillations during monsoon 2002 and 2003. To examine a few characteristics such as their propagation, the station data are first gridded to resolution of

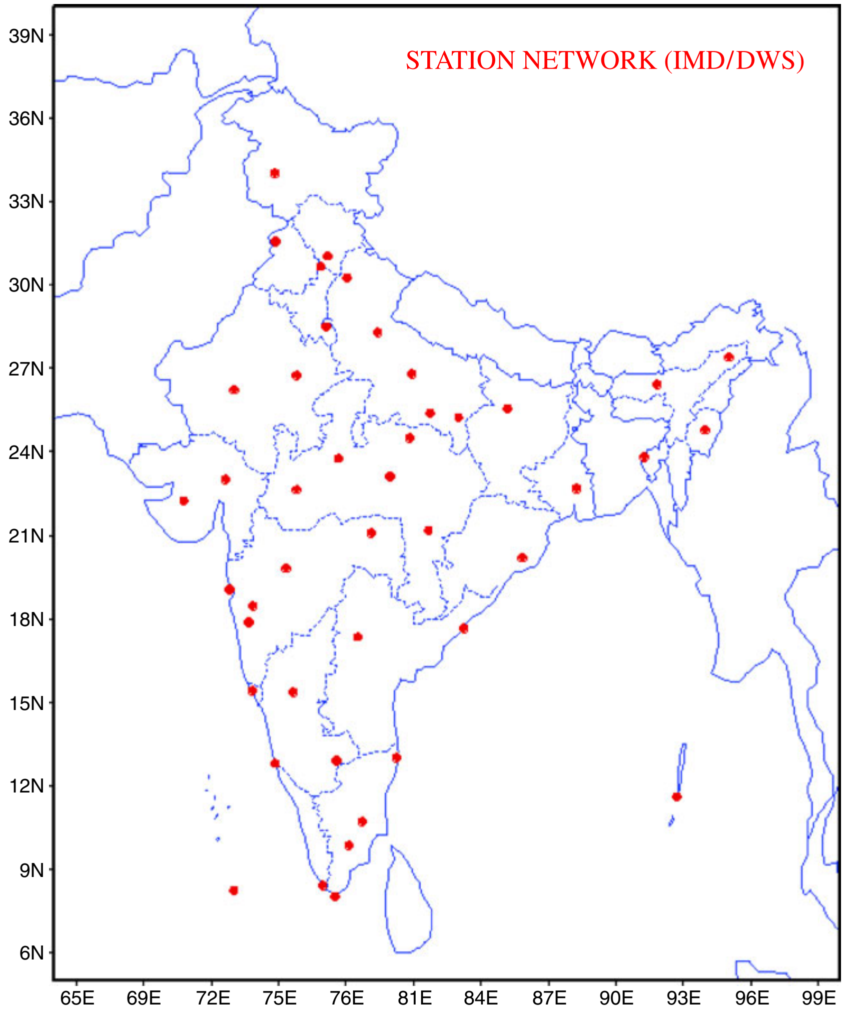

Figure 1. Dots representing the location of the stations for daily rainfall data.

1.0×1.0 (long. × lat.) using inverse square distance method. Comparison of the gridded data with CPC (Climate Prediction Center, USA) high resolution daily rainfall datasets, which show strong correlations with IMD daily rainfall dataset (Preethi *et al* 2011), reveals that the network of these stations are sufficient to capture the daily rainfall fluctuations.

2.2 *Data for other meteorological parameters*

The present study also utilizes the extended reconstructed monthly sea surface temperature (ERSST) from National Ocean Atmosphere Administration (NOAA) at a resolution of 2°×2° (Smith *et al* 2007), and National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset (Kalnay *et al* 1996) for the monsoon months (June to September) for understanding the anomalous features during the summer monsoon drought of 2009.

3. Characteristic features of summer monsoon rainfall 2009

3.1 *Spatial distribution*

The spatial distribution of summer monsoon rainfall over the Indian region based on the IMD subdivisional rainfall data for the year 2009, the long period average (LPA), the percentage departure of 2009 rainfall from LPA are displayed in figure 2. The summer monsoon rainfall exhibits large spatial variability over the Indian region (figure 2a and b). Negative percentage departures from LPA over large parts of the country are clearly visible during the monsoon period over central and northern parts (figure 2c). Out of the 36 meteorological subdivisions, 22 subdivisions received deficient rainfall (less than −19%, as per IMD criteria), 11 subdivisions, in particular over the southern parts experienced normal rainfall (rainfall within ±19%), only three subdivisions – Saurashtra and

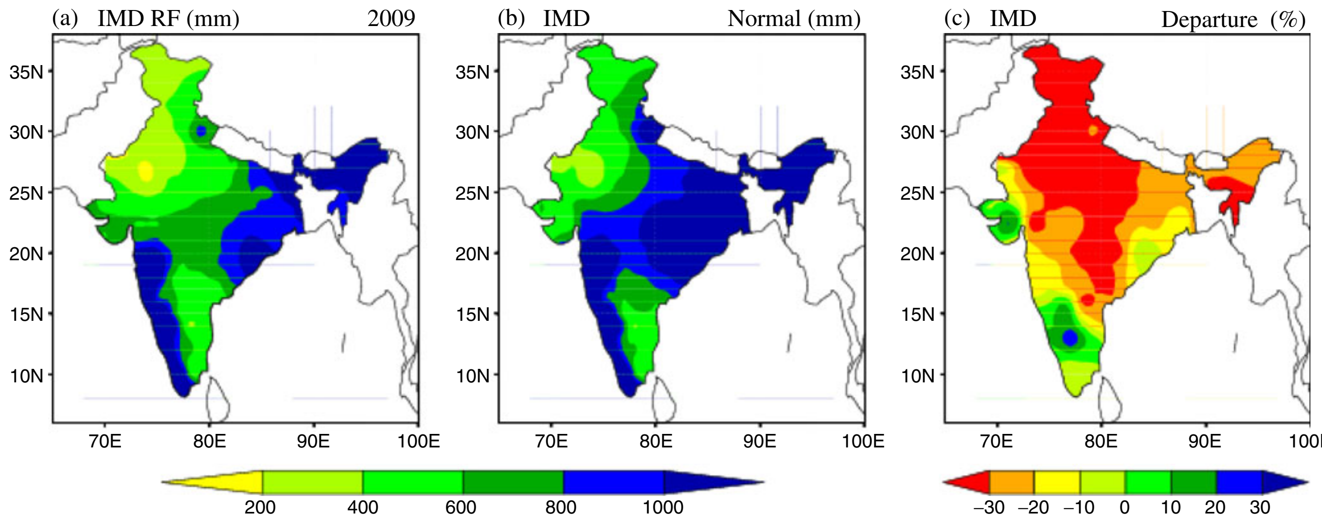

Figure 2. Spatial distribution of summer monsoon rainfall during 2009.

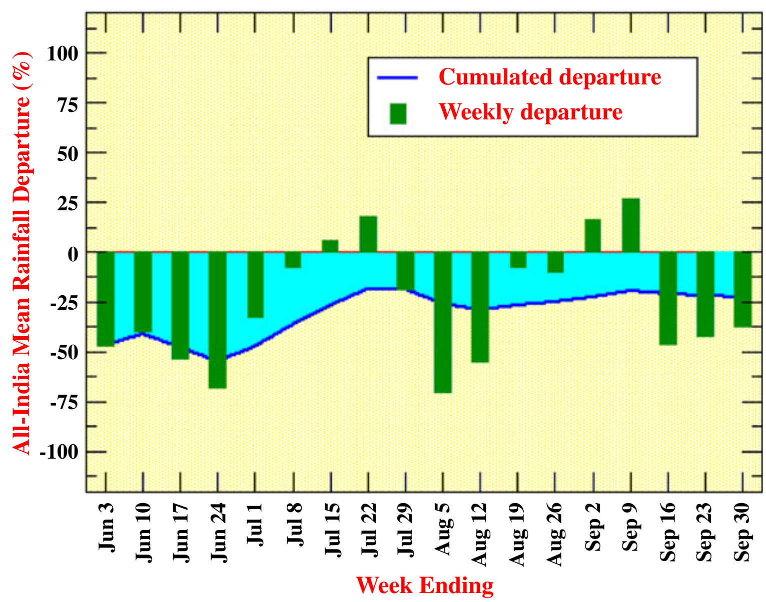

Figure 3. Temporal distribution of the weekly summer monsoon rainfall during 2009 as percentage departure from normal.

Kutch, north interior Karnataka and south interior Karnataka – received rainfall in excess (greater than 19%). Highest negative anomalies of magnitude more than 40% are observed over the two subdivisions namely west Uttar Pradesh and west Rajasthan. Adjoining subdivisions also show negative anomalies of magnitude ranging from 33% to 38%. However, no subdivision shows scanty or no rain category (less than −60% departure).

Anomalous negative percentage departures over northern parts of India can be partly due to internal dynamics and partly due to external forcing mechanisms which prevent the monsoon to be active over the region. Hence, the northward and westward propagation of convective systems, the changes in circulation pattern and the processes occurring in the mid-latitude regions have also been examined to understand the abnormal behaviour of the monsoon.

3.2 *Temporal distribution*

Considering the rainfall activity over India as a whole, out of 18 weeks during the monsoon season, all the weeks during June experienced subdued rainfall, however during July rainfall activity was near normal (figure 3). In August also, all the weeks show negative anomalies, but for the last two weeks of August, the magnitudes of negative anomalies reduced substantially and became positive in the first week of September. Finally monsoon ended with much below normal rainfall activity. In general, out of the four monsoon months, rainfall activity during three months (June, August and September) was subdued. During July, the rainfall activity was near normal (figure 3).

To further examine the dominant periodicities during the monsoon 2009, all-India daily rainfall time series has been subjected to wavelet analysis (computational procedure available on the website http://ion.researchsystems.com/IONScript/wavelet/). Wavelet spectrum determined from the daily rainfall time series for monsoon 2009 is presented in figure 4. The figure indicates that the 30–60 day mode dominates during the monsoon season, especially during mid-June to first week of September. However, oscillations with 4–8 day periodicity show a maximum variance during July and in first week of September when the rainfall anomalies were above normal, indicating that the rainfall activity during these episodes is associated with the faster mode of variability. This is in agreement with earlier studies that the strength of monsoon activity has inverse (direct) relationship with slower 30–60 (faster 10–20) day mode (Kripalani *et al* 2004). Examining intra-seasonal oscillations during a drought and normal year, Kripalani *et al* (2004) have shown that slower 30–60 day mode was dominant during the drought year while faster 10–20 day mode was dominant during the normal year over the Indian subcontinent. These 30–60 day modes are associated with northward moving convective anomalies from the equatorial Indian Ocean region to the Indian landmass. These features are examined further.

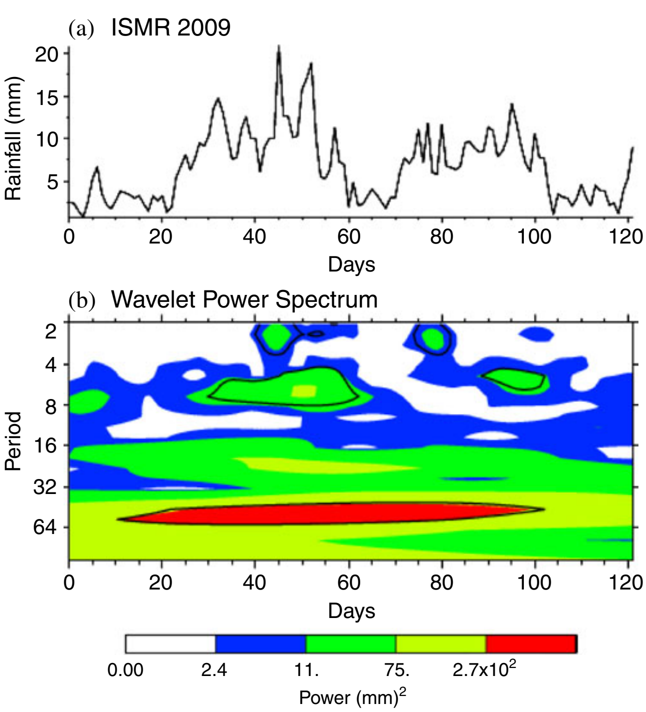

Figure 4. Wavelet spectrum (lower panel) computed from all-India daily rainfall data for monsoon 2009 (upper panel). X-axis denotes days from 1 June to 30 September 2009. In the lower panel, Y-axis denotes periodicity in days.

3.3 *Meridional propagation*

To examine the south-to-north progressions of summer monsoon rainfall, time-latitude sections based on the IMD rainfall data over the Indian longitudes 70°–80°E are depicted in figure 5. Weak northward propagations are observed during June and after mid-August. During July, two standing oscillations can be observed. During first half of July, precipitation occurs between the latitude belt of 10°N and 15°N, thereafter during second half of July, precipitation belt has jumped to 15°N to 20°N.

4. Possible causes for anomalous features

Northward propagation of convection from equatorial Indian Ocean is the manifestation of 30–60 day oscillation. Associated with northward propagation of rainfall (figure 5), cooling is evidenced from the time-latitude section of maximum temperature anomalies (figure not shown). The maximum and minimum temperatures were above normal during most of the days during the season, due to the occurrence of low rainfall activity. The maximum temperature anomalies were generally positive throughout the season except during the periods of increased rainfall activity. Over the landmass of the continent, the relative humidity values are lower than the climatological values and the lack of moisture supply is clearly evidenced (figure not shown), supporting the information available in figure 5.

4.1 *Low pressure systems and depressions*

During the monsoon season, cyclonic disturbances such as depressions and low pressure areas form over the warm waters surrounding the Indian subcontinent. These cyclonic disturbances move inland across the country and provides plenty of rainfall. The frequency of monsoon low pressure systems was much lower than normal during the monsoon 2009. Only four depressions formed during the season, in comparison to normal situation of two systems in average per month, and four low pressure areas formed during the season (source: IMD website: www.imd.gov.in). Out of the four depressions, two were formed over Arabian

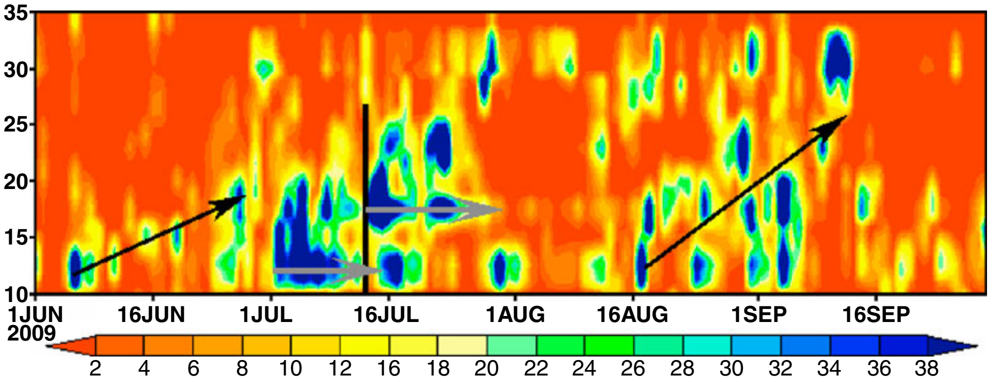

Figure 5. Time (X-axis)-latitude (Y-axis) sections of daily rainfall data averaged over the longitude belt 70°–80°E for monsoon 2009.

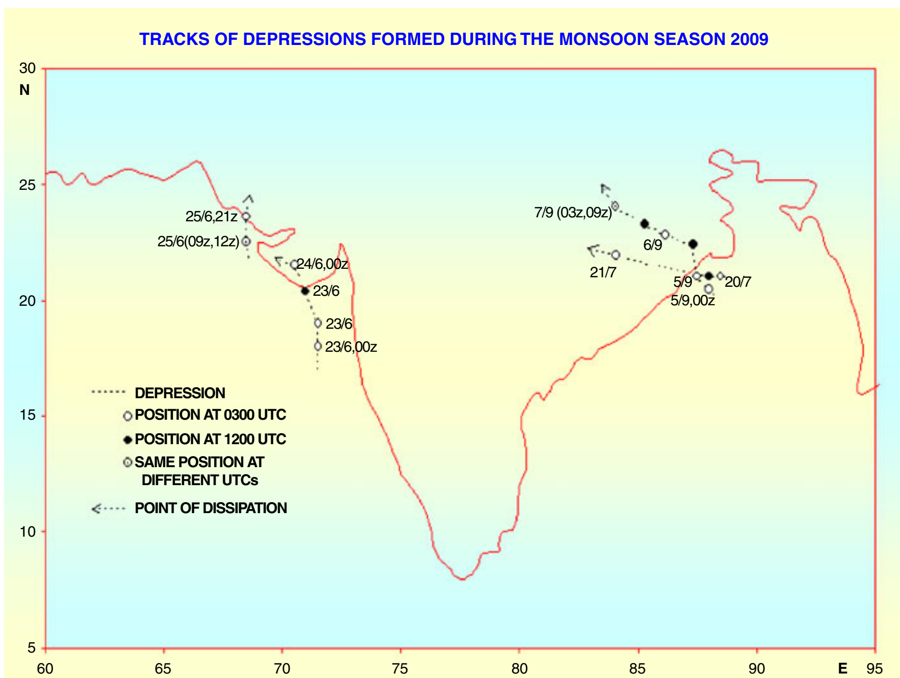

Figure 6. Track of depressions formed during the monsoon 2009 (source: India Meteorological Department, website: www.imd.gov.in).

Sea and two were formed over Bay of Bengal (figure 6). Over Arabian Sea, both the systems formed towards the end of June (23–24 June and 25–26 June). Over Bay of Bengal one depression formed during July (20–21 July) and one during September (5–7 September). However, it can be seen that all the four systems have a short track over the land and dissipated within two days of its landfall (figure 6).

A severe cyclonic storm (*Aila*) formed over the Bay of Bengal on 23rd May, subsequent to the onset of monsoon over Kerala. This might have altered the synoptic conditions leading to subdued rainfall activity during June. The northward movement of the cyclonic storm over the Bay might have resulted in the moisture being dragged away from the Indian landmass. During June, the northern part of the country experienced an anomalous northerly wind component compared to 30-year (1961–1990) climatology, indicating an intrusion of warm and less humid air towards the subcontinent. Anomalous moisture transport shown in section 4.3 also suggests lack of moisture supply over the Indian continental region.

4.2 *Atmospheric circulation*

Circulation patterns associated with the changes in sea surface temperatures (SST) over the Pacific Ocean and the Indian Ocean affect the Indian summer monsoon rainfall. Therefore, anomalies in SSTs and wind at 1000 hPa have been analyzed (figure 7a and c) for the season as a whole. Warm SSTs are seen over entire equatorial region. Positive SST anomalies over the equatorial eastern Pacific indicates occurrence of an El Niño (figure 7a and b). The anomalous easterlies over the Arabian Sea and northerlies over the African coast (45°–60°E, Equator–10°N: figure 7c and d) indicate a weak cross equatorial flow possibly leading to the transport of less moisture towards the Indian subcontinent. An anomalous low level convergence is observed over central and eastern equatorial Indian Ocean (figure 7c), where SSTs are warmer than the western equatorial Indian Ocean and Bay of Bengal, suggesting an enhanced convection over central and eastern equatorial Indian Ocean region. The months of July and August are generally active monsoon months over the Indian region during which the country receives bulk of the rainfall. However in 2009, rainfall during July was near normal and during August it was deficient. Anomalies in SSTs and wind at 1000 hPa during August 2009 (figure 7b and d) convey similar inferences as noted above. The month of August experienced maximum large scale divergence over the Indian subcontinent and convergence over equatorial Indian Ocean (figure 7d) leading to less rainfall over the Indian landmass and more over the equatorial Indian Ocean.

The strength of the monsoon is also determined by the strength of the Walker circulation (east-west circulation over the Pacific) and the regional monsoon Hadley circulation (north-south circulation over the Indian region). Walker circulation is represented as pressure-longitude section of vector winds constructed with zonal wind and negative of vertical pressure velocity averaged over the

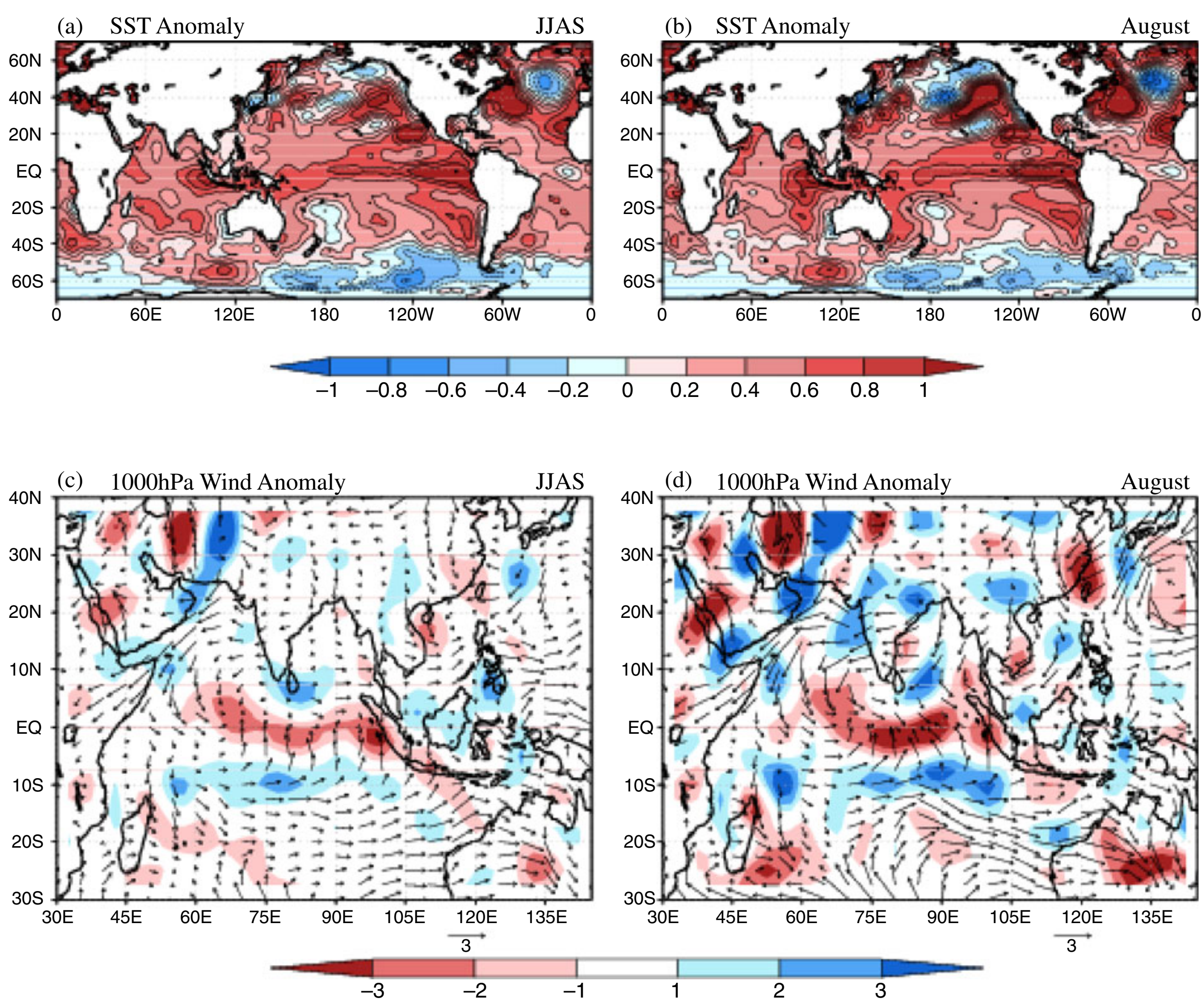

Figure 7. Anomalies in sea surface temperature (°C; **a** and **b**) and wind in m/s at 1000 hPa (**c** and **d**) during monsoon 2009, for JJAS (**a** and **c**) and for August (**b** and **d**). Wind anomalies are shown as vectors, shaded with horizontal divergence ($\times 10^{-6}$/s). (Anomalies are calculated based on 30-year (1961–1990) climatology.)

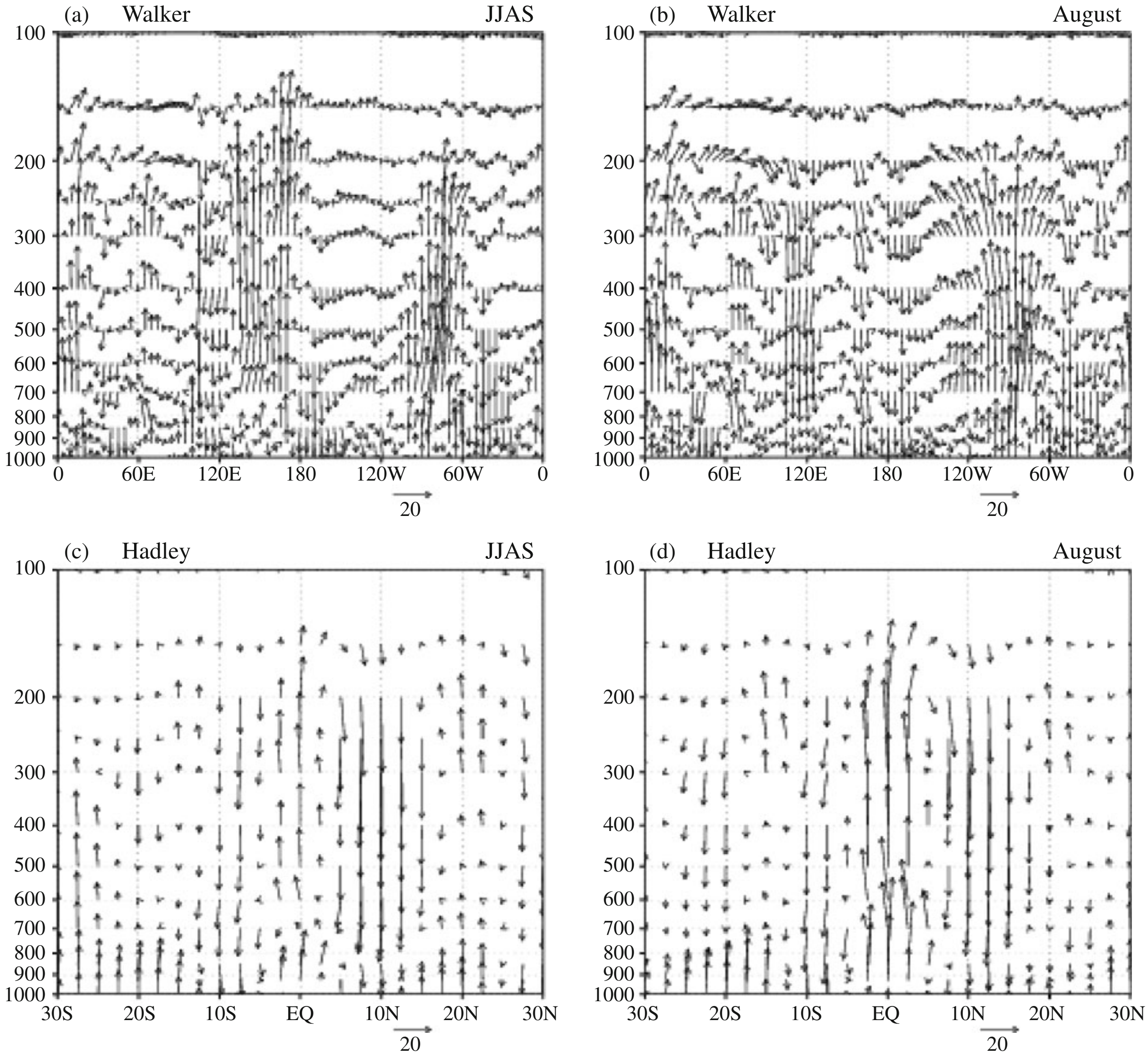

Figure 8. Anomalous Walker circulation and monsoon Hadley circulation during monsoon season JJAS (**a** and **c**) and August (**b** and **d**) 2009. (Anomalies are calculated based on 30-year (1961–1990) climatology.)

equatorial region (10°S–10°N: figure 8a and b). On the other hand, monsoon Hadley circulation is represented as pressure-latitude section of vector winds constructed with meridional wind and negative of vertical pressure velocity averaged over the Indian longitudes (70°–90°E: figure 8c and d). Consistent with the warming over the Niño regions, anomalous ascending motion over the eastern Pacific (120°–80°W) and weak descending motion over the eastern Indian Ocean (40°–80°E) are seen (figure 8a). This feature is more clearly seen during August (figure 8b). The meridional Hadley circulation shows an anomalous subsiding motion over the Indian landmass (5°–20°N: figure 8c and d) and ascending motion over the equatorial Indian Ocean region. This feature is more clearly seen during August (figure 8d). Pai and Sreejith (2010) also noticed similar features of meridional circulation anomalies during the monsoon season.

4.3 *Moisture transport*

Anomalous sea surface temperatures over Indian Ocean modulates surface evaporation and influences moisture transport towards Indian region and hence its accumulation (Li and Zhang 2002). Hence, the moisture transport and its availability over the Indian subcontinent has also been studied. For this, moisture convergence at low levels (1000 hPa) have been computed for the monsoon season and is presented in figure 9 along with the amount of precipitable water content in the atmosphere. Figure 9(a and b) clearly shows a

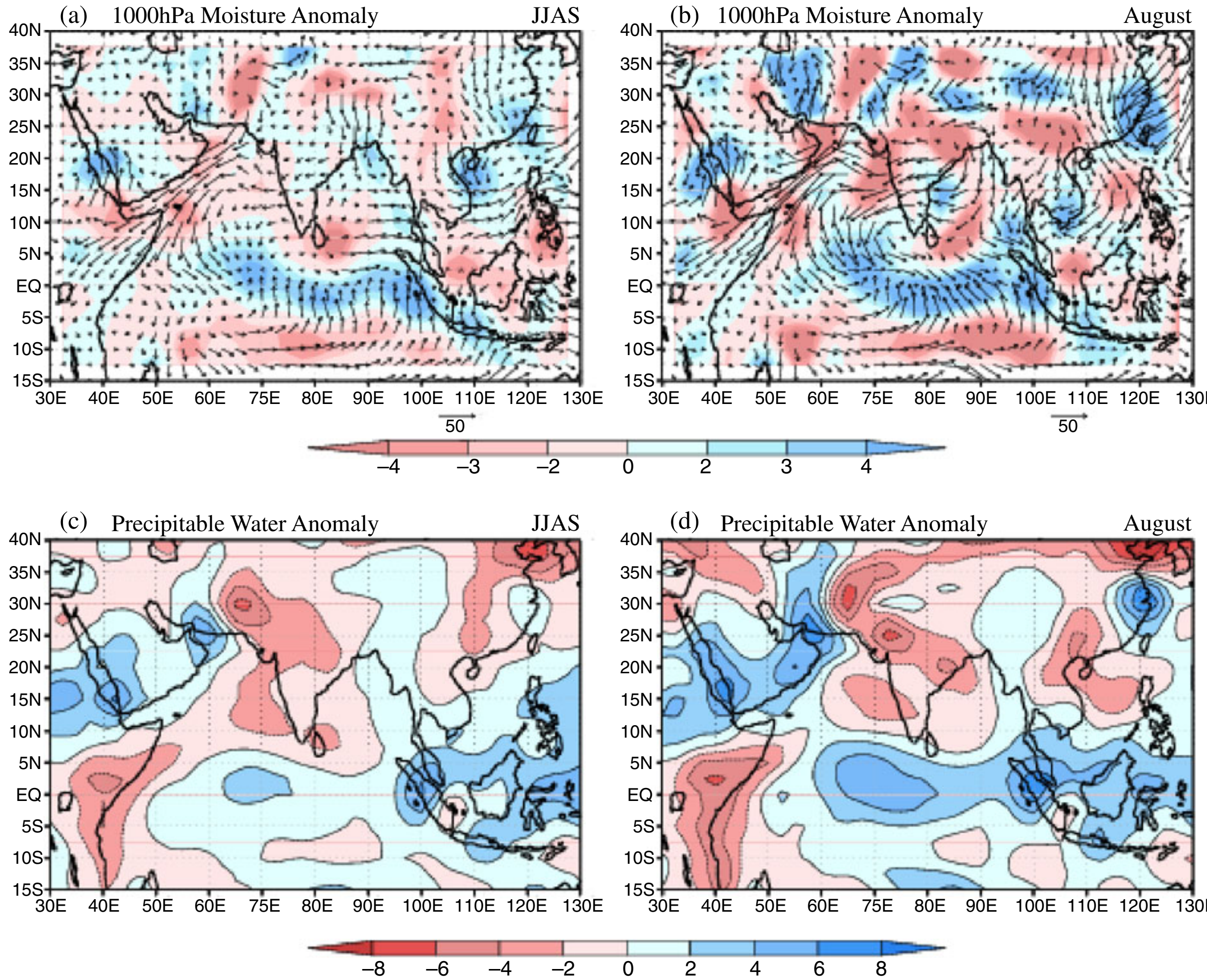

Figure 9. Anomalies in moisture transport (vectors) and moisture convergence (m s^{-1} g kg^{-1}) at 1000 hPa (**a** and **b**) and precipitable water (kg m^{-2}; **c** and **d**) during monsoon 2009, for JJAS (**a** and **c**) and for August (**b** and **d**). (Anomalies are calculated based on 30-year (1961–1990) climatology.)

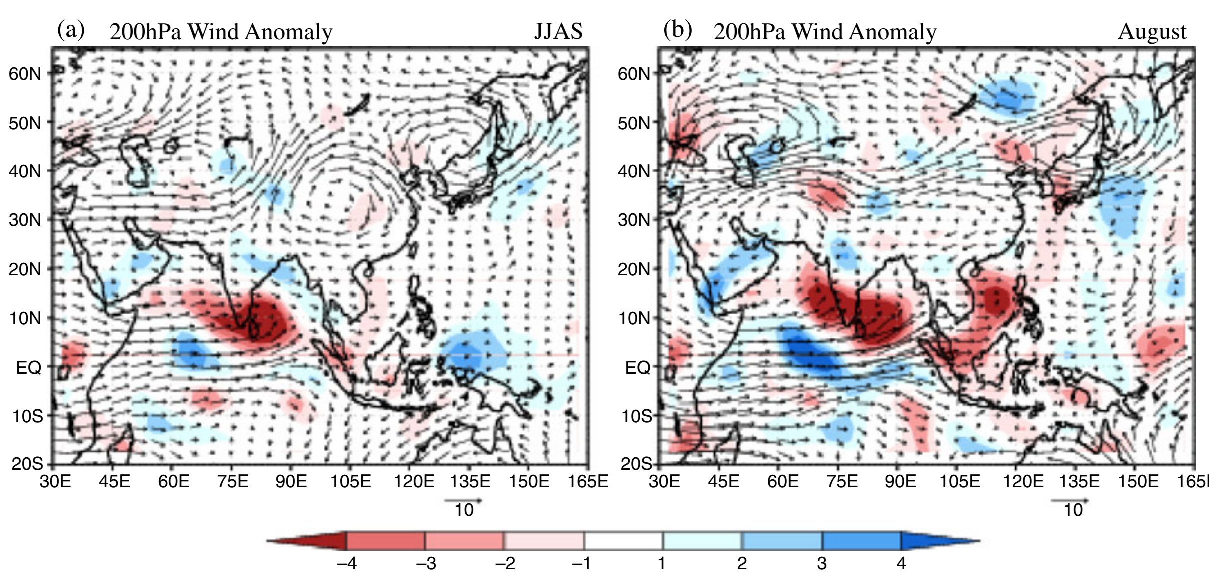

Figure 10. (**a**) 200 hPa wind anomaly (vector) and horizontal divergence ($\times10^{-6}$/s) (shadings) for JJAS 2009 and (**b**) for August 2009. (Anomaly is calculated as deviation from 30-year (1961–1990) climatology.)

substantial southward component of moisture flux, consistent with the anomalies in SST gradient over the Indian Ocean region. The reduction in anomalous transport of moisture from the Indian Ocean, Arabian Sea and Bay of Bengal, resulted in anomalous moisture divergence over Indian subcontinent (figure 9a and b). This anomalous moisture divergence is more pronounced during the month of August (figure 9b). Thus the amount of precipitable water content was also substantially less over the landmass of India (figure 9c and d).

4.4 *Upper tropospheric (200 hPa) winds*

The intrusion of upper troposphere westerlies over north India and weak tropical easterly jet over south India can cause failure of monsoon. The figure 10(a and b) presents the 200 hPa wind anomaly and divergence for the monsoon season and for the month of August. The tropical easterly jet was generally weak as evidenced by the westerly wind anomaly over the southern parts of India (figure 10a and b). Furthermore, a Rossby wave pattern is discernable between 30° and 45°N. This figure also shows an intrusion of upper level westerly wind (east of the Caspian Sea) penetrating over northern parts of India. This may result in the flow of dry air from the northern mid-latitudes. The figure also reveals an upper level divergence along equatorial region and a convergence over Indian region consistent with the lower level convergence and divergence. The upper level divergence is seen over the peninsular region, where the rainfall is normal or excess. The divergence pattern is more pronounced during the month of August.

5. Summary and conclusions

Recently, the Indian subcontinent witnessed a severe monsoon drought in the year 2009. India as a whole received 77% of its long period average during the summer monsoon season (1 June to 30 September) of 2009, which is the third highest deficient all India monsoon season rainfall year during the period 1901–2009 and a most deficient year after 1972. The present study is aimed at studying anomalous behaviour of summer monsoon 2009 over India. An attempt is also made to understand the possible causes behind this anomalous behaviour. For this, analysis have been carried out to study the propagation characteristics of convective systems, the changes in circulation pattern and the processes which occurred in the mid-latitude regions.

The year 2009 experienced a wide-spread deficient monsoon. Out of 36 meteorological subdivisions of India, 22 subdivisions received deficient rainfall during the season. Above normal activity was observed over peninsular India especially over north and south interior Karnataka, while rainfall was below normal over rest of the country. Analysis of weekly rainfall averaged over India revealed that all the weeks during June received subdued rainfall activity. However, during July the rainfall was near normal. In August also all the weeks show negative anomalies, but for last two weeks, magnitudes of negative anomalies reduced substantially and became positive in first week of September. Finally monsoon ended with much below normal rainfall activity. Application of wavelet analysis technique on all-India rainfall data reveals that slower 30–60 day mode was dominant throughout the monsoon season. Slow northward propagations of rainfall is seen during the month of June and also from middle of August until middle of September. However, two standing oscillations are seen during the month of July.

The activity of monsoon low pressure systems during 2009 was much subdued. Only four depressions and four low pressure areas formed during the season and their lifespan over the land was very short. Lack of moisture supply appears to be one of the reasons for the immediate dissipation of these systems over the land. North–south pressure gradient was weak during the entire season, due to which the cross equatorial flow was weak leading to less moisture intrusion over India. The tropical easterly jet was also weak. Intrusion of warm and dry air from the northern mid-latitudes to the subcontinent also appears to be a cause for the large drought over northern parts of the country. Presence of weak El Niño and warming over the central equatorial Indian Ocean have altered the circulation pattern and produced an anomalous low level convergence and ascending motion over Indian Ocean region and large scale subsidence over the Indian landmass.

In summary, the weak cross equatorial flow, monsoon systems not moving inland, penetration of mid-latitute upper tropospheric westerlies and the circulation associated with the Walker and Hadley circulation, with descending motion over the Indian landmass, resulted in less moisture supply, ultimately leading to a drought situation over India during the monsoon 2009.

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