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Delayed withdrawal of southwest monsoon 2010 – A diagnostic study

D. R. PATTANAIK, C. S. TOMAR and S. C. BHAN

India Meteorological Department, New Delhi, India

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e mail : drpattanaik@gmail.com

सार – उत्तर पश्चिमी भारत में मॉनसून की देरी अथवा समय से पहले वापसी, विशेष रूप से मॉनसून की वापसी के समय, मॉनसून के निष्पादन का निर्धारण करता है। दो से तीन सप्ताह पहले मॉनसून की देरी/शीघ्र वापसी का पूर्वानुमान न केवल कृषि समुदायों के लिए अपितु विभिन्न उपयोगकर्त्ताओं के लिए भी बहुत ही महत्वपूर्ण होता है। 2010 में मॉनसून की वापसी लगभग 4 सप्ताह देरी से हुई जबकि उत्तर पश्चिमी भारत से यह 27 सितम्बर को ही वापस हो चुका था। NOAA और कल्पना-। उपग्रहों से प्राप्त किए गए उत्पादों के साथ राष्ट्रीय पर्यावरणीय पूर्वानुमान केंद्र (NCEP) से प्राप्त किए गए दैनिक सतही और उपरितन वायु आँकड़ों का पुनर्विश्लेषण किया गया तथा इनका उपयोग करते हुए 2010 में मॉनसून की देरी से वापसी के संबंध में प्रत्यक्ष कारणों के साथ इनकी जाँच की गई।

2010 में मॉनसून की वापसी के समय साप्ताहिक माध्य और पवन विसंगति से 26 सितम्बर तक असामान्य चक्रवात परिसंचरण का पता चला, यह उस अवधि में उत्तर पश्चिमी भारत में प्रतिचक्रवाती विसंगतियों की वृद्धि के साथ 27 सितम्बर - 3 अक्तूबर 2010 तक के सप्ताह में मॉनसून की वापसी में सहायक मात्र था। मॉनसून द्रोणी की स्थिति में दक्षिणी और पश्चिमी क्षेत्र के मध्य औसतन 850 हैक्टापास्कल क्षेत्रीय पवनों की भिन्नता के साथ दैनिक न्यून स्तर के पवन सूचकांक से मॉनसून की देरी से वापसी का पता चला जो 45° उ. - 50° उ. के अक्षांशीय पट्टी में ऊपरी क्षोभमंडल के मध्य लगभग 2° से. के बृहत मान उष्णता के साथ 35° उ. - 45° उ. के अक्षांशीय पट्टी में मॉनसून द्रोणी क्षेत्र सहित उत्तर पश्चिमी भारत में सक्रिय संवहनों से सम्बद्ध थी। इसके अतिरिक्त उत्तर पश्चिमी भारत में मॉनसून की वापसी से यह पता चला कि वर्षा के जल की मात्रा (PWC) और ऊपरी क्षोभमंडलीय आर्द्रता में कमी धीरे-धीरे आई है। वर्ष 2010 में उत्तर पश्चिमी भारत से देरी से मॉनसून की वापसी से प्रशांत महासागर में लॉ नीना की स्थितियाँ भी जुड़ी हुई थी।

ABSTRACT. The delayed or early withdrawal of monsoon over northwest India determines the performance of monsoon particularly during the withdrawal phase. A forecasting of delay/early withdrawal of monsoon two to three weeks in advance is very crucial not only to the Agricultural communities but also to various users. During 2010 the monsoon withdrawal was delayed by about 4 weeks as it commenced from northwest India on 27th September. The physical reasons associated with the delayed withdrawal of monsoon during 2010 is investigated using daily surface and upper air data obtained from the National Centre for Environmental Prediction (NCEP) reanalysis along with the products available from NOAA and Kalpana-1 satellites.

The weekly mean and anomaly wind during withdrawal phase of 2010 indicated anomalous cyclonic circulation up to 26th September and was only conducive for the withdrawal of monsoon during the week from 27 September 2010-3 October 2010 with development of anticyclonic anomalies over the northwest India during that period. A daily low level wind index in terms of the difference in average 850 hPa zonal winds between a southern and a northern region of the monsoon trough position indicated a delayed withdrawal of monsoon, which was associated with active convections over northwest India along the monsoon trough zone and in the latitudinal belt of 35° N-45° N accompanied by large scale warming of about 2 °C in the middle to upper troposphere over the latitude belt of 45° N-50° N. The withdrawal of monsoon from northwest India was further indicated by gradual decrease of precipitable water content (PWC) and upper tropospheric humidity (UTH). This delay of withdrawal of monsoon from northwest India during 2010 was also accompanied by La Nina conditions in the Pacific.

Key words – Indian monsoon, Withdrawal of monsoon, 2010 monsoon, Delayed withdrawal.

1. Introduction

The withdrawal phase of the Indian south summer monsoon (ISM) over India is an important event, which starts around first week of September from extreme northwest India. Normally, the monsoon withdrawal begins from west Rajasthan by September 1 and it retracts completely from the country in one-and-a-half months,

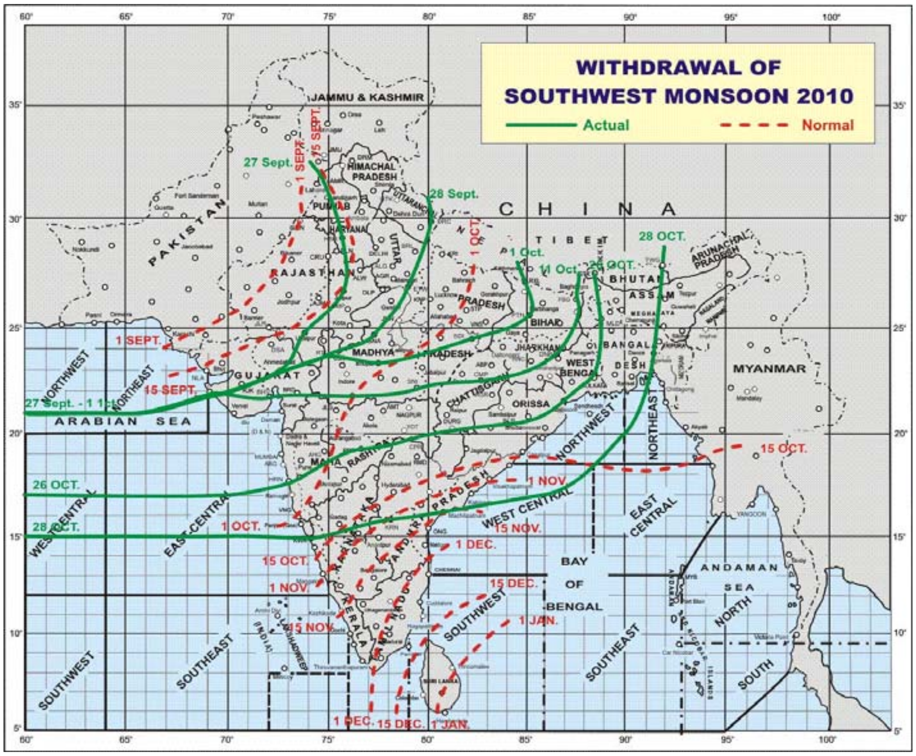
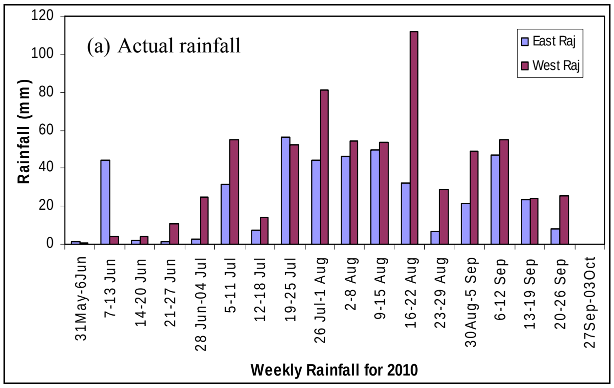
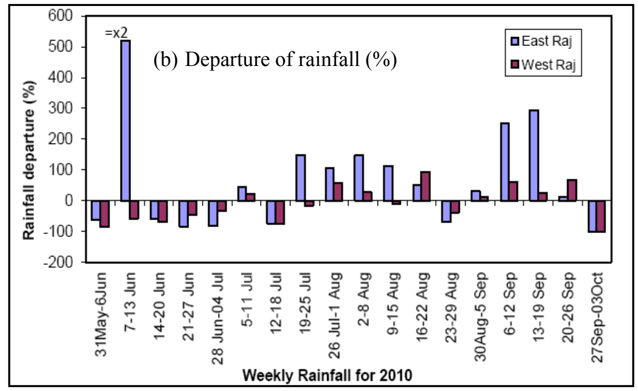


Fig. 1. Actual withdrawal lines of monsoon 2010 along with the normal withdrawal lines

by October 15 (Rao, 1976). While there exist no widely accepted definitions of these monsoon transitions, at the surface the onset is recognized as a rapid, substantial, and sustained increase in rainfall over a large scale while the withdrawal marks the return to dry, quiescent conditions. The northward progression of the monsoon onset is symptomatic of a large-scale transition of deep convection from the equatorial to continental regions (Rao, 1976; Sikka and Gadgil, 1980; Webster *et al*., 1998; Pattanaik, 2003). The withdrawal of the monsoon is more gradual than its onset and is characterized by the reduction in rainfall over India, the decay of the anticyclonic circulation that is established over the Tibetan Plateau during the monsoon, and the reappearance of the upper-level westerly jet stream south of the Himalayas [Dey, 1970; India Meteorological Department (IMD), 1972]. Rao, (1976) defines the withdrawal of the ISM as the southward displacement of the surface trough, the establishment of dry continental air and the development of anticyclonic flow over northern and central India. The withdrawal of monsoon generally preceded by a change in the upper level (200 hPa) circulation in particular the Tibetan anti-cyclone which, starts moving towards south, and with the formation of a low level (850 hPa) anti-cyclonic circulation over North West (NW) India. Subsequent to the formation of the low level anti-cyclonic circulation over NW India, monsoon air mass which is characterized by the warm and humid air is gradually replaced by colder and dry air from the north leading to a decrease in the moisture content of the atmosphere. Under the influence of the above mentioned circulation features, the areal extent of colder and dry air gradually increases in the southeasterly direction starting from NW India leading to the summer monsoon withdrawal. The monsoon transitions occur due to large-scale interactions between surface heating and atmospheric dynamic, thermal, and hydrologic processes (Takagi *et al*., 2000; Kumar *et al*., 1997; Ueda and Yasunari, 1998; Wu and Zhang, 1998). However, during the onset, the extent to which rainfall at Kerala during these transitions is determined by synoptic variability unrelated to the monsoon transitions is not well established. Moreover, given the relatively small scale of west Rajasthan (pocket of northwest India), sensitivity of any withdrawal declaration is based solely on the district's rainfall, whereas the onset over small scale of Kerala (southern tip of India) is influenced by large-scale circulation feature.

The onset, strength and variability of the summer monsoon have been extensively examined (Joseph *et al*., 1994; Webster *et al*., 1998; Pattanaik *et al*., 2005). However, to date there has not been much systematic investigation of the retreat of the monsoon system, although some studies have examined withdrawal process of monsoon (Ramesh *et al*., 1996; Syroka and Toumi,





Figs. 2(a&b). The weekly (a) averaged rainfall (mm) and (b) departure (%) over the meteorological sub-divisions of western Rajasthan and eastern Rajasthan during June to September 2010. Actual % departure for East Rajasthan during 7-13 June is twice of that plotted in (b)

2004). Ramesh *et al*. (1996) using analyses/forecasts of the model of National Centre for Medium Range Weather Forecasting (NCMRWF) have found early withdrawal from the extreme sectors of the NW India compared to that of withdrawal of monsoon declared by conventional process. Syroka and Toumi (2004) defined the withdrawal of monsoon in terms of a physically based 850 hPa wind index, which captures the larger-scale monsoon dynamics and correlates well with rainfall over the Indian subcontinent. Syroka and Toumi (2004) found that the withdrawal of the Indian summer monsoon follows a period of enhanced convective activity over the Indian subcontinent and is associated with a dry phase of the intra-seasonal oscillation which is found to be associated with a mobile latent heat source migrating towards the west Pacific during the monsoon withdrawal. Though there is no one-to-one relationship between withdrawal date of monsoon with all India monsoon rainfall the delay or early withdrawal of monsoon over northwest India determines the performance of monsoon particularly during the withdrawal phase of September. It is also seen that the rainfall during the retreat phase of monsoon (September) influences more about the total rainfall variability of the season (Rupa Kumar *et al*., 1992). Hence a delay/early withdrawal of monsoon is very crucial as it will determine the rainfall during the withdrawal month of September and consequently will influence the inter-annual variability of rainfall for the whole season. The objective of the present study is to investigate the associated large-scale features of delayed withdrawal of monsoon 2010.

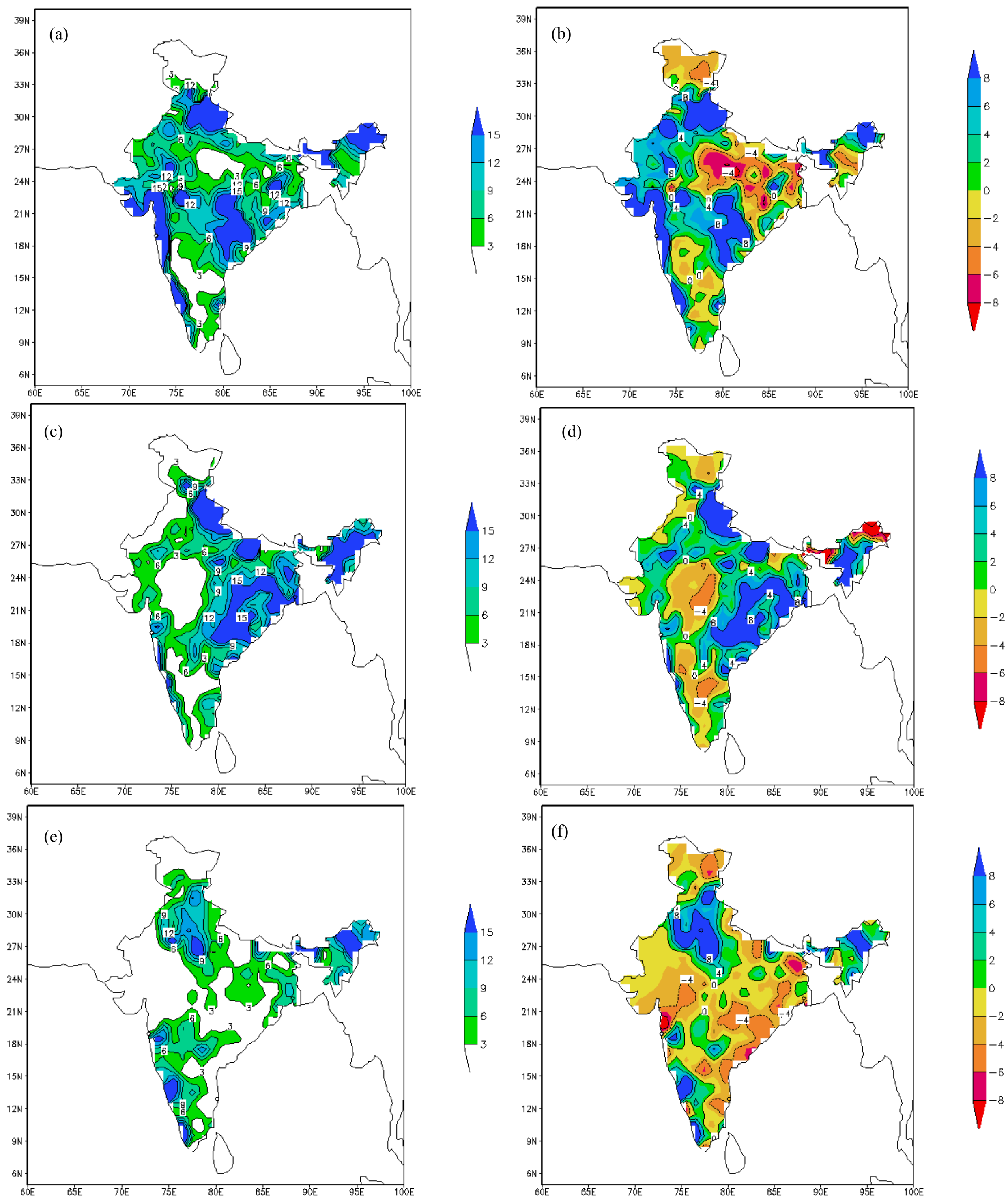
2. Data and methodology

The gridded (1° × 1°) daily rainfall dataset during 2010 monsoon season (JJAS) has been used in the present study. This gridded data has been prepared by National Climate Centre (NCC) at IMD, Pune based on the standard quality-controls and the interpolation analysis (Rajeevan *et al*., 2006). The same data set has been compared with similar global gridded rainfall datasets and it has been found that the present rainfall analysis is a more accurate representation of spatial rainfall variation (Rajeevan *et al*., 2006). To study the circulation and other features during the monsoon season the daily wind, humidity, air temperature obtained from the National Centre for Environmental Prediction (NCEP) reanalysis (Kalnay *et al*., 1996) are used in the present study. The optimum interpolated Sea Surface Temperature (NOAA_OI_SST_V2) data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/ was also used in the present study (Reynolds *et al*., 2002). The daily outgoing long-wave radiation (OLR) data used during the season is from the Advanced Very High Resolution Radiometer (AVHRR) instrument (Gruber and Krueger 1984).

3. Results and discussion

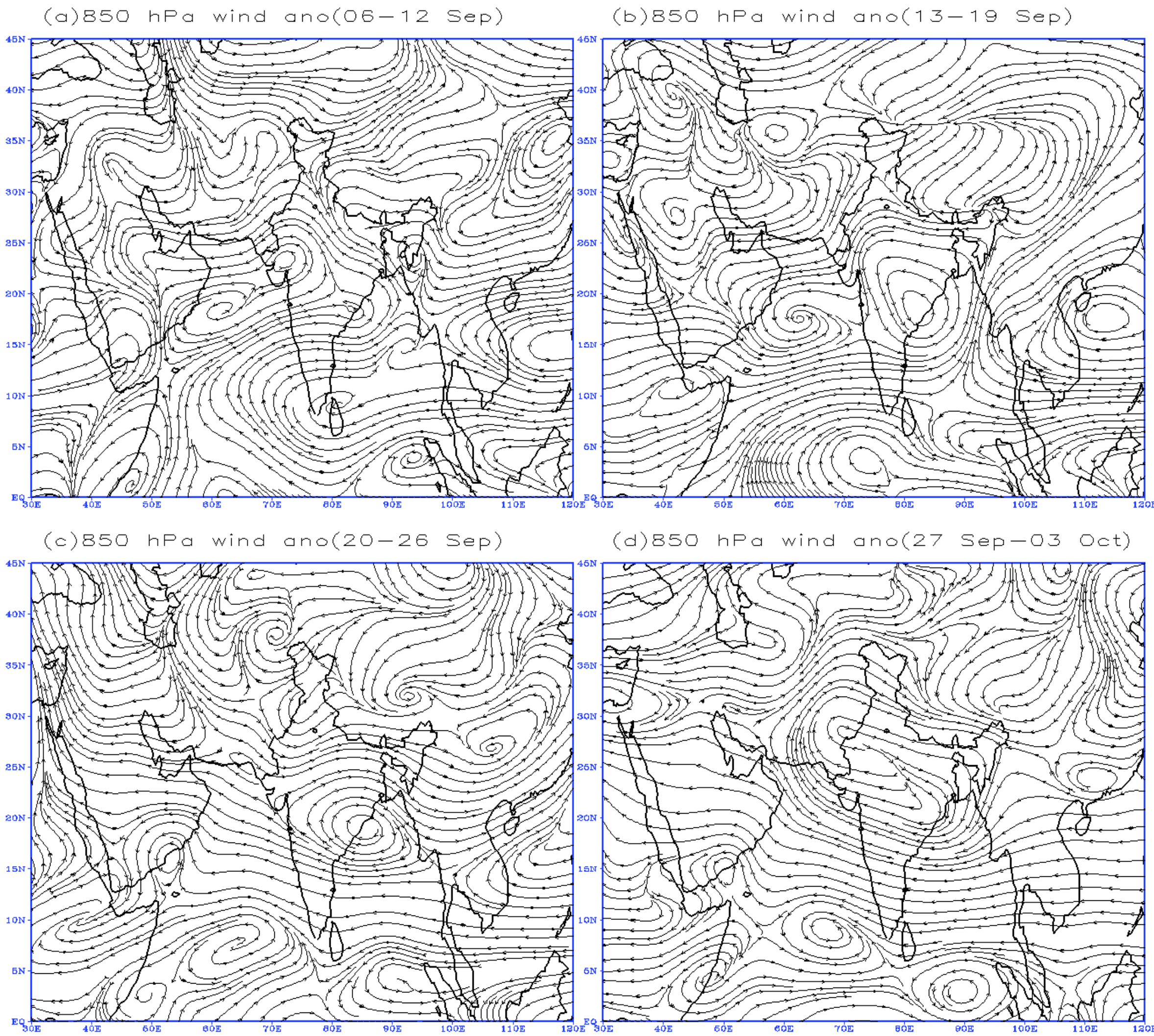
3.1. *Delayed withdrawal of monsoon during 2010 and active September*

During 2010 while the onset of the monsoon over Kerala was one day early (31^{st} May) and it had covered the entire country before the normal date, the withdrawal had been delayed by about 4 weeks (Khole *et al*., 2011; Pattanaik and Khole, 2011). Thus, the withdrawal of monsoon from northwest India (Fig. 1) started from 27^{th} of September with a delay of about 4 weeks as the normal withdrawal date is 1^{st} September. Since the withdrawal of monsoon over India started from the northwest parts of country the withdrawal can also be noticed from the weekly rainfall received over the two meteorological sub-divisions over Rajasthan, *viz*., the west Rajasthan and the east Rajasthan (State of northwestern parts of India touching Pakistan). It is seen from Fig. 2(a) that the two meteorological sub-divisions received good amount of



Figs. 3(a-f). Observed mean rainfall (mm/day) (a) during 6-12 September, 2010, (b) during 13-19 September, 2010, (c) during 20-26 September, 2010. The corresponding observed rainfall anomalies (d) 6-12 September, (e) 13-19 September and (f) 20-26 September, 2010

rainfall from the beginning of monsoon season till the week from 20-26 September and it did not receive any rainfall only during the week from 27 September to 3 October, 2010. The same is also reflected in the



Figs. 4(a-d). 850 hPa weekly wind anomalies prior to and during the withdrawal periods of 2010 monsoon. (a) 6-12 September, 2010, (b) 13-19 September 2010, (c) 20-26 September 2010 and (d) 27 September - 3 October, 2010

percentage departure of rainfall with -100% departure recorded during the week from 27 September to 3 October, 2010 [Fig. 2(b)]. It is not only the Met. Sub-divisions over northwest India that got good rainfall during September, many other parts of north India also received good rainfall during the month. One of the reasons for 2010 having above normal rainfall (102%) was basically due to good rainfall of September, which contributed about ≈115% of monthly long period average rainfall. With the development of La Nina condition from the beginning of the season around June, the positive impact of it in terms of good rainfall activity over India was very prominent in September. During September a total of 4 low pressure areas were formed and associated with these systems the rainfall in September was mostly above normal except last few days (Khole *et al*., 2011 and Pattanaik and Khole, 2011). It is also seen from the spatial distribution of rainfall that wide spread rainfall continued over most parts of India during 6-12 September, 13-19 September and 20-26 September, 2010 as shown in Fig. 3(a), Fig. 3(c) and Fig. 3(e) respectively. As seen from Fig. 3(e) the rainfall continued over northwest India during the period from 20-26 September indicated a delayed withdrawal of monsoon. The good rainfall activity till 26th September is also reflected in terms of positive anomaly in the rainfall anomaly plots shown in Fig. 3(b), Fig. 3(d) and Fig. 3(f). It may be mentioned here that the withdrawal of monsoon during 2010 was started from west Rajasthan on 27th September with a delay of nearly 4 weeks as the normal date of withdrawal from extreme western parts of Rajasthan is 1st of September.

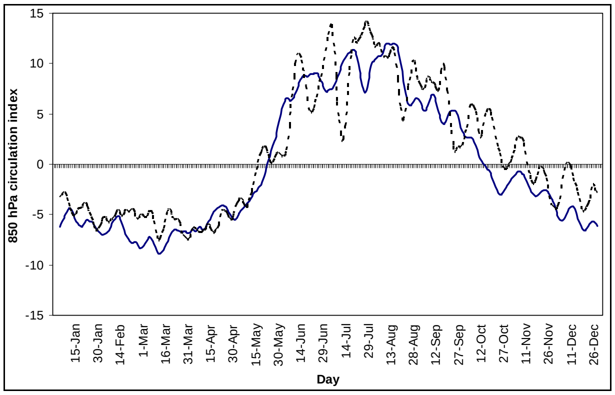


Fig. 5. Mean annual cycle of daily 850 hPa circulation index (see text for definition) 1981-2010 (solid line) and for 2010 (dashed line)

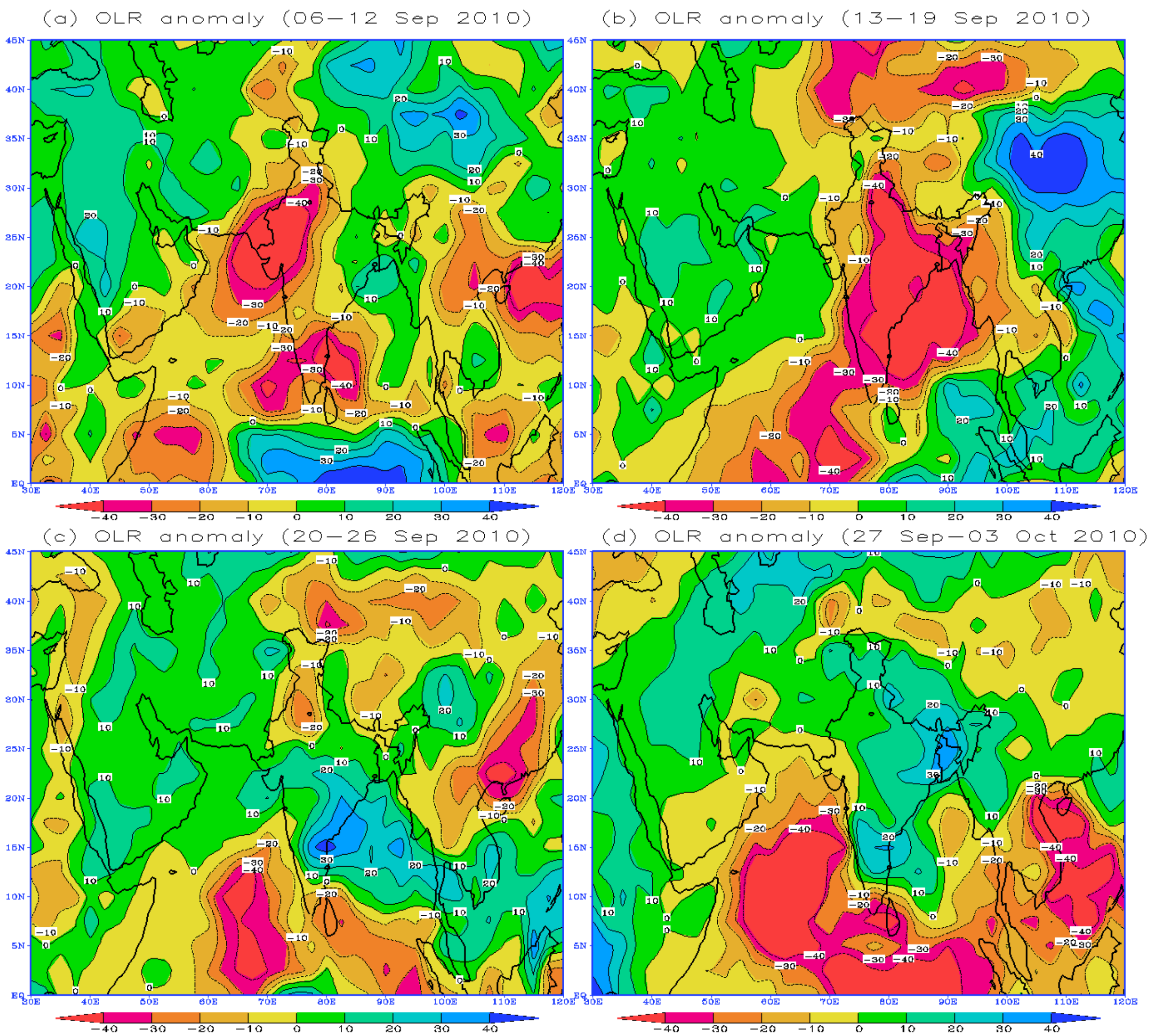
3.2. *Circulation anomalies associated with the withdrawal*

Withdrawal of the SW monsoon generally initiated over NW India only after the southward progression of the Tibetan anti-cyclone at 200 hPa and formation of anti-cyclonic circulation over NW India at 850 hPa. The withdrawal and gradual equator ward movement and deceleration of the low level westerly flow associated with the retreat of the ISM in late September/October is heralded by the seasonal cooling of the Asian continent (Ramage, 1971). The upper-level anticyclone, which during JJAS) is centred over northern India and Pakistan as a result of intense sensible and latent heating in the region, weakens and begins its annual migration southeastward towards Indonesia. Good descriptions of the ISM withdrawal and the march of the monsoon season are found in Ramage (1971) and Rao (1976).

Looking at the weekly wind anomaly during September at 850 hPa [Figs. 4(a-d)] it is seen that even the weekly wind anomaly shows the presence of anomalous cyclonic circulation over northwest India during the active September period for a period of three weeks from 6-12, 13-19 and 20-26 September, 2010 [Figs. 4(a-c)]. It is only during the period from 27th September to 3rd October, 2010 where the anomalous wind shows presence of anticyclonic circulation over northwest India spreading almost over to the central India [Fig. 4(d)]. The monsoon trough from northwest India to Orissa is also seen in the mean chart at 850 hPa during 6-12 September, 2010 [Fig. 4(a)]. Thus, the circulation features was only conducive for the withdrawal of monsoon during the week 27 September - 3 October during 2010 and hence a delay of about 4 weeks. The late withdrawal of 2010 monsoon was also associated with a very active July extending to early August over Pakistan and adjoining northwest India leading to severe flood over Pakistan. As shown by Webster *et al*. (2011) while, the total rainfall over Pakistan during 2010 monsoon season was not unprecedented, the number and intensity of extremely heavy rains over northern Pakistan was very unusual. The flood really kicked off with a burst of rain towards last week of July and continued even during first few days of August. The corresponding low level circulation during this flood period indicated very active monsoon trough extending from northern part of Bay of Bengal to south Pakistan (Pattanaik *et al*., 2013). Thus, as seen in Figs. 4(a-d) the active monsoon trough from northwest India to Bay of Bengal was also seen till 26th of September before the commencement of withdrawal of monsoon.

3.3. *Meridional transition of zonal wind*

Syroka and Toumi (2002) define a daily circulation index as the difference in average 850 hPa zonal winds between a southern region (5° N - 15° N, 50° E - 80° E) and a northern region (20° N - 30° N, 60° E - 90° E). The region is chosen in such that it captures both variability of the position and intensity of the monsoon trough. The index changes sign associated with both the changing intensity of the low-level westerly monsoon flow and the vorticity associated with the monsoon trough and synoptic activity. As seen from the mean annual cycle (mean during the period from 1981 to 2010 shown in Fig. 5), which, shows a steep increase in the index at the onset of the monsoon and a slower decrease during the retreat. The daily circulation index exhibits substantial noise, so a centred 7-day running average is considered in Fig. 5. Also seen from Fig. 5 that the first transition of the index from negative to positive is occurred in the mean pattern on 23rd May and it continued to remain positive during the entire monsoon season from June to September. The reverse transition from positive to negative first appeared on 12th October, however, the continuity of the negative values appeared from 16th October onwards. The date of withdrawal of the monsoon is defined as the first of seven consecutive days for which the index becomes negative (16th October). Similarly, the mean onset date is defined as the first day of seven consecutive days of positive index (23rd May). The 7-day period was found to be the smallest time interval which smoothed synoptic noise sufficiently to define the dates more easily. Syroka and Toumi (2002) also found that the circulation index shows very strong correlation with all India rainfall on monthly scale with the correlation is large towards the end of the summer monsoon season. The circulation index is therefore both a physically sensible and a practical tool to study the withdrawal of the monsoon. In case of 2010 (Fig. 5) the first reversal in sign (positive to negative) of circulation index is seen on 26th October, which lasted for 4 days only and subsequently it became positive. From 14th November onwards, the index was negative continuously. Thus, the

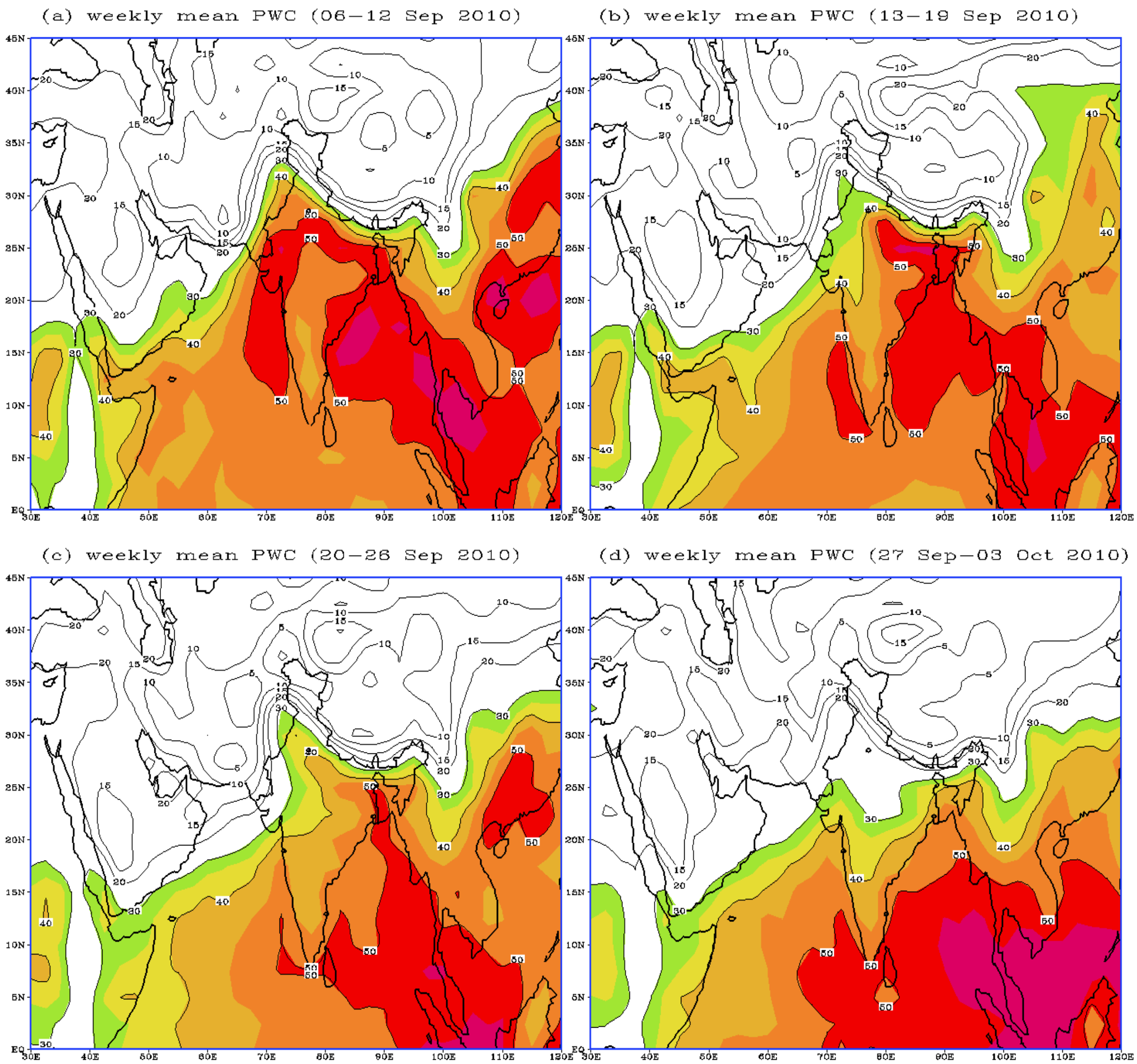


Figs. 6(a-d). Composite weekly OLR anomalies during and after the withdrawal of monsoon. (a) 6-12 September, 2010, (b) 13-19 September, 2010, (c) 20-26 September, 2010 and (d) 27 September - 3 October, 2010

circulation index also indicated a delayed of withdrawal of monsoon during 2010 even if it considered to be 26th October, when for 4 consecutive days the index changes sign for the first time.

3.4. *Anomalous convection and the moisture availability*

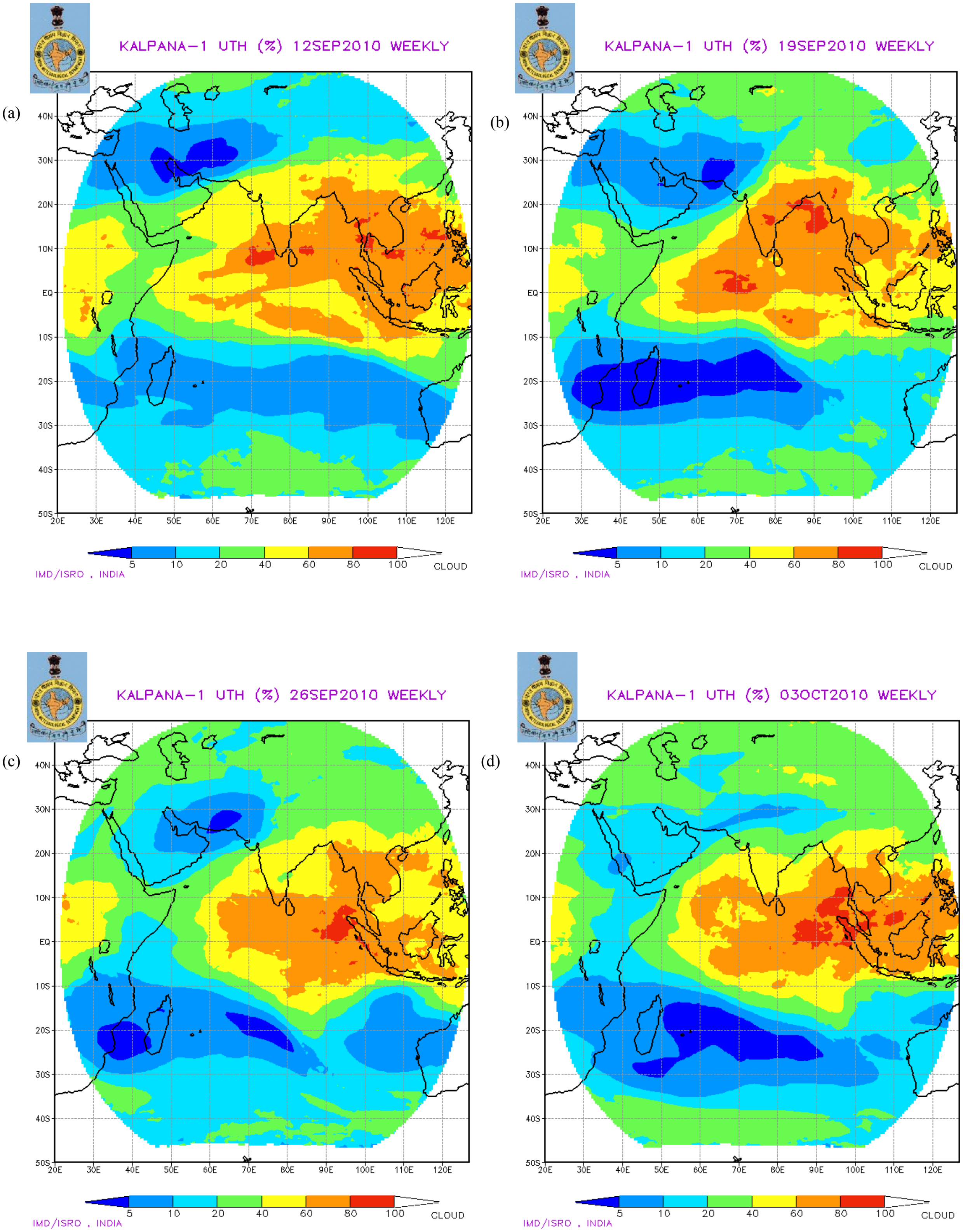
As during onset, the monsoon's major convective zones undergo a meridional migration during withdrawal that results in a northerly migration of deep convection associated with large-scale interactions between thermal, dynamic, and hydrologic processes. As shown by Pattanaik *et al*., (2005) that the locus of OLR minima (a proxy of convection) moves northwards from the warm pool region to Southeast Asia from boreal winter to summer and by May and June the monsoon heating is rapidly increased by the growth of convection to the north of the equator. The locus of OLR minima covers most parts of India during the active monsoon phase of July and August. During September the southward retreat of OLR minima, indicating withdrawal of monsoon. As seen from the weekly OLR anomalies during 2010 the three weeks starting from 6th September shows more convection over northern parts of India [Figs. 6(a-c)] and also more active convection in the belt of 35° N-45° N particularly during the period from September 13-19 and September 20-26 [Figs. 6(b&c)]. During the withdrawal week from September 27 to October 3 the OLR anomalies also indicated subdued convective activity over many regions of India [Fig. 6(d)]. Or during this period the anomalous convective activity is primarily focused on Myanmar and



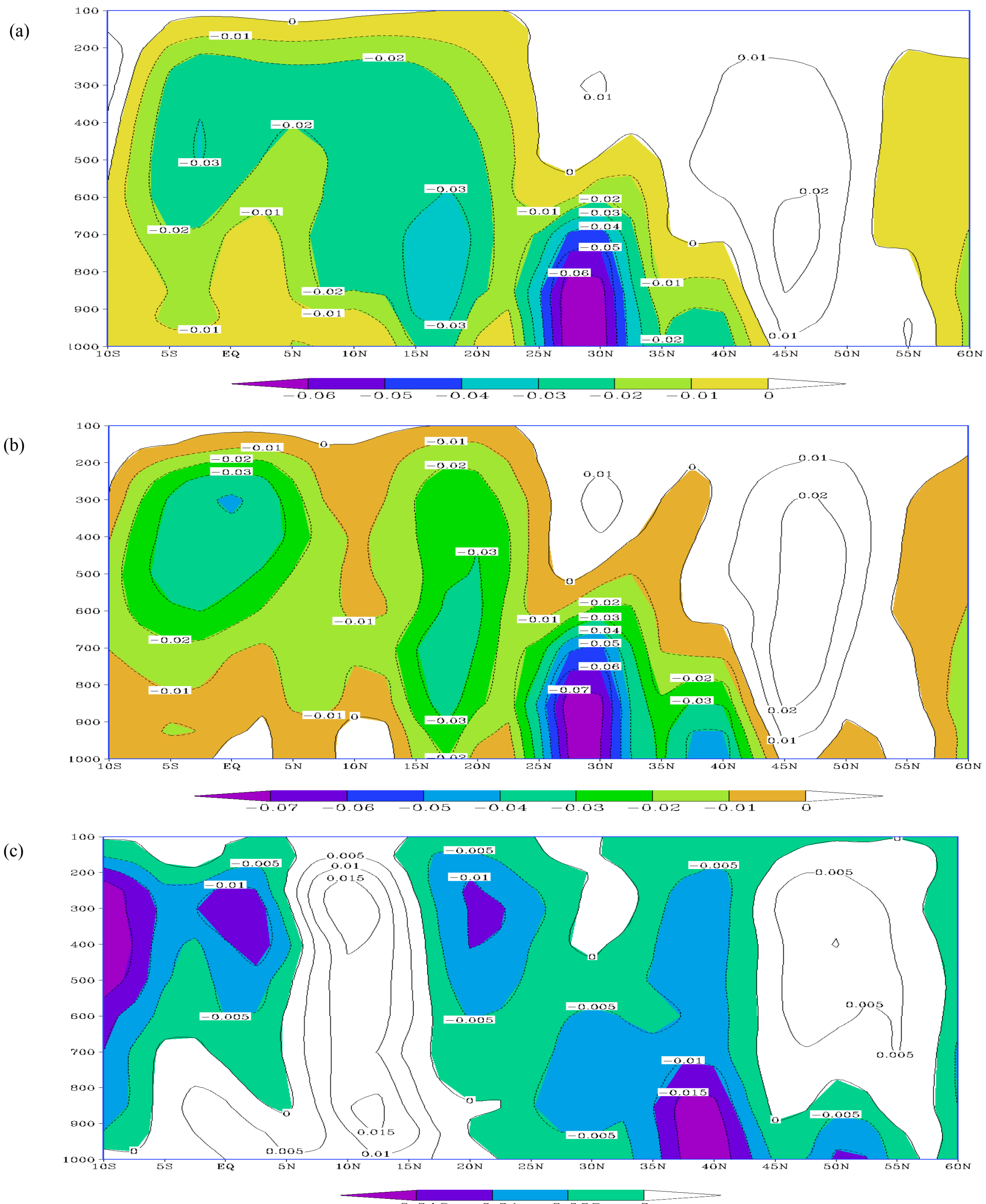
Figs. 7(a-d). Composite weekly mean precipitable water content (PWC) during and after the withdrawal of monsoon. (a) 6-12 September, 2010, (b) 13-19 September 2010, (c) 20-26 September, 2010 and (d) 27 September - 3 October, 2010

southern China as convection over the Indian subcontinent, particularly the north has been suppressed. The withdrawal of monsoon from northwest India is also associated with net reduction of availability of moisture, which is demonstrated in the Precipitable Water Content (PWC; the net moisture in the layer 1000-300 hPa) expressed during the month of September [Figs. 7(a-d)]. As shown in Figs. 7(a-d) the locus of PWC content of 30 kg/m^2 from the extreme northwest India during the period from 6-12 September [Fig. 7(a)] gradually migrate southeastward and finally seen over the central India at the time of withdrawal during the week 27 September to 3 October [Fig. 7(d)]. During the withdrawal week the PWC over northwest India reduces to a value of the order of 20 to 25 kg/m^2. The main area of PWC with more than 50 kg/m^2 gradually concentrates over the Myanmar and southern China during the withdrawal time [Fig. 7(d)].

The Upper tropospheric humidity (UTH) product derived from observations in the water vapor channel (5.6-7.2 μm) of the Indian geostationary satellite (Kalpana-I) is also one of the good products to illustrate the withdrawal features of southwest monsoon (Thapliyal *et al*., 2011). The UTH is defined as the mean relative humidity over a layer between about 500 hPa and 200 hPa. The weekly mean UTH for the week ending on 12th September, 19th September, 26th September and 3rd October, 2010 clearly indicates the gradual decrease of moist air over northwest



Figs. 8(a-d). Composite weekly mean Upper Tropospheric Humidity (UTH) in % during and after the withdrawal of monsoon. (a) 6-12 Sep, 2010, (b) 13-19 Sep 2010, (c) 20-26 Sep, 2010 and (d) 27 Sep-03 Oct, 2010. (The UTH is defined as per the method given in Thapliyal *et al*., 2011)



Figs. 9(a-c). Latitude-height monthly omega velocity (Pa/Sec) averaged over 40°E - 120°E. (a) Climatology mean (1971-2010). (b) Mean for September 2010 and (c) Anomalies for September 2010.

India till week ending on 26th of September 2010 [Figs. 8(a-d)]. The weekly mean UTH for the week ending on 3rd October shows absence of moisture in the 500-200 hPa layer (middle and upper troposphere) over northwest as well as northern plains of India indicating withdrawal of monsoon from that region.

3.5. *Anomalous vertical motion and heating of the atmosphere*

As seen earlier there are strong convective activity persists even over the latitude belt of 35° N - 45° N during the month of September [Figs. 6(a-d)], which was

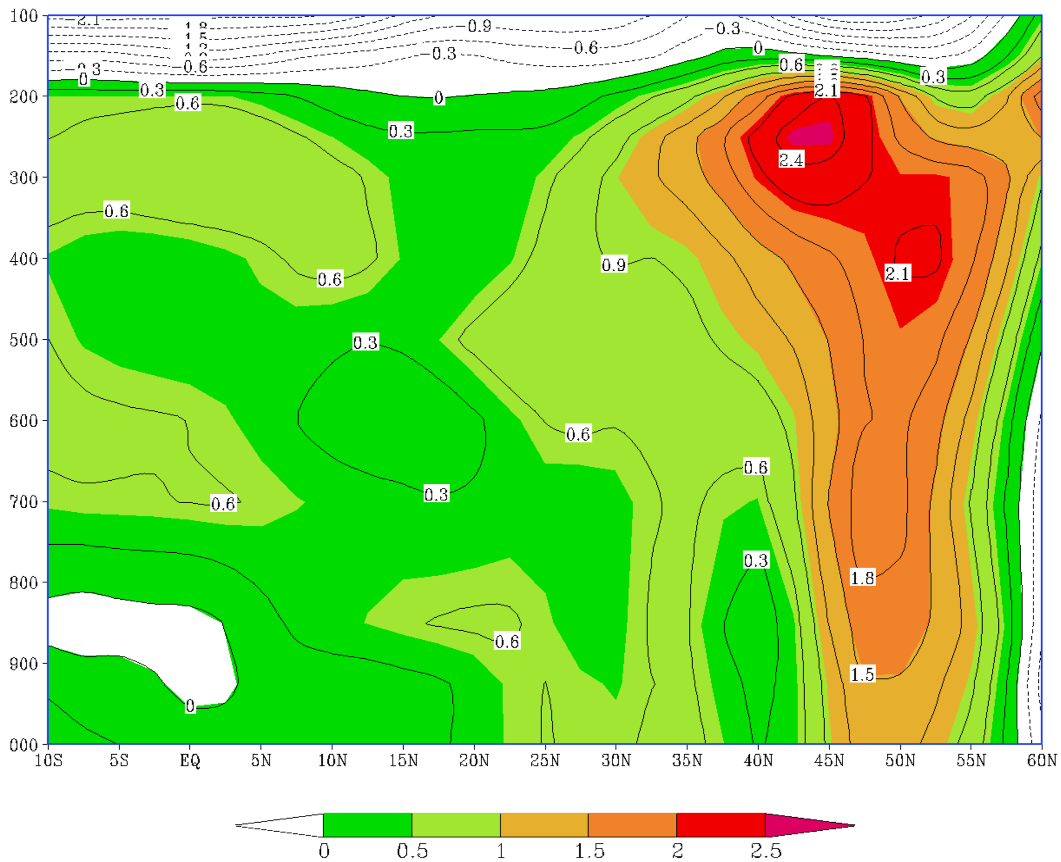


Fig. 10. Latitude-height monthly air temperature (°C) anomalies averaged over the belt from 40° E - 120° E for September 2010

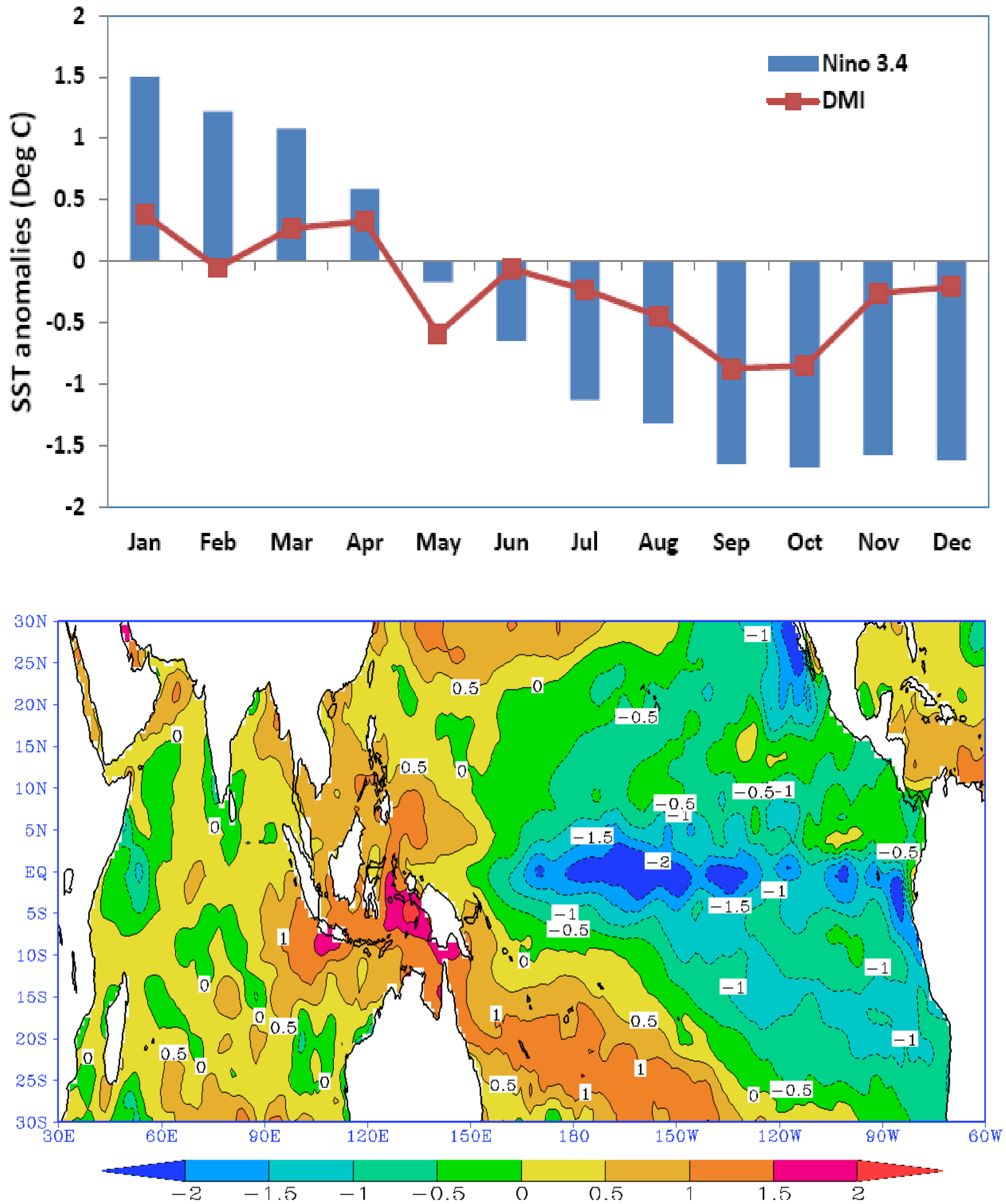
associated with the delay of withdrawal of monsoon. In order to see the impact of this anomalous convection on the atmospheric circulation the long period normal (1971-2010) omega velocity during September, the vertical omega velocity during 2010 September and the anomalies of the same during 2010 averaged over the longitudinal belt of 40° E - 120° E is shown in Figs. 9(a-c). As seen from climatological normal [Fig. 9(a)] that during September 2010, there is primary belt of rising motion over the latitudinal belt of 25° N - 32° N (monsoon trough belt) and in addition there is also a secondary shallow rising motion belt to the north of this is seen along the latitudinal belt of 35° N - 40° N. These two rising motions belts are associated with the sinking motion over the belt of 45° N - 50° N (the region of subtropical anticyclone). It is seen from Figs. 9(b&c) that during 2010 although there is not much difference is seen with respect to the strength of rising motion in the belt over the monsoon trough (25° N - 32° N), whereas, the secondary rising belt over 35° N - 45° N was very active and the anomalous upward motion is penetrated to the upper troposphere as seen from the plots for 2010 and the anomaly plot [Fig. 9(b&c)]. This anomalous strong rising motion in the belt of 35° N - 45° N [Fig. 9(b)] was simultaneously associated with sinking motion in the belt of 45° N - 50° N [Figs. 9 (b-c)]. This anomalous convection over the belt of 35° N - 45° N also contributed to significant warming associated with release of latent heat in the middle to upper troposphere (500 hPa to 200 hPa) over the belt of 45° N-50° N as indicated by positive temperature anomalies of about 2 °C or more (Fig. 10).

3.6. *SST anomalies over Pacific and Indian Ocean region and withdrawal of monsoon*

Two most dominant inter-annual modes of Sea Surface Temperature (SST) variability in the tropics are ENSO (El Nino Southern Oscillation) and the Indian Ocean Dipole/Zonal Mode (IOD; Bjerknes, 1969; Saji *et al*., 1999; Murtugudde *et al*., 2000). The SST anomalies over the eastern and central Pacific region (known as the Nino3.4 region; 5° N - 5° S, 120° W - 170° W) is used to define the El Nino index. Similarly an index to calculate the strength of IOD is the Dipole Mode Index (DMI), which is a measure of the anomalous zonal SST gradient across the equatorial Indian Ocean. It is defined as the difference between SST anomaly in a western (60° E - 80° E, 10° S-10° N) and an eastern (90° E-110° E,10° S-EQ)

(a)

(b)



Figs. 11(a&b). (a) The monthly SST anomalies over the Nino3.4 (5° N - 5° S, 120° W - 170° W) region and Dipole mode index (DMI) during 2010 and (b) SST anomalies during September, 2010

box with a positive IOD winds over the Indian Ocean blow from east to west. To investigate the association of delayed withdrawal of monsoon during 2010 with that of El Nino and IOD the monthly values of Nino 3.4 SST anomalies along with the DMI is plotted in Fig. 11(a). As seen from Fig. 11(a) the El Nino condition was prevailing till the month of May 2010 and gradually the SST anomalies became negative and the La Nina condition was noticed from the month of July onwards. There are many occasions where the La Nina condition has helped in contribution more rainfall in the month of September, 2010. It is also indicated from Fig. 11(a) that during the monsoon season the DMI indicates a negative dipole year. The Spatial patterns of SST anomalies during the month of September, 2010 also indicate the La Nina conditions with eastern and central Pacific indicating large negative anomalies of SST [Fig. 11(b)]. Thus, the delayed withdrawal of monsoon during 2010 is associated with La Nina condition. Similar result were also found by Goswami and Xavier (2005) and Xavier *et al.* (2007), where the withdrawal dates defined in terms of the meridional gradient of the tropospheric temperature averaged between 200 and 700 hPa is found to be having significant relationship with ENSO and most of the early (late) withdrawals are associated with El Nino (La Nina). As shown by Syroka and Toumi (2004) late ISM withdrawals are associated with La Nina conditions in the following winter/spring. However, as also discussed by them this does not necessarily mean a late (early) ISM withdrawal causes a La Nina (El Nino) to develop in the tropical Pacific. Since it is well known that the mature phase of ENSO can be locked to the end of the calendar year (Tziperman *et al*., 1998), an alternative interpretation may be that there is a preferred occurrence of a late (early) ISM withdrawal during a developing phase of La Nina (El Nino).

Fig. 11(b) further indicates that the late withdrawal of monsoon during 2010 was associated with positive SST anomalies over the southeastern equatorial Indian Ocean and negative SST anomalies over the western equatorial Indian Ocean in September similar to the negative phases of IOD (Saji *et al*., 1999; Webster *et al*., 1999; Murtugudde *et al*., 2000), which is very similar to the observation obtained from the recent study by Sabeerali *et al*. (2012), where they indicated that the composite structure of September-October averaged SST anomaly for early (late) withdrawal years is negative (positive) over the southeastern equatorial Indian Ocean, similar to the positive (negative) phases of IOD. Thus, the La Nina condition associated with the positive SST anomalies over the eastern equatorial Indian Ocean particularly during September was linked to delayed withdrawal of monsoon during 2010.

4. Summary

The cause of delayed withdrawal of southwest monsoon over India during 2010 and associated thermodynamic and dynamic features are investigated. The low level circulation anomalies during first three to four weeks of September were associated with anomalous circulation anomalies over the northwest India and positive rainfall anomalies. The low level circulation features was only conducive for the withdrawal of monsoon during the week 27 September - 3 October, 2010 associated with decrease of Precipitable water content and upper tropospheric humidity from northwest India during the week. A low level circulation index defined as the difference of zonal wind between a southern region (5° N -15° N, 50° E - 80° E) and a northern region (20° N - 30° N, 60° E - 90° E), which represents the intensity of the monsoon trough position also indicated a delayed withdrawal of monsoon during 2010. The delayed withdrawal of monsoon from northwest India was associated with above normal convective activity over the monsoon trough belt (25° N - 32° N) and in the sub-tropics latitudes between 35° N - 45° N accompanied by large scale warming over middle to upper troposphere of about 20° C in the latitude belt of 45° N - 50° N. The delayed withdrawal of monsoon during 2010 was also associated with the La Nina condition in the Pacific.

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References

Bjerknes, J., 1969, "Atmospheric teleconnections from the equatorial Pacific", *Mon. Wea. Rev*., **97**, 163-172.

Dey, B., 1970, "Rainfall variability during the Indian summer monsoon", M.S. thesis, Deptt. of Geography, University of Wisconsin, p129.

Goswami, B. N. and Xavier, P. K., 2005, "ENSO control on the south Asian monsoon through the length of the rainy season", *Geophys. Res. Lett*., **32**, L18717. doi:10.1029/2005GL023216.

Gruber, A. and Krueger, A. F., 1984, "The status of the NOAA outgoing long-wave radiation dataset", *Bulletin of the American Meteorological Society*, **65**, 958-962.

Indian Meteorological Department, 1972, "Upper Air Atlas of India and Neighborhood", IMD, New Delhi, India, p60.

Joseph, P. V., Eischeid, J. K. and Pyle, R. J., 1994, "Interannual variability of the onset of the Indian summer monsoon and its association with atmospheric features, El Ni˜no, and seas surface temperature anomalies", *Journal of Climate*, **7**, 81-105.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R. and Joseph, D., 1996, "The NCEP/NCAR 40-year reanalysis project", *Bull. Am. Meteorol. Soc*., **77**, 437-471.

Khole, Medha, Mazumdar, A. B., Devi, S. S. and Yadav, B. P., 2011, "Onset, advance and withdrawal of southwest monsoon 2010", In Monsoon 2010 - A Report, Ajit Tyagi, A. B Mazumdar and D. S Pai (ed.), IMD Met. Monograph No. 10/2011, 1-19.

Kumar, K. K., Kumar, K. R. and Pant G. B., 1997, "Pre-monsoon maximum and minimum temperatures over India in relation to the summer monsoon rainfall", *International J Climatology*, **17**, 1115-1127.

Murtugudde, R., McCreary, J. P. and Busalacchi, A. J., 2000, "Oceanic processes associated with anomalous events in the Indian Ocean with relevance to 1997-1998", *J. Geophys. Res*., **105**, 3295-3306.

Pattanaik, D. R. and Khole, M., 2011, "Performance of extended range forecast during Southwest monsoon 2010", In Monsoon 2010 - A Report, Ajit Tyagi, A. B. Mazumdar and D. S. Pai (ed.) IMD Met. Monograph No. 10/2011; 133-157.

Pattanaik, D. R., 2003, "The northward moving low frequency mode : A case study of 2001 monsoon season", *MAUSAM* , **54**, 937-940.

Pattanaik, D. R., Kalsi, S. R. and Hatwar, H. R., 2005, "Evolution of convection anomalies over the Indo-Pacific region in relation to Indian monsoon rainfall", *Mausam*, **56**, 811-824.

Pattanaik, D. R., Rathore, L. S. and Kumar, Arun, 2013, "Observed and Forecasted Intraseasonal Activity of Southwest Monsoon Rainfall over India During 2010, 2011 and 2012", *Pure and Appl. Geophysics*, DOI 10.1007/s00024-013-0670-1.

Rajeevan, M., Bhate, J., Kale, J. D. and Lal, B., 2006, "High resolution daily gridded rainfall data for the Indian region: Analysis of break and active monsoon spells", *Current Science*, **91**, 296- 306.

Ramage, C. S., 1971, "Monsoon meteorology", Academic Press, New York, USA.

Ramesh, K. J., Basu, S. and Begum, Z. N., 1996, "Objective Determination of Onset, Advancement and Withdrawal of the Summer Monsoon Using Large-scale Forecast Fields of a Global Spectral Model over India", *Meteorology and Atmos. Physics*, **61**, 137-151.

Rao, Y. P., 1976, "Southwest monsoon: Synoptic Meteorology", Meteorology Monograph, No. 1/1976, India Meteorological Department, 1- 367.

Reynolds, R. W., Rayner, N. A., Smith, T. M., Stokes, D. C. and Wang, W., 2002, "An improved in situ and satellite SST analysis for climate", *J. Climate*, **15**, 1609-1625.

Rupa Kumar, K., Pant, G. B., Parthasarathy, B. and Sontakke, N. A., 1992, "Spatial and sub-seasonal patterns of long term trends of the Indian summer monsoon rainfall", *International J. Climatology*, **12**, 257-268.

Sabeerali, C. T., Rao, S. A., Ajayamohan, R. S. and Murtugudde, Raghu, 2012, "On the relationship between Indian summer monsoon withdrawal and Indo-Pacific SST anomalies before and after 1976/1977 climate shift", *Climate Dynamics*, **39**, 841-859.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N. and Yamagata, T., 1999, "A dipole mode in the tropical Indian Ocean", *Nature*, **401**, 360-363.

Sikka, D. R. and Gadgil, S., 1980, "On the maximum cloud zone and the ITCZ over Indian longitudes during the southwest monsoon", *Mon. Wea. Rev.*, **108**, 1840-1853.

Syroka, J. and Toumi, R., 2002, "Recent lengthening of the south Asian summer monsoon season", *Geophys. Res. Lett*., **29**, 1458. doi: 10.1029/2002GL015053.

Syroka, Joanna and Toumi, R., 2004, "On the withdrawal of the Indian summer monsoon", *Q. J. R. Meteorol. Soc*., **130**, 989-1008.

Takagi, T., Kimura, F. and Kono, S., 2000, "Diurnal variation of GPS precipitable water at Lhasa in pre-monsoon and monsoon periods", *J. Meteor. Soc. Japan*, **78**, 175-180.

Thapliyal, P. K., Shukla, M. V., Shah, Shivani, Joshi, P. C., Pal, P. K. and Ajil, K. S., 2011, "An algorithm for the estimation of upper tropospheric humidity from Kalpana observations: Methodology and validation", *J. of Geophysical Res*., **116**, D01108, doi:10.1029/2010JD014291.

Tziperman, E., Cane, M. A. and Blumenthal, B., 1998, "1998 Locking of El Ni˜no peak time to the end of the calendar year in the delayed oscillator picture of ENSO", *J. Climate*, **11**, 2191-2203.

Ueda, H. and Yasunari, T., 1998, "Role of warming over the Tibetan Plateau in early onset of the summer monsoon over the Bay of Bengal and the South China Sea", *J. Meteor. Soc. Japan*, **76**, 1-12.

Webster, P. J., Palmer, T., Yanai, M., Tomas, R., Magana, V., Shukla, J. and Yasunari, A., 1998, "Monsoons: Processes, predictability and the prospects for prediction", *J. Geophys. Res*.. **103**, 14451-14510.

Webster, P. J. A., Moore, J., Loschnigg, M. Leban, 1999, "Coupled ocean dynamics in the Indian Ocean during the 1997-1998", *Nature*, **401**, 356-360.

Webster, P. J., Toma, V. E. and Kim1, H. M., 2011, "Were the 2010 Pakistan floods predictable?", *Geophysical Research Letters*., **38**, L04806, doi:10.1029/2010GL046346.

Wu, G. X. and Zhang, Y. S., 1998, "Tibetan Plateau forcing and the timing of the monsoon onset over South Asia and the South China Sea", *Mon. Wea. Rev*., **126**, 913-927.

Xavier, P. K., Marzin, C. and Goswami, B. N., 2007, "An objective definition of the Indian summer monsoon season and a new perspective on the ENSO-monsoon relationship", *Q. J. R. Meteorol. Soc*., **133**, 749-764.