

The role of low-frequency intraseasonal oscillations in the anomalous Indian summer monsoon rainfall of 2002

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We analyze the dynamical features and responsible factors of the low-frequency intraseasonal time scales which influenced the nature of onset, intensity and duration of active/break phases and withdrawal of the monsoon during the anomalous Indian summer monsoon of 2002 – the most severe drought recorded in recent times. During that season, persistent warm sea surface temperature anomalies over the equatorial Indian Ocean played a significant role in modulating the strength of the monsoon Hadley circulation. This in turn affected the onset and intense break spells especially the long break during the peak monsoon month of July. Strong low-frequency intraseasonal modulations with significant impact on the onset and active/break phases occurred in 2002 which were manifested as a good association between low-frequency intraseasonal oscillations and the onset and active/break spells. Further, SST anomalies over the equatorial Indo-Pacific region on low-frequency intraseasonal time scales were found to affect the equatorial eastward and thereby off-equatorial northward propagations of enhanced convection over the Indian region. These propagations in turn modulated the active/break cycle deciding the consequent severity of the 2002 drought.

1. Introduction

Fluctuations in monsoon rainfall have a decided impact on the society and economy of monsoon countries. In spite of the remarkable consistency in the seasonal reversal of the large-scale circulation features associated with monsoon, the Indian summer monsoon rainfall (ISMR) exhibits considerable interannual variability. Some of this variability of the monsoon can be related to ENSO where the enhanced convection associated with warm sea surface temperature (SST) anomalies in equatorial eastern Pacific can induce anomalous subsidence of Walker circulation over the Indian region and thereby suppress monsoon rainfall (Sikka 1980; Palmer *et al* 1992; Sikka 2003). However, there appear to be modulations that occur independently of ENSO extrema (e.g., 1979, 1986, and 1994), particularly noteworthy is the recent abnormally

low ISMR in 2002 (Sikka 2003; Kalsi *et al* 2004). This most severe drought season recorded in recent times (with rainfall about 19% below the long term all-India normal) was associated with only a weak, warm SST anomaly developing in the central Pacific during the latter half of the season. Apart from the anomalously low seasonal rainfall, the remarkably different nature of the onset and subseasonal evolution of the monsoon during this year are compelling reasons for undertaking this study.

Many studies have investigated the possible causes for the 2002 drought over India (e.g., Gadgil *et al* 2002, 2003; Bhat 2003; Sikka 2003; Kalsi *et al* 2004; Narayanan *et al* 2004; Srivastava *et al* 2004). Many contributing planetary scale factors which developed close to the region, almost simultaneously with the evolution of 2002 monsoon were suggested as possible causes for the 2002 July

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break and the consequent seasonal monsoon deficit. These were:

- the persistent wave-like pattern over Eurasia with a trough in the middle and upper troposphere over the Caspian Sea–Aral Sea region which exerted influence over northwest India leading to persistent subsidence over northwest India and the adjoining Arabian Sea,
- southward shift of the Mascarene high and
- eastward anchoring of organised convection over the NW Pacific (Sikka 2003; Kalsi *et al* 2004).

Among these, the third factor caused an eastward shift in the genesis of tropical storm/typhoon activity and northward steering of their tracks. These factors weakened the monsoon on the one hand by preventing their remnants reaching the Bay of Bengal for a possible revival there, or on the other hand by inducing subsidence over the adjacent Indian region. Gadgil *et al* (2003) examined the simultaneous relationship between equatorial Indian Ocean and Indian summer monsoon rainfall. They showed that every monsoon season with excess rainfall/drought during 1979–2002 can be explained in terms of the favourable/unfavourable phase of EQUINOO (Equatorial Indian Ocean Oscillation, defined as the oscillation in surface zonal wind anomalies between west and east equatorial Indian Ocean). Bhat (2006) suggested that the major July 2002 break was associated with persistent and strong multiple inversions due to the prevalence of the air of desert origin, over the eastern Arabian Sea and the west coast of India.

In addition to the large-scale forcings, significant modulations occur on intraseasonal time scales due to internal variability of the Indian summer monsoon system (Goswami 1998). This intraseasonal variability plays a major role in the evolution of monsoon, of which the low-frequency component is the dominant factor in deciding seasonal monsoon rainfall. During 2002, the low-frequency component of intraseasonal variability in the range of 20–60 days was found to be much stronger than other intraseasonal modes such as 10–20 days (Narayanan *et al* 2004; Sabade *et al* 2006; Saith and Slingo 2006). In this study we investigate the nature of the prominent low-frequency intraseasonal oscillations (hereafter referred to as ‘ISO’) during the drought of 2002, and their contribution in modulating the evolution of the 2002 summer monsoon rainfall. In particular, this study focuses on the role of the northward propagating ISO (NPISO, Sikka and Gadgil 1980) and its global component associated with the Madden–Julian Oscillation (MJO, Madden and Julian 1994) in the 2002 monsoon and the connection between their

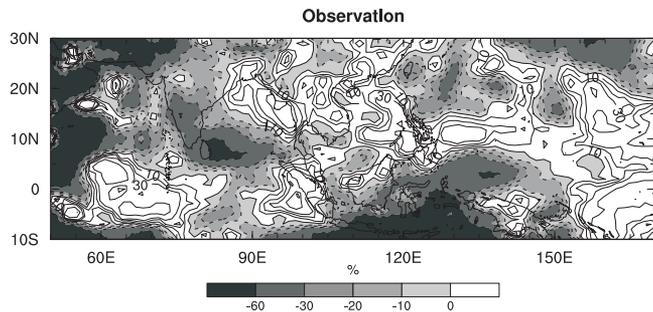


Figure 1. 2002 JJAS mean rainfall departure as percentage of climatological JJAS mean based on TRMM 3B42 rainfall.

phases and the onset and active/break spells of the 2002 Indian summer monsoon. For the analysis we made use of the recent TRMM based datasets with the objective of assessing their utility for tropical ISO studies.

The datasets used for the analysis are described in section 2. The observed features of 2002 Indian summer monsoon and the role played by ISO are discussed in section 3. Concluding remarks are given in section 4.

2. Datasets

We make use of data from the microwave radiometer onboard the Tropical Rainfall Measuring Mission (TRMM) satellite. For the analysis of 2002 monsoon rainfall, daily 3B42 TRMM-adjusted merged-infrared precipitation (Version 5) since 1998 (Adler *et al* 2000) is used. For computing the long-term daily mean data used in figures 1 and 3, a combined data set of daily rainfall estimates interpolated from Global Precipitation Climatology Project (GPCP) pentad precipitation data for the period 1979–1997 (Xie *et al* 2003) and daily TRMM 3B42 data at $1^\circ \times 1^\circ$ resolution are used. The other TRMM Microwave Imager (TMI) data used in this study are 3-day running means of surface wind speed derived using 11 GHz radiometer channel (<http://trmm.gsfc.nasa.gov>). In addition, daily NCEP/NCAR reanalysis datasets (Kalnay *et al* 1996), daily SSTs interpolated from 1982–2002 Reynolds’s weekly SSTs (Reynolds *et al* 2002) and monthly NOAA OI.v2 SST datasets (Reynolds and Smith 1994) are also used. Daily raingauge observations over the Indian landmass based on COLA GTS data (<http://www.monsoondata.org>) for the period 1979 to 15 September 2002 is also used.

3. Indian summer monsoon of 2002

The abnormal Indian summer monsoon of 2002 is the most severe drought recorded in recent times

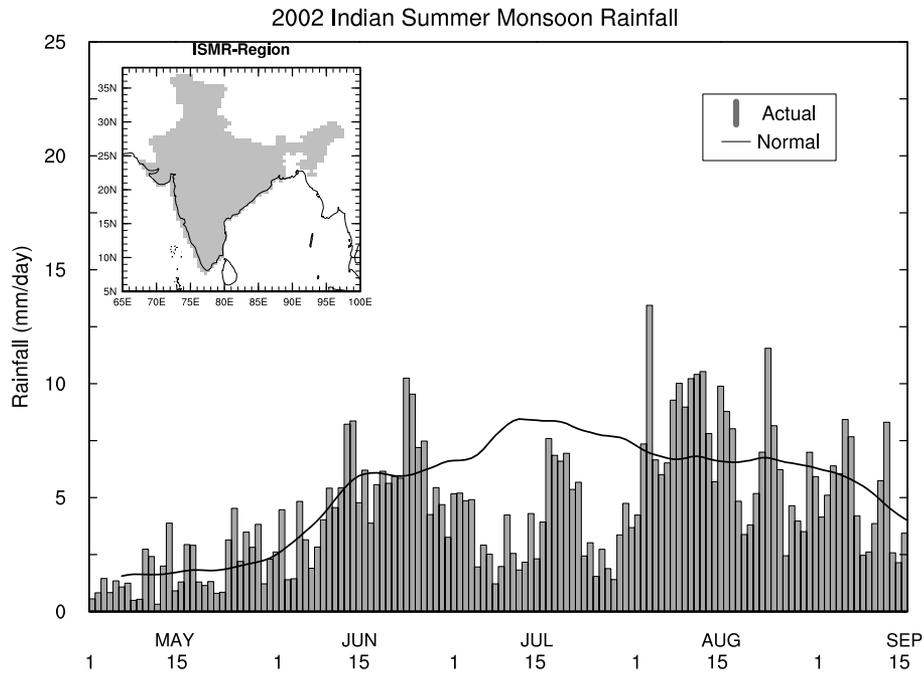


Figure 2. Daily all-India (region highlighted in the inset map) average rainfall from COLA GTS data during 2002 summer season. Daily long term mean is represented by the solid line.

with the observed rainfall about 19% below the long term all-India normal. Here, we present a detailed analysis of this severe drought monsoon and its contributing factors on intraseasonal time scales.

Observed June–July–August–September (JJAS) mean rainfall departure during 2002 based on TRMM 3B42 rainfall shows that severe drought conditions prevailed over most of the Indian subcontinent with large areas in western India and southern peninsula where the monsoon rainfall was deficient by more than 30% of the normal (figure 1). At the same time of widespread decrease of seasonal monsoon rainfall over land, the equatorial Indian Ocean (EQIO) experienced intense rainfall anomalies more than 20% of normal extending longitudinally across most of the ocean basin. The maximum value of the anomaly over 60°E – 75°E around the equator is close to 50%.

Daily variation of the 2002 all-India summer monsoon rainfall (figure 2) based on COLA GTS data comprising raingauge estimates over the Indian landmass (highlighted in the inset India Map), distinctly shows the special nature of the onset and evolution of monsoon during the 2002 summer season. A notable aspect of 2002 season is the special onset (Ananthakrishnan and Soman 1988; Joseph *et al* 1994; Flatau *et al* 2003) where the false onset occurs around 11 May with mild and intermittent rainfall continuing until around 28 May. The region experiences a dry spell afterwards

which results in a late onset of bountiful monsoon rains over India compared to the climatological onset date in the end of May/beginning of June. The real onset of rainfall occurs around mid-June that persists until the last week of June. Unlike during the false onset, associated with the real onset, the low-level jet (LLJ) reaches sufficient strength to provide sustained cross-equatorial flow of moist air which is seen typically associated with the actual monsoon onset. The sustained seasonality in monsoon regional components such as LLJ and the monsoon Hadley circulation associated with the real onset will be discussed subsequently. The primary feature of the season is the intense and long dry spell extending from the end of June until the beginning of August.

The large-scale variation of ISMR is associated with fluctuations in rainfall over the monsoon convergence zone (MCZ) coinciding with the mean location of seasonal trough over India (Sikka 1980; Gadgil 2003). The variation in rainfall over the MCZ is closely related to active and break phases characterized by enhanced and reduced precipitation over central and northern India with associated changes in large-scale circulation. The daily normalized anomalies of rainfall averaged over central India (15°N – 25°N ; 75°E – 85°E , coinciding the MCZ) and EQIO (10°S – 5°N ; 50°E – 100°E) shows all the major characteristics of 2002 season viz., the double onset, intense break in July, and the early withdrawal of monsoon (figure 3).

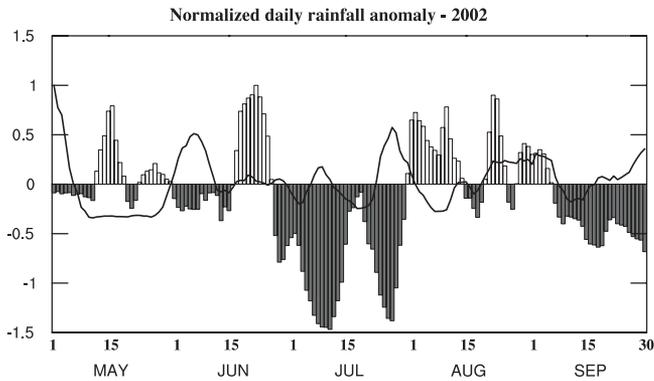


Figure 3. Normalized daily rainfall anomalies during 2002 summer season based on TRMM 3B42 rainfall data. The bars represent average over the central Indian region (MCZ) and the line represents average over the equatorial Indian Ocean (EQIO).

The false onset occurs in mid-May with mild and intermittent rainfall continuing until the beginning of June. The region experiences a dry spell afterwards with the real onset of rainfall occurring in the middle of June and continuing up to the last week of June. This results in a late onset of bountiful monsoon rains over India compared to the climatological onset date in the beginning of June. It can be seen that there is an intense and long dry spell extending from the end of June until the beginning of August. Finally the season experiences an early withdrawal of monsoon due to a long break spell extending from the second week of September. These active/break phases over the MCZ have been consistent with the 2002 ISMR daily variation entirely based on the *in situ* rainfall over Indian stations (figure 2, and also with the corresponding variation based on IMD dataset available at <http://www.tropmet.res.in>). A notable feature in figure 3 is the near-inverse rainfall variation between MCZ and EQIO where increased (decreased) rainfall over EQIO coincides with decreased (increased) rainfall over the MCZ throughout most of the summer season. This can be understood in terms of the modulations in the two limbs of the reverse Hadley cell (monsoon cell) with one on the warm equatorial Indian Ocean and the other over the heated continent in the north.

3.1 Role of equatorial SST

The mean SST departure during the peak monsoon months of July and August of 2002 (figure 4, based on Reynold's monthly OI SST) shows that the entire equatorial Indian Ocean was anomalously warm with anomalies stronger than that over the west Pacific Ocean. These anomalies over regions with warm mean SSTs (greater than the

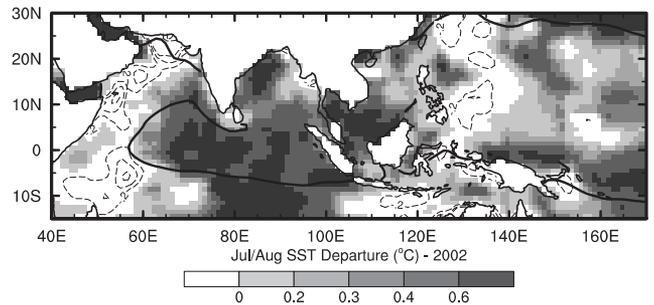


Figure 4. July–August mean SST anomaly (positive: shaded; negative: dashed contours) in 2002. Solid line highlights the region with climatological July–August mean SST greater than 28°C .

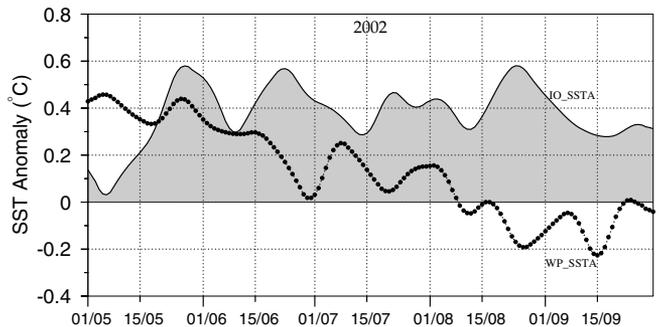


Figure 5. SST anomalies averaged over equatorial Indian Ocean (denoted as IO_SSTA) and western Pacific (denoted as WP_SSTA) during 2002.

basin threshold value of $\sim 28^{\circ}\text{C}$ for the commencement of organized convection, Gadgil *et al* (1984) are important and can modulate the meridional land–ocean temperature contrast and the local Hadley circulation resulting in increased ascent (descent) and convection (subsidence) over the equatorial Indian Ocean (Indian subcontinent). On the seasonal mean time scale, observational (Krishnan *et al* 2003) and sensitivity studies based on idealized Indian Ocean SST anomalies (Chandrasekar and Kitoh 1998) suggest that rainfall increased (decreased) over the equatorial Indian Ocean domain of warm (cold) SST anomaly. This was found to be associated with anomalous negative (positive) rainfall departures on the seasonal time-scale over the Indian land region accompanied by the weakening (strengthening) of the cross equatorial flow and local Hadley circulation.

The normalized daily SST anomalies (interpolated from Reynold's weekly SSTs) averaged over EQIO and western Pacific warm pool region (5°S – 5°N ; 120°E – 160°E) also show that in spite of sub-seasonal fluctuations, the warm SST anomalies persisted over EQIO throughout the season (figure 5). To understand the mechanisms responsible for sustaining this persistent warmer anomalies

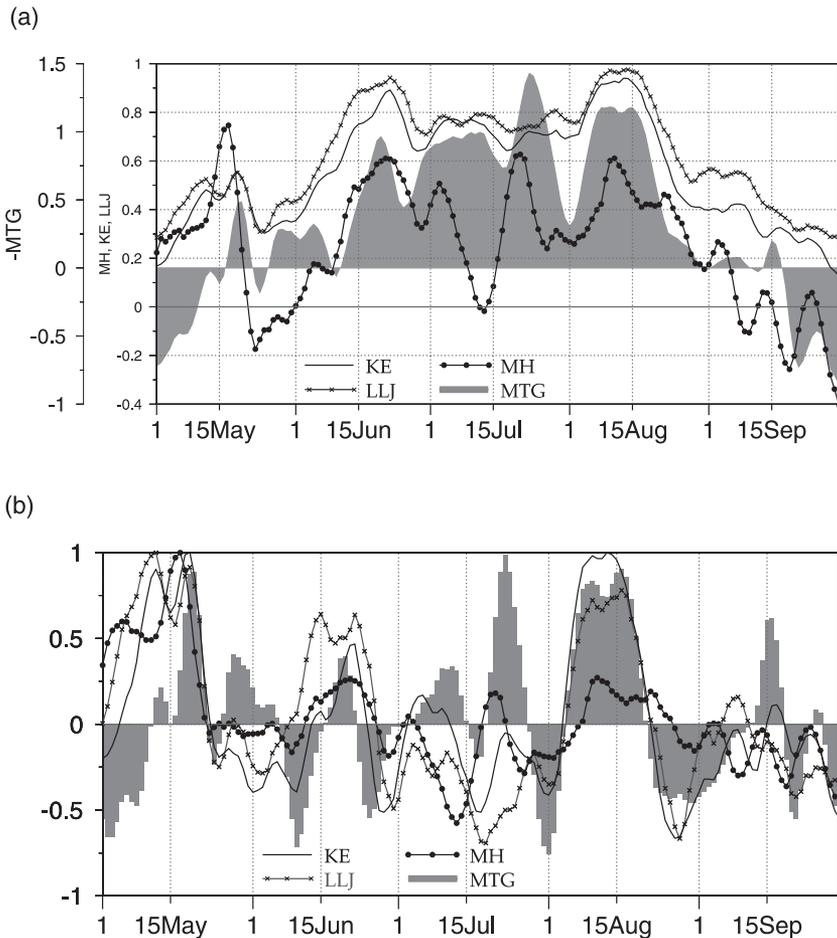


Figure 6. Daily (normalized and then 5-day running mean applied) (a) time series of different monsoon indices and (b) time series of anomalies of different monsoon indices during 2002 Indian summer monsoon season.

throughout the season, the role of the developing El Niño and surface and subsurface ocean circulation needs to be investigated in detail. These anomalies were larger than the anomalies over west Pacific especially in later months of the season when weak warm El Niño anomalies started developing in the central Pacific. This can impact both the local Hadley circulation over the Indian sector and the Walker circulation along the Asia–Pacific sector resulting in the equatorial Indian Ocean having an anomalously stronger convection compared to Indian landmass and west Pacific warm pool regions (figure 1).

3.2 Subseasonal variation

It is known that the duration and strength of break spells in a certain year are important in deciding the seasonal mean rainfall anomaly during that year (Krishnamurti and Bhalme 1976). In addition, the majority of the years that experienced double onset has been found to be associated with below normal rainfall (Flatau *et al* 2001). Thus, the occurrence of long and intense break spells

and a double onset over India assumes great significance in deciding the seasonal anomaly during 2002. Therefore, it is pertinent to examine the sub-seasonal time-scale response of convection to this persistent SST anomaly over the Indian Ocean. Also a consistent understanding of the relationship between the EQIO SST anomalies and ISO variability in convection is thus essential for interpreting the intense break spells particularly in the peak monsoon month of July.

To further understand the fluctuations in monsoon activity within the season, different monsoon indices that reflect the intraseasonal circulation changes, are analyzed. For this, a monsoon circulation index (MH, Goswami *et al* 1999, based on the strength of the local Hadley cell created by the off equatorial monsoon heating, is defined as the shear between 850 and 200-hPa meridional winds averaged over 10°N–30°N; 70°E–110°E), the kinetic energy of the surface winds (KE) averaged over 5°N–20°N; 40°E–110°E, the strength of cross-equatorial flow associated with the low-level Somali jet (LLJ) based on the 850-hPa wind speed averaged over 5°N–20°N; 50°E–80°E and

the meridional temperature gradient index (MTG, Kawamura 1998, based on the difference in area-averaged upper tropospheric (500–200 hPa) thickness between the Tibetan Plateau (20°N–40°N; 50°E–100°E) and the Indian Ocean (0°N–20°N; 50°E–100°E) regions) are used.

Actual and normalized (with respect to the daily long term mean over the last 30-year period) anomalies of these indices (figure 6a and b) show the close relationship between subseasonal variation of large-scale circulation and that of the monsoon rainfall (figure 3). The peaks of the indices in mid-May corresponds to the false onset and the peaks in mid-June corresponds to the real onset. The weakening of large-scale monsoon circulation parameters during July till the beginning of August corresponds to the intense break spell and the revival afterwards coincides with the short active spell in the first week of August. The indices show weakening of large-scale monsoon circulation after the first week of September and the commencement of the next intense break spell results in an early withdrawal of monsoon. One notable aspect is the pronounced fluctuations in MH, LLJ and KE and to some extent in MTG that are markedly consistent with the MCZ rainfall fluctuations. These variations indicate significant subseasonal modulations in the local Hadley circulation. Another notable aspect is the difference in actual monsoon indices between the false and real onset phases (figure 6a). Unlike during the false onset phase, the actual indices show a sharp and sustained strengthening of the indices associated with the real onset until the withdrawal. Whereas, during the false onset, the indices do not show a sustained increase in amplitudes which indicates the absence of organized seasonal changes in all forcing factors of monsoon.

3.2a Northward Propagating Intraseasonal Oscillations (NPISO)

The dominant mode of monsoon low-frequency intraseasonal variation that is associated with the onset and active-break spells over the Indian region is the northward propagating ISO (NPISO, Sikka and Gadgil 1980; Gadgil 2003). NPISOs comprise successive 30–40-day time-scale northward propagations of organized convection in summer over the Asia–west Pacific sector (Yasunari 1979; Sikka and Gadgil 1980; Srinivasan and Smith 1996). The time-latitude variation of 20–80-day band pass filtered (following Duchon 1979) TRMM 3B42 rainfall and TMI surface winds averaged over Indian longitudes (figure 7) shows the close relationship between propagating signals of active convection and the onset, active and break phases and withdrawal of monsoon. The false onset was

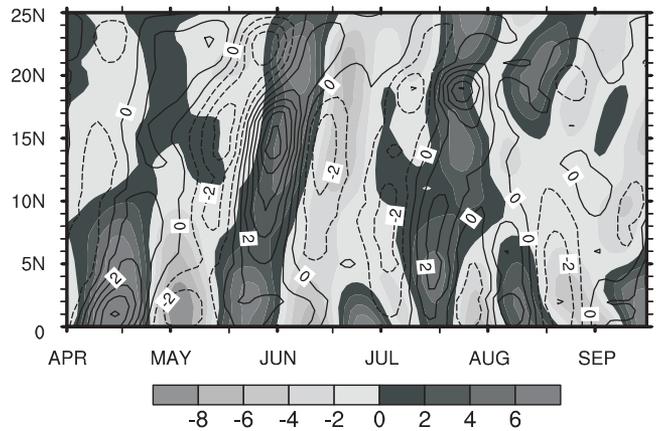


Figure 7. Time–latitude variation of 20–80-day filtered TRMM 3B42 rainfall anomalies averaged over 75°E–85°E (shaded) and filtered TMI surface zonal wind speed anomalies (contours) averaged over western Indian Ocean (50°E–80°E).

characterized by a propagating rainbelt from the equatorial Indian Ocean reaching the southern peninsula in the middle of May. A later real onset of heavy precipitation over India by the middle of June coincides with the next propagating anomaly reaching the central Indian latitudes. The intense break spell during July and after the first week of September resulting in an early withdrawal are associated with prolonged periods of suppressed convection and absence of any active propagations. The enhancement (weakening) of the cross equatorial flow that is a measure of the strength of local Hadley circulation and the large-scale monsoon leads the propagating convective (non-convective) anomalies. This shows that the evolution of the monsoon and fluctuations in ISMR during 2002 were strongly associated with variations in cross equatorial flow.

3.2b Madden–Julian Oscillation (MJO)

Due to the significant role of NPISOs on monsoon, several studies have attempted to address the responsible mechanism behind NPISOs (e.g., Goswami and Shukla 1984; Nanjundiah *et al* 1992; Wang and Xie 1997). Some of these studies suggest that NPISOs are closely related to the eastward propagations associated with the MJO (e.g., Krishnamurti and Subrahmanyam 1982; Wang and Rui 1990; Wang and Xie 1997; Rajendran and Kitoh 2006). Wang and Xie (1997) used an intermediate model to show that the northward propagations over the Indian region are caused by emanation of the moist Rossby waves over maritime continents of west Pacific. The emanation occurs when coherent equatorial MJO propagation as a coupled Kelvin–Rossby wave packet attenuates over the Maritime Continent due to decreased moist

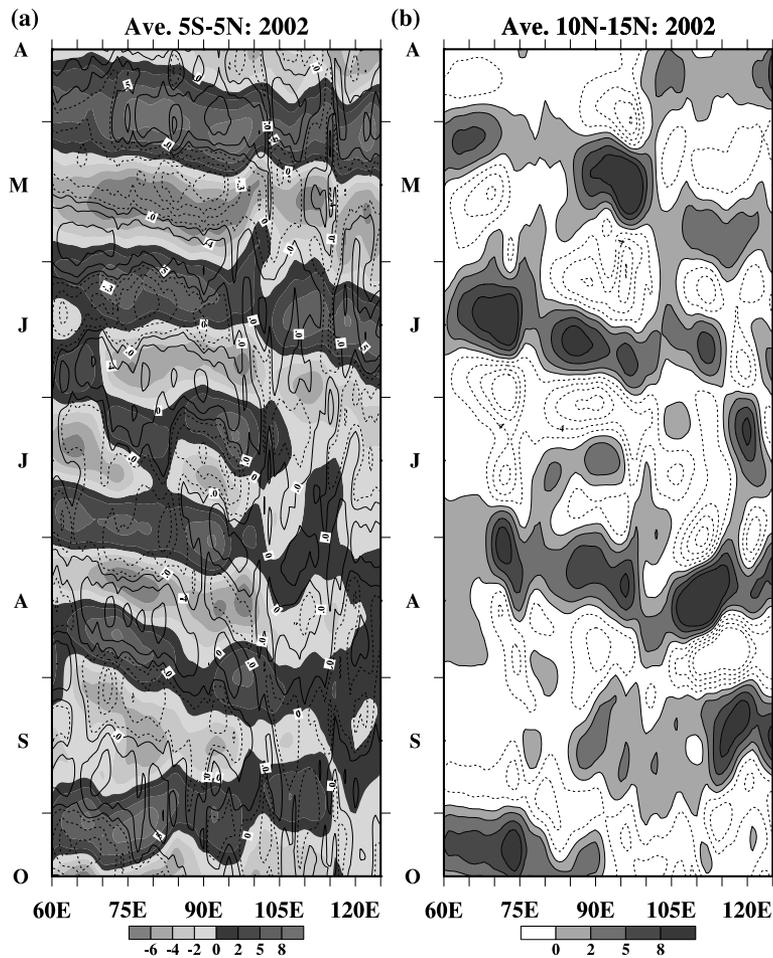


Figure 8. (a) Time-longitude variation of 20–80-day filtered TRMM 3B42 rainfall and filtered SST (contour) anomalies averaged over the equator (5°S – 5°N) and (b) filtered observed rainfall averaged over the off-equatorial region (10°N – 15°N).

static energy stored in the boundary layer. Hence, the fact that the NPISOs in the Indian sector are one aspect of the equatorial eastward moving Kelvin–Rossby wave packet will be reflected in the eastward propagation of the off-equatorial convection (Lawrence and Webster 2002; Rajendran and Kitoh 2006). Figure 8 shows the time-longitude variation of (a) 20–80-day filtered anomalies of rainfall (shades) and SST (contour) averaged over the equator (5°S – 5°N) and (b) filtered rainfall averaged over the off-equatorial region (10°N – 15°N). Consistent with the hypothesis of Wang and Xie (1997), coherent MJO propagations reaching the maritime continents of the western Pacific (figure 8a) lead to later off-equatorial eastward propagations over the Indian region (figure 8b) which in turn are associated with subsequent NPISOs (figure 7) over the north Indian Ocean coinciding with the active and break spells of ISMR. Thus, the evolution of MJO activity during the summer of 2002 (figure 8) provides important forecasting clues about the onset and break spells. For example, the development of false onset depended on the timing

of intraseasonal oscillation (ISO) in the Indian Ocean and the propagation of convective episodes into the western Pacific. The false onset in 2002 was initiated by the northward motion of equatorial convection related to the ISO that developed in the Indian Ocean in early May.

The SSTs and coupled air–sea interaction are found to be crucial for both equatorial MJO and NPISO propagations (Rajendran and Kitoh 2006). On intraseasonal time scales, SSTs are found to have a coherent phase relationship with convection where warm (cold) SSTs lead (lag) enhanced convection by about a week (figure 8a). In addition to the fact that tropical ISOs evolve through coherent air–sea convective intraseasonal interaction among SST, convection and surface fluxes, the SST is also modulated with significant impact from convection through a coupled feedback process on intraseasonal time scales over the Indian and west Pacific Oceans. Thus, as the ISO propagated eastward to the western Pacific, intense convection feedbacks to cool off the SSTs that inhibit further convection till the next SST warming phase

is invigorated by suppressed convection. The short dry spell after the false onset is led by cooler intraseasonal SSTs and the real onset lags the next warm SST propagation. The next MJO propagation lags a propagating warm SST signal eastward into the west Pacific with slightly faster speed over the western Pacific. Corresponding to the prolonged break conditions over India in July and September, there are signals of aborted MJO propagations over the eastern Indian Ocean. Their advancement into the western Pacific is terminated by the negative intraseasonal SST anomalies over the west Pacific which may have also been associated with the developing El Niño condition. Due to their failure to progress further eastward, these aborted events do not result in the northward advancement of convection over the Indian sector (figure 8b) and absence of active NPISO over north Indian Ocean. Consequently, the absence of NPISO propagations across the Indian longitudes (figure 7) favours break condition over India. During these periods, the persistent warm SST anomalies over Indian Ocean (figures 6 and 8a) result in intense convection over the equatorial Indian Ocean (figures 3 and 8a). This reveals the significant role of equatorial waves on the onset and break spells during 2002 and the influential role played by SST anomalies over equatorial Indian Ocean. Analysis of other recent extreme years (e.g., 2000) also indicates that the propagations associated with equatorial MJO combined with the evolution of SST anomalies over equatorial warm oceans can give important forecasting leads about the real onset of rainfall in the case of a false onset and the dry spells over India in advance.

4. Conclusions

The dynamical features and contributing factors responsible for the evolution of monsoon during the anomalous season of 2002 reveal the significant roles played by equatorial intraseasonal wave activity in deciding the onset and active/break spells and SST anomalies over the equatorial Indian Ocean. Further, the intraseasonal SST anomalies over the entire warm equatorial oceans of the Asia–Pacific region significantly modulate the MJO propagations which in turn feedback into the NPISO propagations and impact the onset and break phases deciding the consequent severity of drought over India.

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