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On the relationship between Indian summer monsoon withdrawal and Indo-Pacific SST anomalies before and after 1976/1977 climate shift

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Abstract A clear shift in the withdrawal dates of the Indian Summer Monsoon is observed in the long term time series of rainfall data. Prior (posterior) to the 1976/1977 climate shift most of the withdrawal dates are associated with a late (an early) withdrawal. As a result, the length of the rainy season (LRS) over the Indian land mass has also undergone similar changes (i.e., longer (shorter) LRS prior (posterior) to the climate shift). In this study, probable reasons for this significant shift in withdrawal dates and the LRS are investigated using reanalysis/observed datasets and also with the help of an atmospheric general circulation model. Reanalysis/observational datasets indicate that prior to the climate shift the sea surface temperature (SST) anomalies in the eastern equatorial Pacific Ocean and the Arabian Sea exerted a strong influence on both the withdrawal and the LRS. After the climate shift, the influence of the eastern equatorial Pacific Ocean SST has decreased and surprisingly, the influence of the Arabian Sea SST is almost non-existent. On the other hand, the influence of the southeastern equatorial Indian Ocean has increased significantly. It is observed that the upper tropospheric temperature gradient over the dominant monsoon region has decreased and the relative influence of the Indian Ocean SST variability on the withdrawal of the Indian Summer Monsoon has increased in the post climate shift period. Sensitivity experiments with the contrasting SST patterns on withdrawal dates and the LRS in the pre- and post- climate shift scenarios, confirm the observational evidences presented above.

Keywords Indian monsoon · El Niño · Indian Ocean Dipole · Climate shift

1 Introduction

One of the notable annual features of the south Asian summer monsoon system is the remarkable regularity in the sudden onset and the gradual withdrawal of rainfall over the Indian subcontinent indicating the beginning and the end of the rainy season. The south Asian summer (June–September) monsoon precipitation shows no long-term trend over the last several decades (e.g., Goswami et al. 2006a) despite the rise in global mean surface temperature. However, few recent studies highlight the importance of the timing and the variability of the withdrawal phase of the monsoon as it is intrinsically linked with the length of the summer monsoon season. The seasonal mean rainfall can be influenced by changes in the length of the rainy season. In this context, withdrawal of the monsoon and the associated teleconnection patterns assume significance. Studies to date have tended to concentrate on the June–September (JJAS) definition of south Asian summer monsoon, limiting the number of detailed studies on the variability and the effect of warmer climate on the retreat phase.

The withdrawal of the Indian summer monsoon is characterized by the southward movement of the monsoon trough, the displacement of the moist marine air by a dry continental air mass and the development of an

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anticyclonic flow over north and central India. The upper level anticyclone at 200 mb centered over northern India in JJAS shifts to Southeast Asia. It is also characterized by the reduction of rainfall over India, the decay of anticyclonic circulation seen over the Tibetan Plateau during the monsoon season, a weakening and the disappearance of the easterly jet stream from south of the Himalayas to be replaced by the reappearance of the subtropical westerly jet stream (Dey 1977). The withdrawal phase faithfully begins over northern India in September with a gradual equatorward movement and a deceleration of the low-level westerly flow.

Since the Indian summer monsoon withdrawal over central India (the monsoon core region) is a relatively fast process but the whole process occurs over a month (the withdrawal dates over the monsoon core area vary from September 16 to October 16), we have taken the mid-September to mid October to study the basic characteristics of the withdrawal phase. The southward march of the Inter Tropical Convergence Zone (ITCZ) during the withdrawal is accompanied by reduced rainfall over the Indian subcontinent and a shift of maximum rainfall to the south of the equator (Fig. 1a). During the June–September period, the farthest northward position of the ITCZ places the rainfall maximum over the northern Bay of Bengal close to 20°N (Gadgil 2003). The low-level winds during September–October consist of westerlies in the tropical northern Indian Ocean and easterlies in the tropical Pacific (Fig. 1c). The cross-equatorial monsoon low level jet in the Indian Ocean, which is normally observed in JJAS, is weakened during the withdrawal. Strong easterlies in the Southern Hemisphere subtropics are also a feature of the withdrawal phase. The upper level anticyclone, which is observed to propagate northwestward in JJAS (Hsu et al. 1999), starts to transit southward during the retreat of the Indian summer monsoon (Fig. 1e). Also seen are easterlies in the tropical Indian Ocean and jet-like strong westerlies in the subtropics of both the hemispheres. Climatological SSTs in the withdrawal period show maximum values in the tropical western Pacific and the equatorial Indian Ocean (Fig. 1f).

The conventional definition of the Indian monsoon withdrawal date defined by the India Meteorological Department (IMD) is based on a reduction in rainfall totals and the establishment of lower tropospheric anticyclonic circulation over certain regional subdivisions (http://www.imd.gov.in/section/nhac/dynamic/withdrawal_criteria.htm). Dynamically, a complete reversal of lower tropospheric flow patterns is used to define the withdrawal date. Syroka and Toumi (2002, 2004) defined a low-level (850 hPa) circulation index as the difference between a southern region (5°N–15°N; 50°E–80°E) and a northern region (20°N–30°N; 60°E–90°E) to represent the withdrawal phase of monsoon. The withdrawal of the monsoon is strongly correlated with ENSO when the above mentioned circulation index is used (Syroka and Toumi

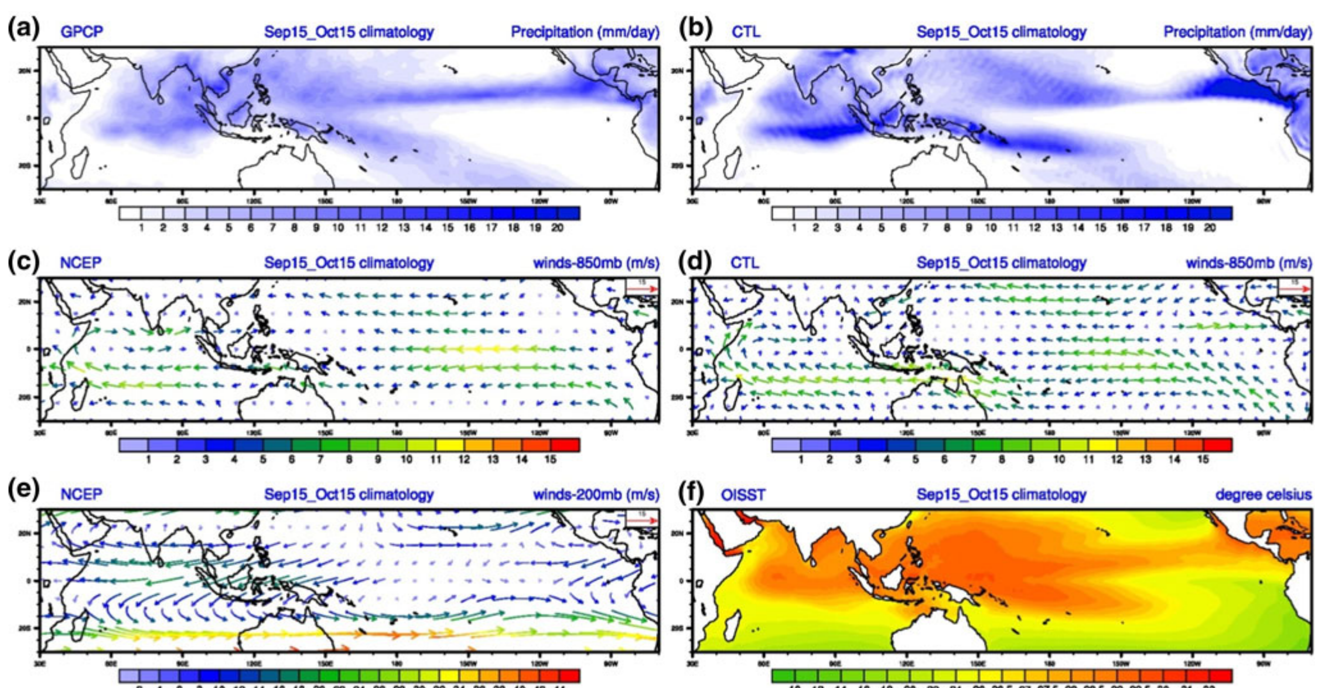

Fig. 1 The mid-September to mid-October climatology of precipitation (mm day^{-1}) from **a** observations, **b** ECHAM5. **c** and **d** same as **a** and **b** respectively but for 850-hPa wind (m/s). **e** and **f** same as **a** but for 200-hPa wind (m/s) and SST (°C) respectively. The observational precipitation is from GPCP 1° daily data (1996–2008), wind is from NCEP/NCAR reanalysis (1950–2008) and SST is from 0.25° daily Optimum Interpolated Seas Surface Temperature (OISST) from 1981 to 2008

2004). Wang and Linho (2002) defined the onset and withdrawal of the monsoon based on the relative climatological pentad mean rainfall, which is the difference between the climatological pentad mean rainfall for May–September and that for January. They defined the withdrawal of the monsoon as the transitional pentad in which the relative climatological pentad mean rainfall falls below 5 mm day^{-1}. Based on the hydrological cycle, Fasullo and Webster (2003) used the vertically integrated moisture transport as a proxy for defining the monsoon onset and withdrawal dates. Their index has a significant relation with the monsoon onset and ENSO, but the relationship with the monsoon withdrawal and ENSO is not significant. Later, Goswami and Xavier (2005) and Xavier et al. (2007) used the meridional gradient of the tropospheric temperature averaged between 200 and 700 hPa (details in Sect. 2) as a proxy to define the onset and withdrawal dates. The onset, withdrawal and the length of the Indian summer monsoon calculated using such a thermodynamic index exhibit significant relationship with ENSO (Goswami and Xavier 2005). Most of the early (late) withdrawals are associated with El Niño (La Niña) which shortens (extends) Indian summer monsoon season (Xavier et al. 2007).

In short, the dynamical/thermodynamical definition of the monsoon withdrawal hints at changes in the timing of withdrawal of monsoon in recent decades and thereby shortening/extending the LRS and rainfall totals. The aforementioned studies also confirm the significant relationship between the Pacific SST anomalies and the monsoon withdrawal. It should be noted that the tropical Pacific underwent a major climate shift around 1976/1977 (Graham 1994). The 1976–1977 shift in both the eastern and central North Pacific Ocean was caused by unique atmospheric anomalies, which acted several months before the 1976–1977 winters (Miller et al. 1994). It is hypothesized that the Pacific shift is also associated with a tropical Atlantic shift (Murtugudde et al. 2001) and Atlantic SSTs are argued to influence Indian monsoons at interannual and longer time-scales (Zhang and Delworth 2006; Kucharski et al. 2008, 2009). The focus of this study is however on the impact of Indo-Pacific SST variability on the monsoon withdrawal. The Atlantic SST effects on the same will be reported elsewhere as a separate study.

Previous studies have reported an increase in SST and convective activity over the eastern and central Pacific since 1976–1977 (Nitta and Yamada 1989; Wang 1995; Kachi and Nitta 1997) and at the same time a cooling in the extratropical North Pacific and South Pacific is reported to have occurred (Wang 1995). Due to the changes in the Pacific background state since 1976–1977, the characteristic of ENSO evolution is hypothesized to be different across the 1976–1977 climate shift (Wang 1995). The SST anomalies associated with the PRE76 ENSOs appear first in the eastern Pacific and extend to the central Pacific and conversely, during POST76 ENSOs, the SST anomalies evolve first in the central Pacific and spread to the east (Wang 1995). The period of ENSO is also shown to increase during the POST76 period (An and Wang 2000). Terray and Dominiak (2005) showed a remarkable change in the lead-lag relationship between Indian Ocean SSTs and ENSO evolution after the 1976–1977 climate shifts. They pointed out that, the southern Indian Ocean SSTs during late boreal winter are a highly significant precursor to ENSO evolution after 1976–1977 while a surface warming is also noted over the Indian Ocean since 1976–1977 (Nitta and Yamada 1989; Aoki et al. 2003). Before the 1976/1977 climate shift, SST anomalies in the tropical Indian Ocean consisted of a basin wide warming during most of the developing phases of ENSO whereas after this shift, SST anomalies have displayed an east–west gradient (Annamalai et al. (2005). They found that the formation (absence) of the South China Sea anticyclone during PRE76 (POST76) is the prime reason for the difference in Indian Ocean SST anomalies. The changes in the convective activities over the tropical central, eastern Pacific and the Indian Ocean and the associated circulation patterns after the 1976 climate shift (Nitta and Yamada 1989; Wang 1995) can influence many aspects of Indian summer monsoon variability such as the timing of the onset, withdrawal, interannual variability, and the active/break cycles. Ajayamohan and Rao (2008) have also shown that the extreme rainfall events over central India increased after the 1976/1977 climate shift. In the present study, we investigate the timing of the withdrawal phase of the monsoon season in detail over the period of 1950–2008, during which a reliable dataset for circulation and convection is available and therefore also for the LRS. The relationship between the monsoon withdrawal and the Indo-Pacific SST variability before and after the 1976/1977 climate shift is critically examined. In addition, the underlying mechanism behind this association is also analyzed to present some possible avenues for these multiple teleconnections. Clearly, many more sensitivity studies with reliable models are necessary to extract the exact lead-lag relations between the various players mentioned above.

The rest of the paper is organized as follows. Section 2 provides descriptions of the data, methodology and model setup. Section 3 discusses the outcome of the observational analysis. Results from an atmospheric general circulation model (AGCM) are presented in Sects. 4 and 5 offers a summary of the present study.

2 Data, methodology and modelling approach

2.1 Data and methodology

In this study, daily and monthly averaged NCEP/NCAR reanalysis data (Kalnay et al. 1996) for zonal and meridional winds and air temperatures at different levels for the period 1950–2008 have been used. For SST, the *NOAA_ERSST_V3* (Smith et al. 2008) data set (2.0° × 2.0° grid) over 1950–2008, obtained from the website http://www.esrl.noaa.gov/psd/ were employed. Monthly and daily averaged reanalysis data obtained from the 40-year, European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala et al. 2005) were also used for additional verification. The ICOADS 2 degree enhanced data is used to verify the SST before 1975. The daily Optimum Interpolated high resolution (0.25° × 0.25° grid) SST data developed by NOAA is another product analyzed for the present study (Reynolds et al. 2007). To understand the transition of rainfall during the monsoon withdrawal period, the India Meteorological Department (IMD) gridded daily rainfall (version-2) dataset (Rajeevan et al. 2006) are also used.

The role of tropospheric temperatures over the Tibetan plateau and its role in the onset and retreat of the monsoon are highlighted by some seminal studies (e.g. Li and Yanai 1996). The reversal is the result of large temperature increases in May and June centered on Tibetan plateau with no appreciable change over the Indian Ocean (Liu and Yanai 2001; Syroka and Toumi 2004). In this study, we rely on the meridional gradient of tropospheric temperature to define monsoon onset and withdrawal (similar to Goswami and Xavier 2005; Xavier et al. 2007). First, tropospheric temperature (TT) is computed as the vertical average between 200 and 700 hPa. Then, the meridional gradient of TT is computed as the difference between TT averaged over two boxes; 30°–110°E, 10°N–35°N and 30°–110°E, 15°S–10°N. The northern and southern boxes are chosen to represent the large scale heating gradients driving the monsoon circulation. We define the onset (withdrawal) of the Indian summer monsoon as the date when the meridional tropospheric temperature gradient changes sign from negative to positive (positive to negative). The mean withdrawal date for the period 1950–2008 is October 03 (with a standard deviation of 7 days) and is taken as the reference date. If the monsoon withdrawal takes place 5 days (0.75 STD deviations) earlier (later) than the reference date we consider it an early (late) withdrawal.

Anomalies of sea surface temperature (SST) and zonal and meridional winds are computed by removing the mean annual cycle from each time series. From this we construct the September–October (SO) mean anomalies for each year. The two-tailed Student's test is used to quantify the statistical significance of the composites and the Pearson's test is used to determine the statistical significance of correlation coefficients.

2.2 Modelling approach

To understand the processes via which the Indo-Pacific SST variability affects the withdrawal of the Indian summer monsoon, we rely on the AGCM ECHAM5, the most recent version of the model from the Max Plank Institute for Meteorology. It is a spectral model, which we ran at T106 resolution with 19 levels in the vertical. The details of the model ECHAM5 are provided in Roeckner et al. (2006).

Previously Annamalai et al. (2005) and Rao et al. (2010) used this model to understand the impact of the Pacific and the Indian Ocean SSTs on the Indian summer monsoon. They showed that the model captures the climatological annual cycle of the Indian summer monsoon reasonably well. Further, the model also reproduces the impact of the Indian/Pacific SST on the Indian summer monsoon. Therefore the same model is selected for the present study, as this study makes an attempt to understand the response of the withdrawal of Indian summer monsoon to the Pacific/Indian Ocean SSTs. The present model reproduces a realistic spatial structure of precipitation and the low-level circulation during mid-September to mid-October (Fig. 1b, d). The model simulates a strong cross-equatorial flow over the Indian Ocean and weak easterlies over the tropical Pacific (Fig. 1d) compared to the reanalysis data (Fig. 1c). However, the circulation pattern is generally in good agreement with the observations. Although, the model overestimates precipitation over the equatorial Indian Ocean and along the SPCZ during the withdrawal period, it is able to capture the monsoon annual cycle reasonably well (Fig. 2b) and the spatial pattern of precipitation is also in very good agreement with the observations (Fig. 1a, b). Consistent with observations, the model also shows a maximum value of the TT index during boreal summer months and minimum during boreal winter months (Fig. 2a, b). Even though the onset of monsoon is slightly early in the model, the withdrawal is fairly consistent with observations (Fig. 2a, b). Considering this bias we have focused our effort on explaining the withdrawal process by using model sensitivity experiments.

Two most dominant interannual modes of SST variability in the tropics are ENSO and the Indian Ocean Dipole/Zonal Mode (IOD; see Bjerknes 1969; Saji et al. 1999; Murtugudde et al. 2000; Rao et al. 2002; Yamagata et al. 2004). In order to test the response of the SST modes on the withdrawal dates of Indian summer monsoon, four sets of sensitivity experiments along with a control run (CTL) are carried out in this study. In the CTL run, the model is forced with monthly climatological SST and sea ice as the lower boundary condition and is integrated for 20 years. The SST anomalies in the months of September/October (representing IM withdrawal season) are superimposed on climatological SSTs in the tropical Indian and Pacific basins separately for sensitivity experiments to test the relative role of the Indian and Pacific Ocean SSTs on withdrawal dates, and are integrated for a full calendar year. Each sensitivity experiment is an ensemble-average

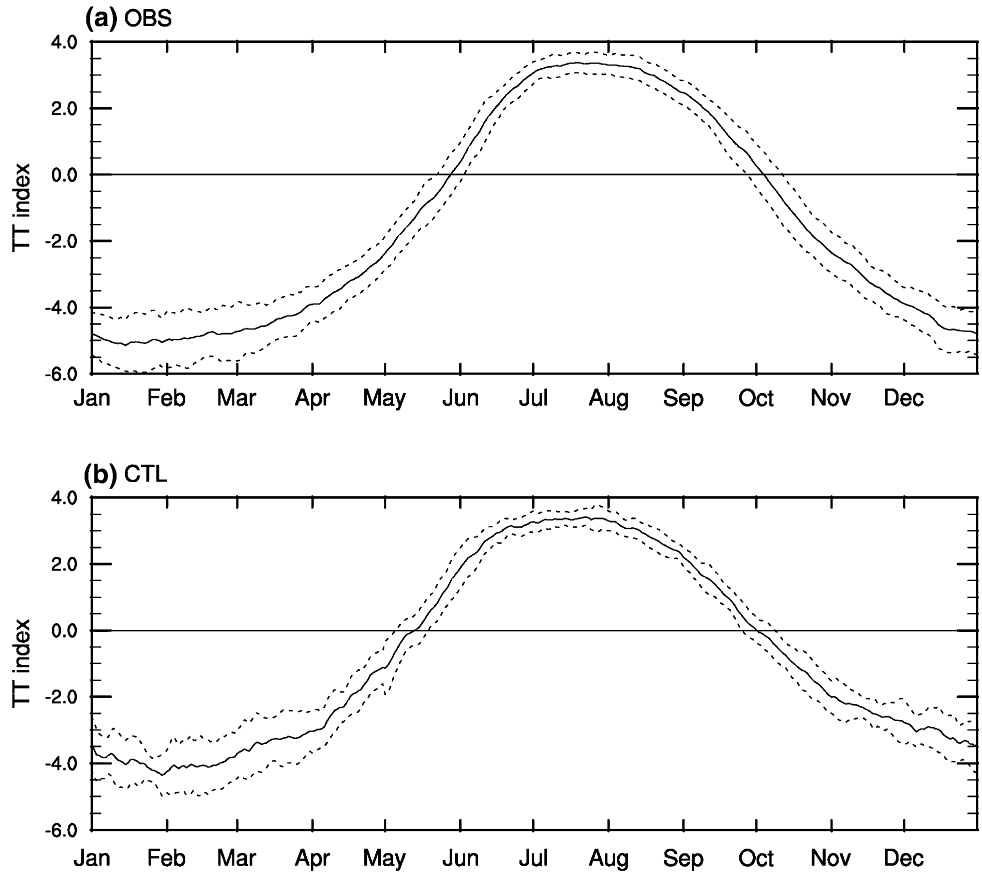

Fig. 2 **a** The climatological values of daily TT index (*solid line*; see text for definition) with ±1 standard deviation of each day (*dashed lines*) from observation (1950–2008), **b** same as **a** but for the control run

of five realizations, which differ in the initial conditions and are obtained from 5 snapshots of the climatological run. Thus, from these sets of experiments, the separate influences of the Indian and Pacific Oceans on the withdrawal of the Indian summer monsoon can be deconvolved. Table 1 summarizes the experiments described above.

3 Results of the observational analysis

3.1 Monsoon withdrawal date before and after the 1976/1977 climate shift

The TT index computed from observations using the procedure mentioned in Sect. 2.1 shows a strong annual cycle with a maximum in July and August and a minimum in boreal winter months (Fig. 2a). The climatological values of TT index shows that the normal onset date for the period 1950–2008 is 30th May and the normal withdrawal date for the period 1950–2008 is 3rd October (Fig. 2a). The standard deviation of TT index at each day shows a difference in the variability of TT index at the beginning and the end of the Indian summer monsoon as shown by Syroka and Toumi (2004) in their circulation index (Fig. 2a). To understand the relationship between the TT index withdrawal date and the conventional IMD withdrawal date, a composite of 850 hPa winds for different lead/lag from IMD withdrawal date is compared with the 850 hPa wind composite corresponding to a zero-lag TT index withdrawal date (figure not shown). It shows that, on an average the TT index withdrawal is 5 days earlier than the conventional IMD withdrawal date. The TT index withdrawal date and the IMD withdrawal date, based on central Indian (~19°N) monsoon withdrawal obtained from the isochrones of the withdrawal of south west monsoon published in Mausam for the period 1983–2005, are significantly correlated ($r = 0.66$). Therefore, it is reasonable to assume that TT index withdrawal date accurately represents the monsoon withdrawal from central India (the monsoon core area). Therefore the TT index is a useful tool to study the timing of monsoon withdrawal from the Indian subcontinent. The monsoon withdrawal and onset dates computed using the TT index show an early withdrawal trend during the recent decades (Fig. 3b), but no long term trend in the onset dates (Fig. 3a), which is consistent with Xavier et al. (2007).

The deviation of the monsoon withdrawal date from the mean withdrawal/reference date (3rd October) shows that, before (after) the 1976/1977 climate shift, majority of the years experienced late (early) monsoon withdrawals

Table 1 List of experiments used in this study

Experiment name	Forcing	No. of years of simulation	Ensembles
CTL run	Monthly varying climatological SSTs	20	
Negative_IOD_Type run	Climatological SSTs + PRE76 late withdrawal years' SST anomalies in September–October over tropical Indian Ocean (30°S–30°N, 40°E–120°E)	1	5
Positive_IOD_Type run	Climatological SSTs + POST76 early withdrawal years' SST anomalies in September–October over tropical Indian Ocean (30°S–30°N, 40°E–120°E)	1	5
LaNina_Type run	Climatological SSTs + PRE76 late withdrawal years' SST anomalies in September–October over tropical Pacific (30°S–30°N, 120°E–80°W)	1	5
ElNino_Type run	Climatological SSTs + POST76 early withdrawal years' SST anomalies in September–October over tropical Pacific (30°S–30°N, 120°E–80°W)	1	5

(Fig. 4a). Prior to the 1976/1977 shift, the number of late withdrawal years are eleven (1950, 1954, 1955, 1956, 1958, 1959, 1960, 1961, 1964, 1971 and 1975) and early withdrawal years are three (1965, 1966 and 1972). Whereas after the shift, the number of early withdrawal years increased to seven (1979, 1984, 1986, 1994, 1997, 2000 and 2002) and the number of late withdrawal years decreased to three (1983, 1989 and 2001). The mean value of withdrawal deviation for POST76 also decreased compared to the PRE76 period (3 in PRE76 vs. −1 in POST76).

The transition of the rain belt during the withdrawal duration (−6 to +6 days) can be seen in the composite rainfall anomalies (Fig. 5). Prior to the withdrawal date (withdrawal −6 days), positive anomalies of rainfall are observed all over the Indian land mass (Fig. 5a). When it is approaching the withdrawal date (withdrawal −3 days), negative rainfall anomalies are observed in some regions of northwest India spreading towards central India (Fig. 5b). On the date of withdrawal, almost everywhere in the monsoon core region (central India) negative rainfall anomalies are seen and the rain belt is confined to the southern peninsula (Fig. 5c). The strength of the monsoon decreases all over India within 6 days from the withdrawal of the monsoon from central India (Fig. 5d, e).

The LRS is defined as the difference between the onset date and the withdrawal date. The average LRS for the period 1950–2008 is 127 days with a standard deviation of 10 days. The interannual variation of LRS also shows a decreasing trend (Fig. 3c) similar to that for withdrawal. The association between the TT index and the withdrawal date extends to LRS also as the LRS is defined based on withdrawal and onset dates. The significant positive correlation between the TT index withdrawal dates and LRS ($r = 0.83$) indicates that when the withdrawal date is early, the LRS is also shorter and vice versa. There is also a significant negative correlation between the TT index onset dates and LRS ($r = -0.75$), i.e., if the onset date is early (late) the LRS increases (decreases). The deviation of LRS from the mean LRS (127 days) shows a decreasing trend in the recent decades compared to previous decades (Fig. 4b). The linear trend lines for both withdrawal and LRS deviations in the entire period (1950–2008) are significant above 90% confidence level. The mean LRS deviation in the POST76 period also decreased compared to PRE76 (3 in PRE76 vs. −2 in POST76). Since the onset dates show no long term trend over the last several decades (Fig. 3a), the decreasing trend in the LRS is a consequence of the decreasing trend of withdrawal dates. Xavier et al. (2007) also reported a similar result from their study on the definition of the seasonal cycle and monsoon-ENSO relationship. However, their study did not delineate the role of the Indo-Pacific SSTs on LRS.

3.2 The withdrawal date and sea surface temperatures

The correlation map of the Indian summer monsoon withdrawal date and September–October mean SST anomalies indicates a significant difference between the PRE76 and POST76 periods (Fig. 6d, e). During the PRE76 period, significant negative correlation between September and October mean SST anomalies and the withdrawal date is observed over the equatorial eastern and central Pacific, the Arabian Sea and the Bay of Bengal (Fig. 6d). The composite picture of September–October mean SST anomalies corresponding to the PRE76 late withdrawal years also shows negative SST anomalies over the same regions (figure not shown). The negative SST anomalies in the equatorial eastern and central Pacific are essentially identical to a La Niña pattern. Rao and Goswami (1988) also noted a negative correlation between September–October–November (SON) SST and the seasonal monsoon rainfall. To zeroth-order, negative SST anomalies in the Arabian Sea during the PRE76 late withdrawal years are due to the increased wind speed, which enhances the evaporation and thus cools the SST and may help maintain the meridional temperature gradient.

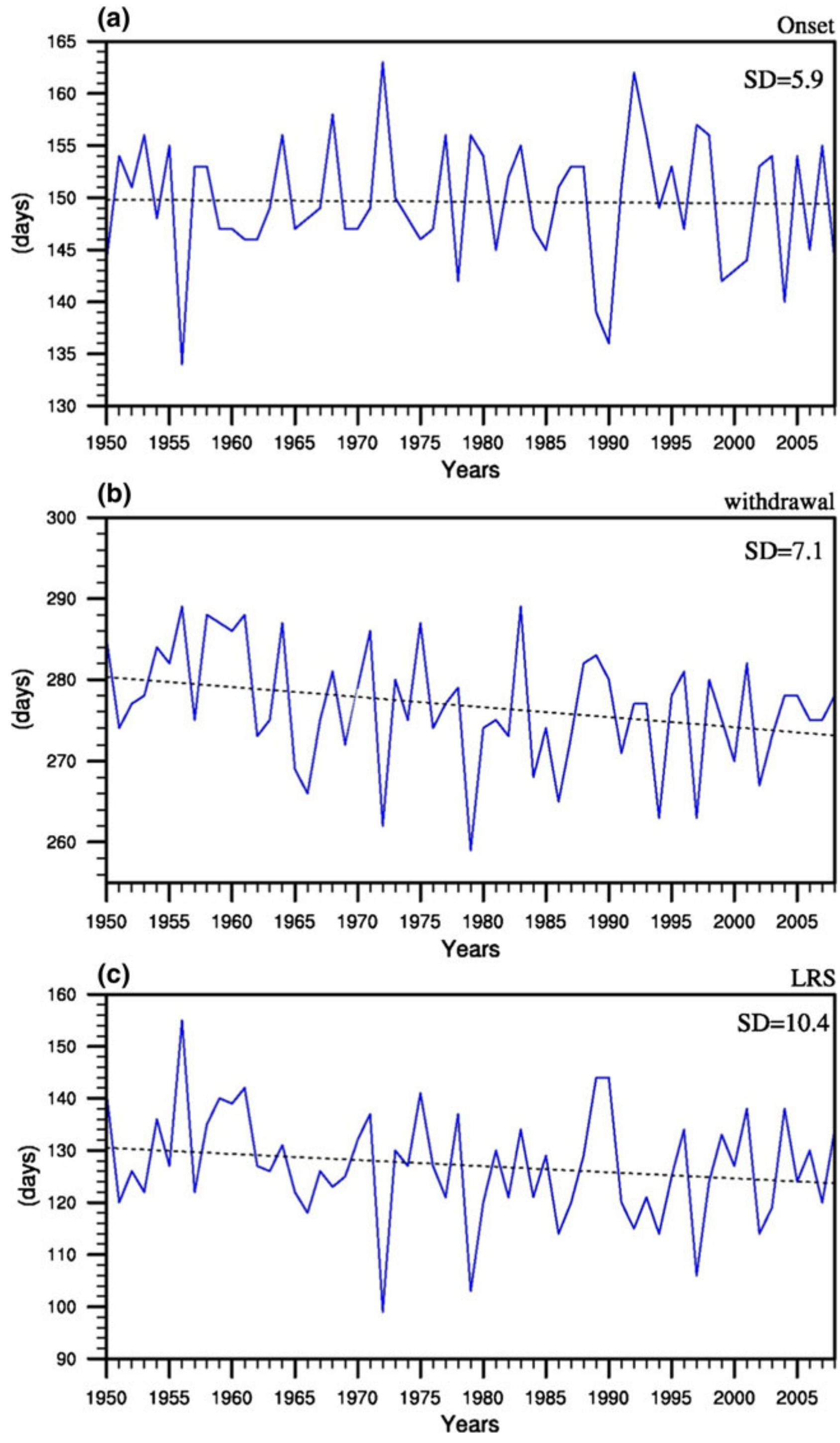

Fig. 3 Interannual variations of **a** onset date, **b** withdrawal date, **c** length of rainy season (LRS) for Indian summer monsoon. The *dashed lines* show the linear trend. Standard deviation of the time series is shown in the *upper right* hand corner

Interestingly, during the POST76 period (Fig. 6e), the influence of southeastern equatorial Indian Ocean SST variability on the withdrawal date becomes dominant when compared to the PRE76 period (Fig. 6d). A significant positive correlation between the September–October mean SST anomalies and withdrawal date is observed over the southeastern equatorial Indian Ocean and equatorial western Pacific and a negative correlation is observed in central/eastern equatorial Pacific Ocean (Fig. 6e). Surprisingly, the negative correlation observed in the PRE76 period in the Arabian Sea and the Bay of Bengal is not seen during the POST76 period (Fig. 6e). Since the time-span of withdrawal of the Indian summer monsoon is a relatively fast process compared to the whole September–October time-span, we constructed the mid-September to mid-October (depending on the earliest and the latest

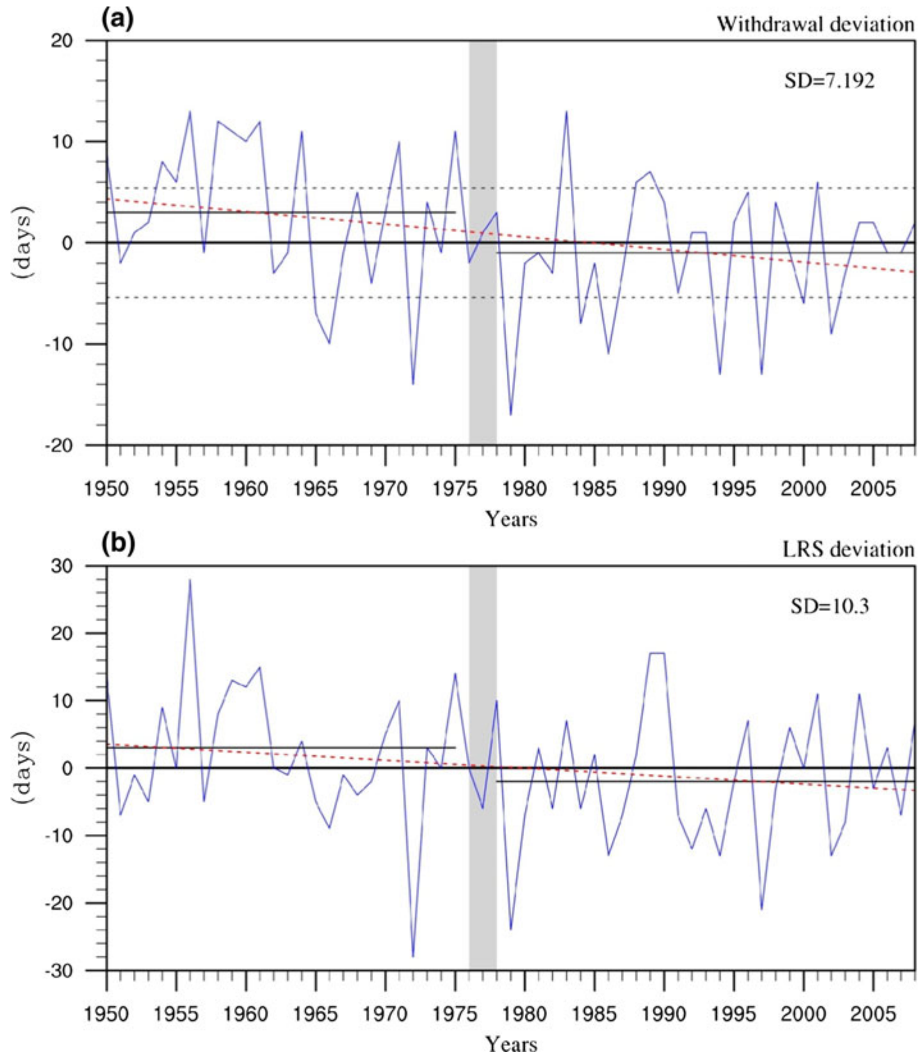

Fig. 4 Time series showing **a** the deviation of withdrawal dates from mean withdrawal date (03 Oct); **b** the deviation of LRS from mean LRS (127 days). The *horizontal dotted lines* indicate ±0.75 Standard deviation. The *colored dotted line* shows the linear trend for the period 1950–2008. The *shaded* region represents the 1976/1977 climate shift. The *horizontal solid lines* on *left* and *right* of the *shaded* area indicate the mean value of deviation for PRE76 and POST76 periods respectively. Standard deviation of the time series is shown in the *upper right* hand corner

withdrawal dates over the 1950–2008 record) averaged daily SST anomalies and correlated them with the withdrawal dates from 1981 to 2008. The resulting correlation map between September and October mean SST anomalies and withdrawal dates confirms the increasing influence of southeastern equatorial Indian Ocean SST variability on the withdrawal date in the latter study period (Fig. 6f). The composite structure of September–October averaged SST anomaly for POST76 early withdrawal years is negative over the southeastern equatorial Indian Ocean, similar to the positive phases of IOD (Saji et al. 1999; Webster et al. 1999; Murtugudde et al. 2000) in the Indian Ocean, and a positive SST anomaly over tropical central/eastern Pacific ocean indicating an El Niño event (figure not shown).

The correlation maps constructed based on LRS also show similar patterns as with withdrawal albeit with a slightly reduced amplitude (Fig. 6a–c). Although the correlations are reduced, they are still significant indicating the influence of late/early withdrawals on LRS. The correlations of September–October SST anomalies with the LRS are reduced owing to the fact that the monsoon onset dates show no significant trend (Fig. 3a).

Although both the Indian and Pacific Oceans influence the monsoon withdrawal after the climate shift, the forcing in the Indian Ocean shifts towards the southeastern equatorial IO from the Arabian Sea when compared to the period before the climate shift. Note that the cooling in the eastern Indian Ocean is also shown to affect the local Hadley Cell and alter the monsoon-ENSO relation (Slingo and Annamalai 2000; Ashok et al. 2004). The influence of the western Pacific has increased after 1976/1977 shift, even though the central Pacific influence has diminished (Fig. 6d, e). As reported by Wang (1995), a difference in the evolution of SST anomalies is also evident in the Pacific Ocean between the PRE76 and POST76 periods. As stated earlier, the PRE76 ENSOs evolved from east to west while the POST76 ENSOs originated in the west and evolved eastward (Fig. 6d, e). A similar correlation map created using the TT index withdrawal dates based on the ERA-40 daily air temperature dataset for the period

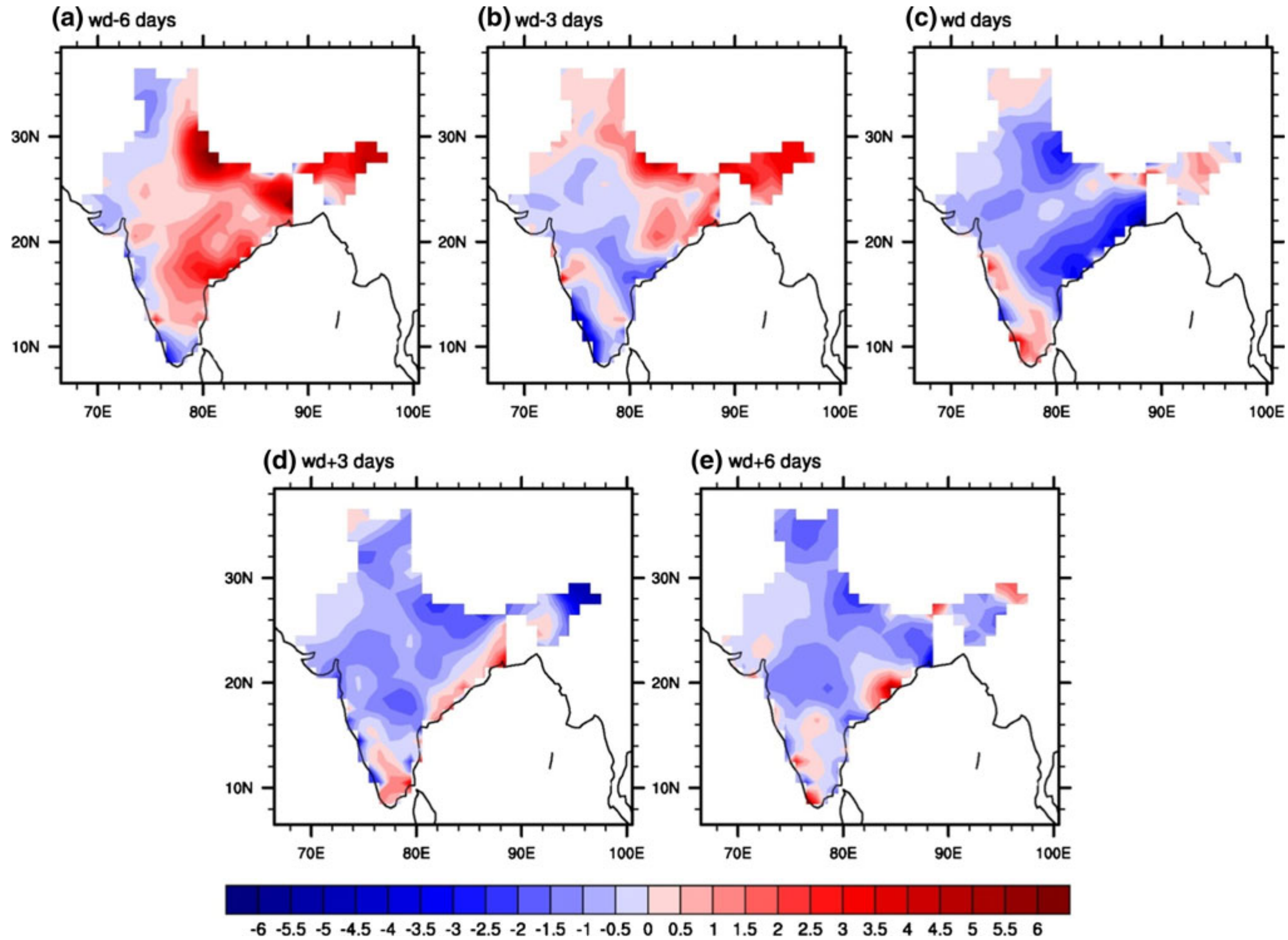

Fig. 5 The composite of rainfall anomaly (mm/day) corresponding to **a** withdrawal −6 days, **b** withdrawal −3 days, **c** withdrawal date, **d** withdrawal +3 days, **e** withdrawal +6 days

(1957–2001) supports the above results (figure not shown). To account for the sparseness of SST data prior to 1975, we also used the ICOADS 2° enhanced SSTs to create the correlation map as above, which also confirms the evidences presented above.

The 11 year running correlation between the Indian summer monsoon withdrawal date and the area averaged SST anomalies over the southeastern equatorial Indian Ocean (10°S-EQ, 90°E–110°E) representing the eastern pole of IOD and the NINO3 region (5°S–5°N, and 160°W–90°W) further confirms the increasing influence of southeastern equatorial Indian ocean SST variability on the withdrawal of the Indian summer monsoon in the recent period (Fig. 7). The dependence of withdrawal of the monsoon on nino3 SST is decreasing after mid seventies and at the same time the eastern equatorial Indian Ocean influence is becoming stronger than the nino3 SST influence. It should be noted that, after 1984 the southeastern equatorial Indian Ocean SST appears to dominate over the NINO3 SST. The caveat of course is that we have not considered the impact of Atlantic SSTs over the monsoon withdrawal in this study. It should also be noted that while Slingo and Annamalai (2000) note the decoupling of the ENSO impact on the monsoons during the IOD year of 1997, their study did not consider the detailed impact of the local Hadley Cell on the LRS and the withdrawal. They do note that the ENSO impacts on the monsoon are strongest during the onset and the termination phases but the more specific relation of the southeastern Indian Ocean cooling with the monsoon withdrawal is more critical for process understanding and hence for improving monsoons forecasts.

3.3 The onset date and sea surface temperature

The change in correlation between the onset date of the Indian summer monsoon and the May–June averaged SST anomaly has been investigated separately for PRE76 and POST76 periods (Fig. 8d, e). A dramatic change in correlation patterns are seen here as well just as for the withdrawal dates. Significant positive SST anomalies prevail

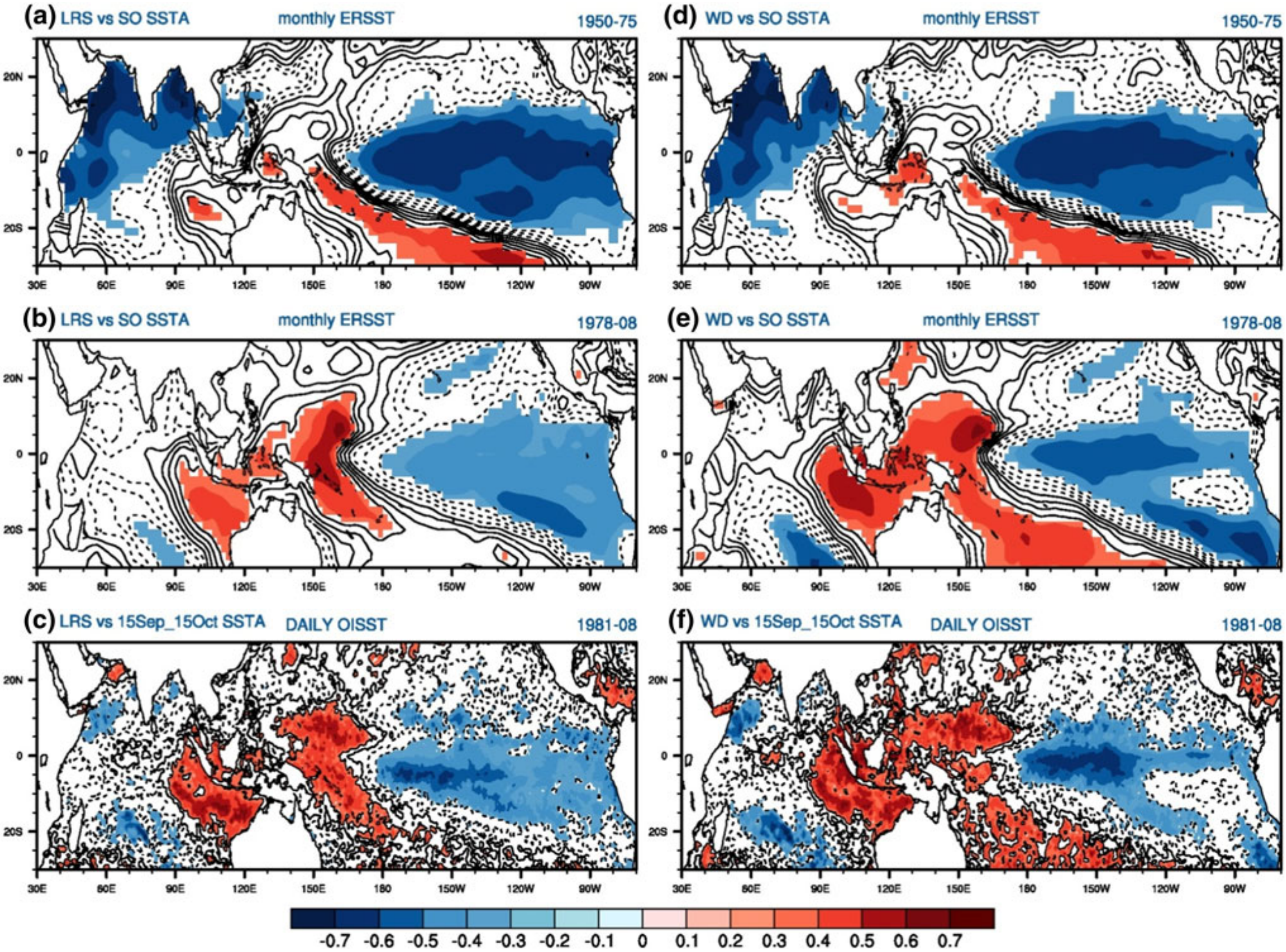

Fig. 6 **a** The spatial map of correlation coefficient (CC) between the September–October mean anomalies of SST(°C) and LRS for 1950–1975 (PRE76), **b** for 1978–2008 (POST76), **c** same as **b** but the CC between the mid-September to mid-October averaged SST anomalies (daily OISST) and LRS for 1981–2008. **d**, **e**, **f** same as **a**, **b**, **c** respectively but instead of LRS; the withdrawal date is used to find the CC. The *shaded* regions represent CC exceeding 90% confidence level. The contour interval is 0.1

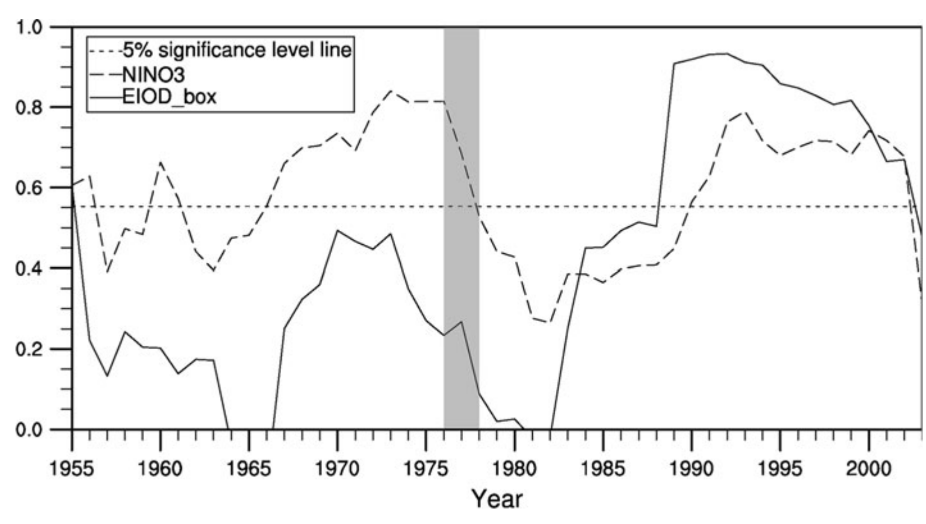

Fig. 7 The 11 year sliding correlation between withdrawal date and area averaged NINO3 (*dotted line*: multiplied by −1) and eastern Indian Ocean Dipole box (*solid line*) sea surface temperature anomaly (°C). The values are plotted at the center of the 11 year period. The shaded frame represents the 1976/1977 climate shift

over both the central and eastern Pacific and the northern IO in the POST76 period compared to the PRE76 period. The southeastern equatorial Indian Ocean SST variability does not seem to play a role in the onset of the Indian summer monsoon in either the PRE76 or the POST76 period as IOD is in its infant stages during May–June. Since the onset of the Indian summer monsoon occurs fairly rapidly, we have constructed the correlation plot of the mid-May to mid-June averaged high resolution daily OISST with the onset of Indian summer monsoon (Fig. 8f), which is similar to the monthly SST correlation patterns (Fig. 8e). After the climate shift, the influence of northern IO, particularly Arabian Sea increases during the onset period (May–June) whereas such an influence is reduced during the withdrawal season (Sept–Oct).

The correlation between May and June SST anomalies and LRS (Fig. 8a, b) are unlike that with the onset dates (Fig. 8d, e). The negative correlation of the tropical Pacific remains unchanged between two epochs. The correlation of LRS with mid-May to mid-June averaged high resolution OISST (Fig. 8c) is also similar to the correlation pattern observed in Fig. 8b. By comparing Figs. 6 and 8, it appears that the LRS shortening in the recent years seems to be borne out of the SST conditions over the Indo-Pacific Oceans during the withdrawal phase.

Previous studies have shown the importance of Rossby wave dynamics during monsoon breaks (Krishnan et al. 2000) and withdrawals (Syroka and Toumi 2004). The composite of September–October mean low-level wind anomalies during late (early) withdrawal years show an anomalous cyclonic (anticyclonic) feature on each side of the equator, resembling the Rossby wave response (Matsuno 1966; Gill 1980) to a tropical heat source (Fig. 9a, b). The prevailing easterlies in the tropical Pacific Ocean strengthen (weaken) during the late (early) withdrawal years. The mean low-level wind during boreal summer

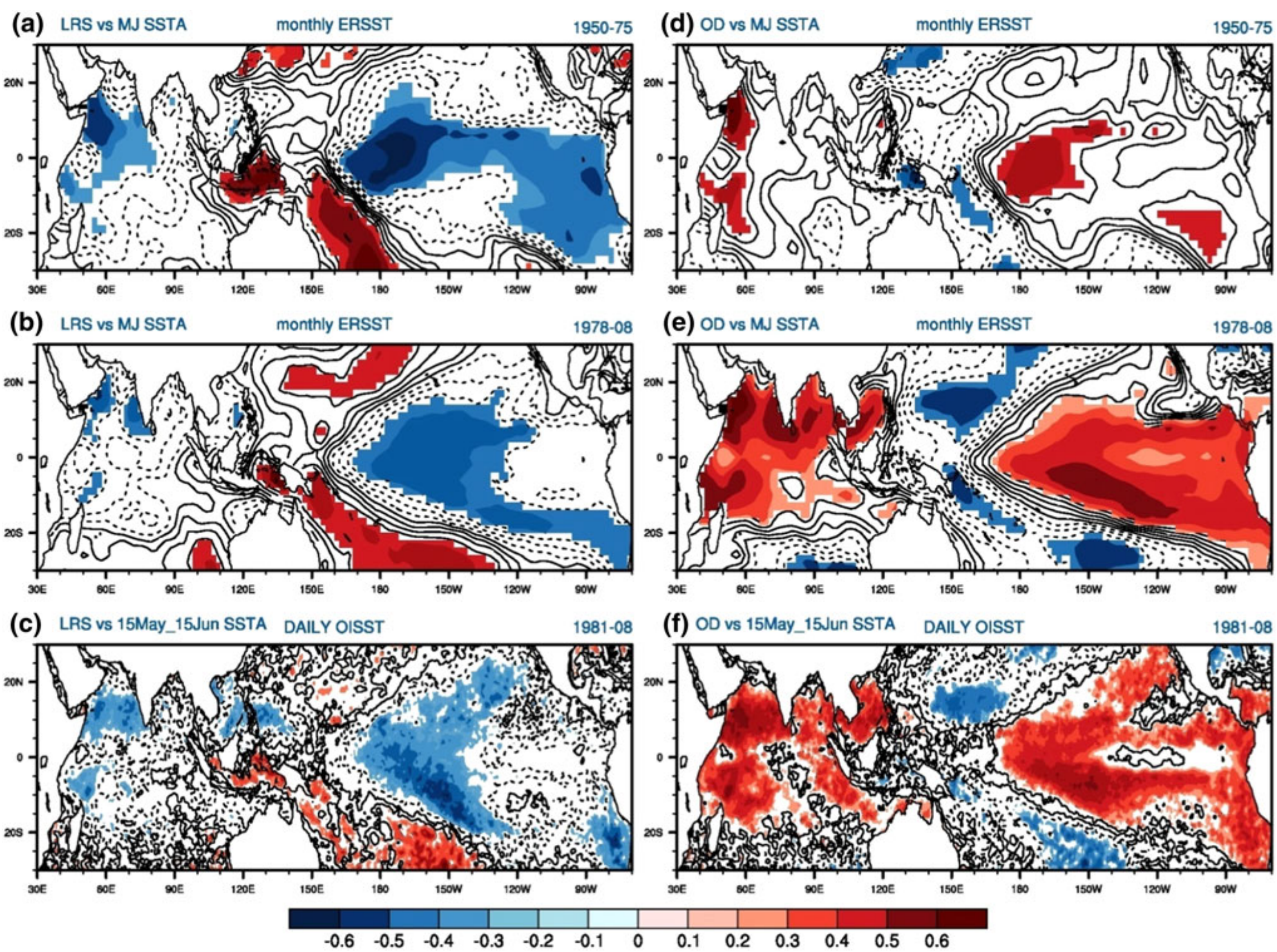

Fig. 8 **a** The spatial map of correlation coefficient (CC) between the May–Jun (MJ) mean anomaly of SST (°C) and LRS for PRE76 **b** for POST76. **c** same as **b** but the CC between the mid-May to mid-Jun averaged SST anomalies (daily OISST) and LRS for 1981–2008. **d**, **e**, **f** same as **a**, **b**, **c** respectively, but instead of LRS, the onset date is used to find the CC. The *shaded* regions represent CC exceeding 90% confidence level. The contour interval is 0.1

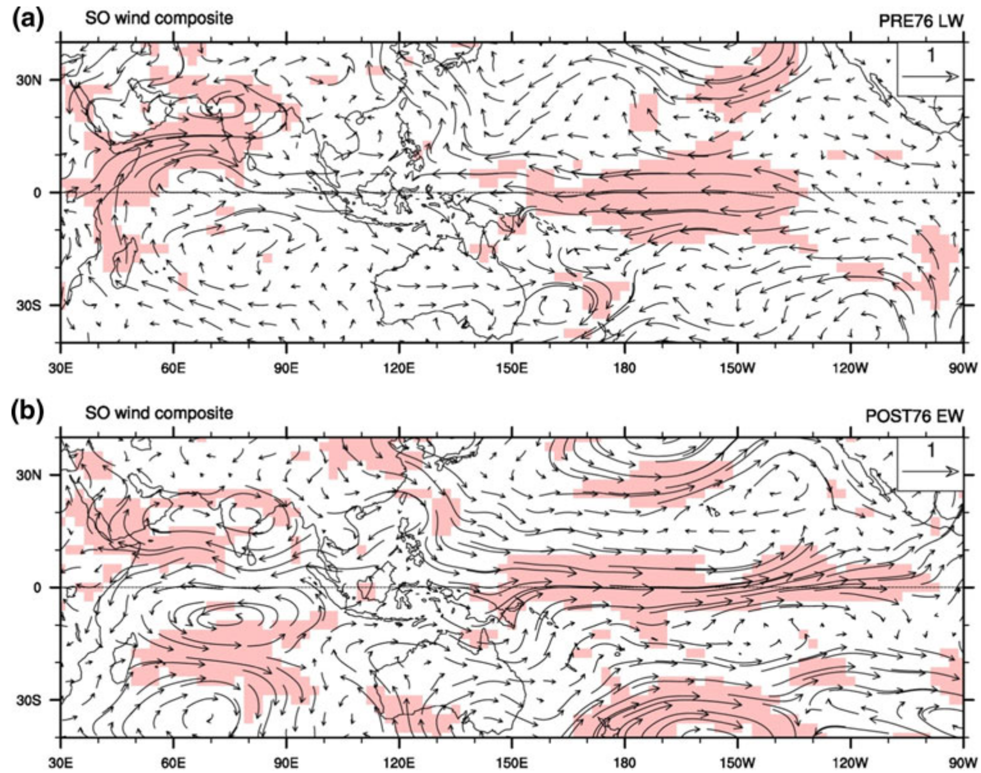

Fig. 9 **a** Composite of September–October mean 850 hPa wind anomalies (m/s) corresponding to PRE76 late withdrawal years. **b** same as **a**, but for POST76 early withdrawal years. Regions where either of the wind vectors exceeds significance above 90% confidence level are *shaded*

monsoon is southwesterly in the northern Indian Ocean and southeasterly in the southern Indian Ocean. For the northern Rossby-like vortex, the wind at its southern side strengthens (weakens) the cross equatorial monsoon flow into the Indian subcontinent during the late (early) withdrawal years and facilitate the late (early) withdrawal of the Indian summer monsoon (Fig. 9a, b). Similarly, the southern Rossby-like vortex also contributes to the strengthening (weakening) of the cross-equatorial monsoon flow into the region during the late (early) withdrawal years. Due to the absence of a southeastern Indian Ocean heat source during the PRE76 period, the northern Rossby cell contributes more to the strengthening of cross-equatorial flow during PRE76 late withdrawal years. But the presence of the southeastern equatorial Indian Ocean heat anomaly in the latter period makes the southern Rossby cell also prominent and hence both the Rossby-like vortices contribute to the weakening of cross-equatorial flow. Syroka and Toumi (2004), also indicate the role of Southern Hemisphere anticyclonic flow in inhibiting the cross-equatorial flow.

3.4 Indian summer monsoon withdrawal and upper tropospheric temperatures

Several studies have proposed a role for the tropospheric seasonal warming in the transition phases of the Asian monsoon (Murukami and Ding 1982; He et al. 1987; Yanai et al. 1992). It has been shown that the meridional gradient of tropospheric temperature plays an important role in the abrupt onset (Li and Yanai 1996; Ueda and Yasunari 1998; Yanai and Li 1994; He et al. 2003; Yanai et al. 1992) and withdrawal (Goswami and Xavier 2005; Xavier et al. 2007; Syroka and Toumi 2004) of the Indian summer monsoon. An earlier study showed a significant positive correlation between the JJAS All India Rainfall (AIR) and upper tropospheric temperature over Tibetan Plateau during September and October (Liu and Yanai 2001). They also found that the increased rainfall during the late monsoon season enhances the September upper tropospheric temperature over the Tibetan Plateau due to the release of latent heat of condensation and the increased upper tropospheric temperatures persist into the post-monsoon month of October and facilitates the late monsoon withdrawal.

The upper tropospheric temperature (UTT) pattern during the withdrawal time for both PRE76 and POST76 periods has also been investigated through the correlation analysis. The upper tropospheric temperature gradient corresponding to the withdrawal time has undergone major changes between the PRE76 and POST76 periods (Fig. 10d, e). While a significant negative correlation between withdrawal dates and UTT prevails over the tropical Indian and Pacific Oceans, a positive correlation prevails over the Indian subcontinent during the PRE76 periods (Fig. 10d). During POST76, negative correlations can be seen in both the hemispheres over Pacific Ocean and

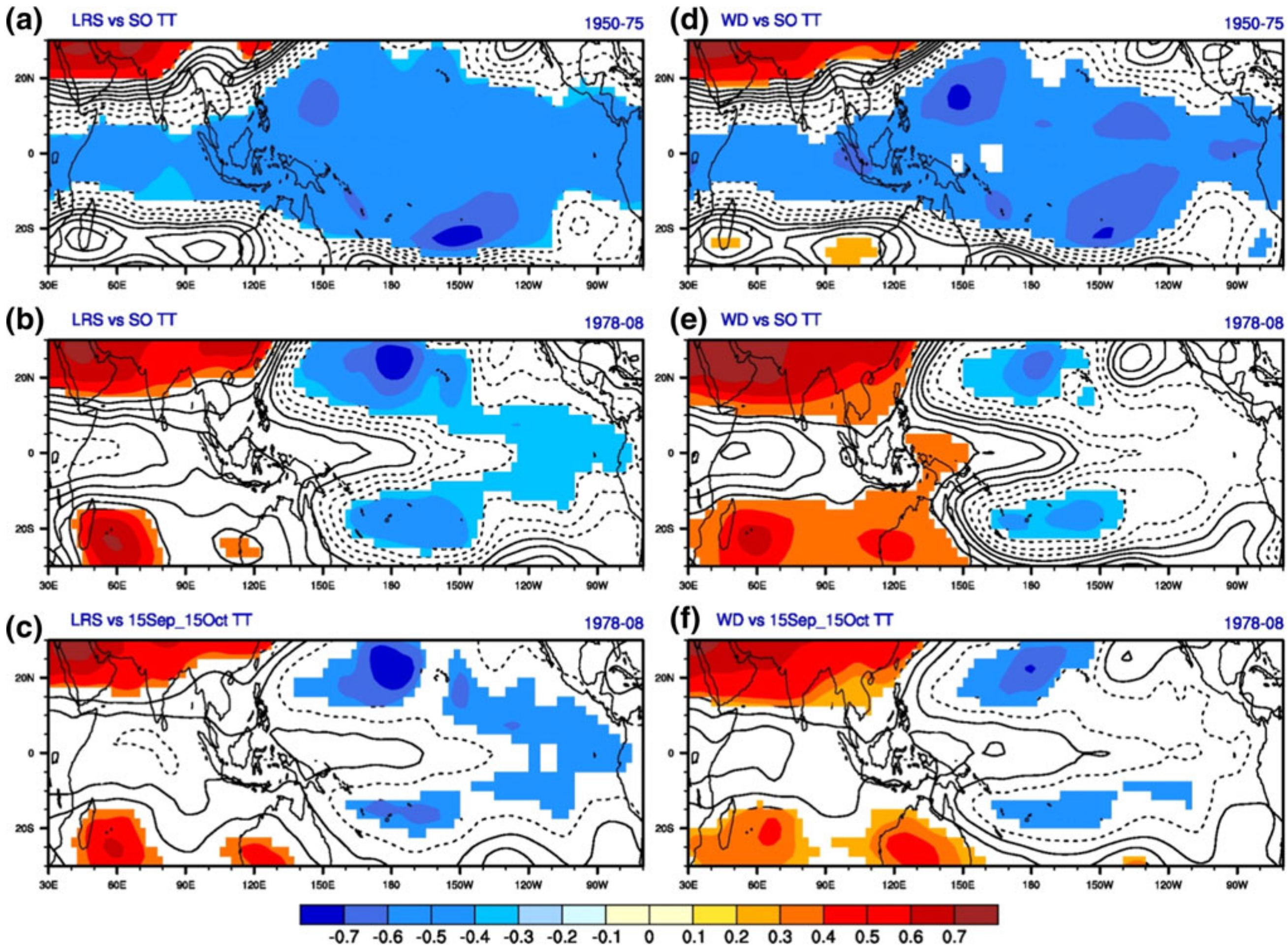

Fig. 10 a The spatial map of correlation coefficient (CC) between the LRS and September–October mean tropospheric temperature averaged from 700 to 200 hPa pressure levels for PRE76 period; **b** for POST76; **c** same as **b**, but the CC between the mid-September to mid-October averaged *upper* tropospheric temperature and LRS. **d**, **e**, **f** same as **a**, **b**, **c** respectively, but instead of LRS, the withdrawal date is used to find the CC. The *shaded* regions represent CC exceeding 90% confidence level. The contour interval is 0.1

the whole south equatorial Indian Ocean shows a positive correlation (Fig. 10e, f). The upper tropospheric correlation pattern for both PRE76 and POST76 also confirm the Rossby wave (Matsuno 1966; Gill 1980) response to a tropical heating, which is discussed in the previous section. In short, a strong meridional upper tropospheric temperature gradient is observed in the PRE76 period and it facilitates the continuation of the monsoon beyond the normal termination resulting in a late withdrawal. In contrast to the PRE76 period, the meridional gradient of UTT gradient is decreased in the latter epoch, which leads to an early withdrawal of Indian summer monsoon. The decrease in UTT in the recent decades has been verified by correlating the withdrawal date with mid-September to mid-October averaged tropospheric temperature (Fig. 10f), which is also identical to Fig. 10e. The detailed mechanism is discussed in Sect. 4 (also see the schematic diagram: Fig. 15).

Similar to the withdrawal date, we also carried out the correlation analysis between the LRS and September–October mean UTT for both PRE76 and POST76 periods (Fig. 10a–c). The correlation map of LRS with UTT is similar to the correlation maps between withdrawal dates and UTT.

3.5 Association of monsoon withdrawal with IOD and ENSO

The number of early, late and normal withdrawal years associated with positive (negative) IOD and El Niño (La Niña) events are shown in Fig. 11 as a scatter plot. Positive (negative) IOD years are characterized by a cooling (warming) in the southeastern equatorial Indian Ocean and a warming (cooling) in the western Indian Ocean, which peaks in the boreal fall (Saji et al. 1999; Murtugudde et al. 2001). Saji et al. (1999) defined a Dipole Mode Index

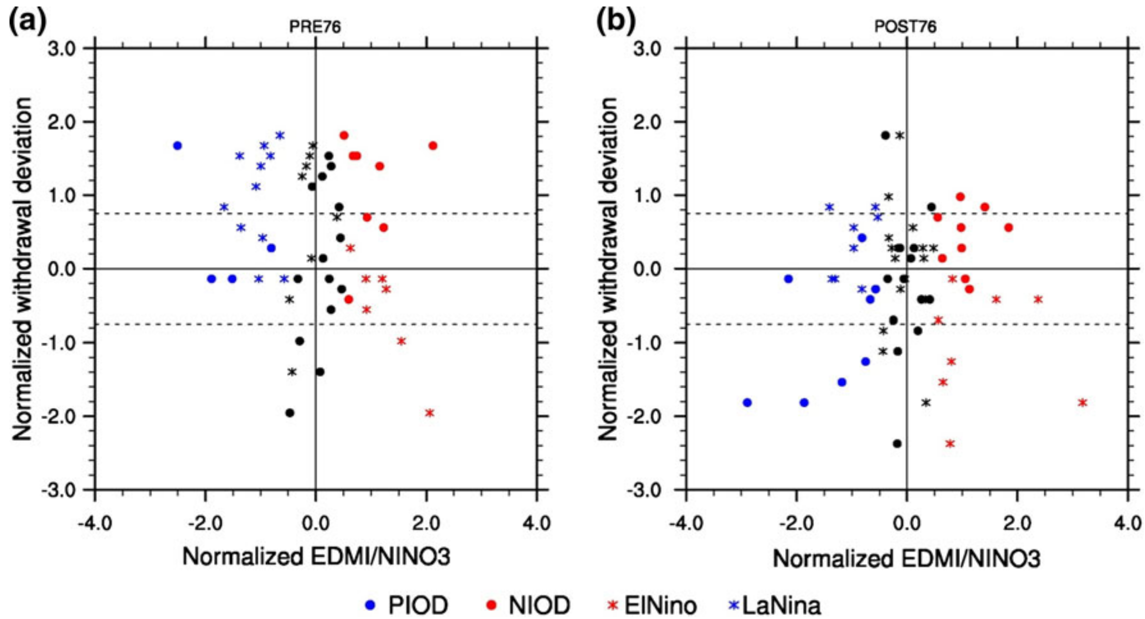

Fig. 11 The association of withdrawal years with positive (negative) IOD and El Niño (La Niña) events for **a** PRE76 and **b** POST76. The two *dotted lines* in the plot indicate the 0.75 (−0.75) standard deviations (SD) of withdrawal deviation. The withdrawal deviation above (below) the 0.75 (−0.75) SD is late (early) withdrawal

(DMI) to sort out the positive and negative IOD years. It is defined as the SST anomaly difference between the western (60°–80°E, 100S–10°N) and eastern (90°–110°E, 10°S–0°) Indian Ocean. Previous studies have shown that the warming (cooling) in the western Indian Ocean is a consequence of a Rossby wave emanating from the south equatorial Indian Ocean (Murtugudde and Busalacchi 1999; Rao et al. 2002; Annamalai et al. 2003). As a result, the strong warming (cooling) in the western Indian Ocean is evident a few months after the cooling (warming) is initiated in the southeastern equatorial Indian Ocean. Since the present study deals with the relationship between the Indian summer monsoon withdrawal and Indo-Pacific SST, a slightly different criteria is used to define the positive (negative) IOD and El Niño (La Niña) events. The years for which September–October averaged SST anomalies in the southeastern equatorial Indian Ocean is below (above) −0.5 (+0.5) standard deviation is defined as the positive (negative) IOD. Similarly, the El Niño (La Niña) is defined as the years for which the September–October averaged NINO3 (5°S–5°N, 150°W–90°W) SST anomaly is above (below) +0.5 (−0.5) standard deviation.

It is observed that none of the early (late) withdrawals of the Indian summer monsoon are associated with La Niña (El Niño), and none of the early withdrawal years are associated with negative IOD (Fig. 11a, b). Compared to PRE76 (Fig. 11a), the influence of positive IOD is strong in POST76 period (Fig. 11b). The majority of the late withdrawal years are associated with La Niña/negative IOD and they mostly occur during PRE76. Similarly, the majority of the early withdrawal years are associated with El Niño/positive IOD and most of them occur in POST76 period. In short, La Niña and negative IOD are the dominant features in the PRE76 late withdrawal years, while the positive IOD and El Niño are the dominant drivers for the POST76 early withdrawal years.

4 AGCM sensitivity experiments

It is noted above from observations that the tropical Pacific Ocean SST variability exerted a larger influence on the withdrawal of the Indian summer monsoon before the 1976/1977 climate shift (Fig. 6d). It is also argued that the influence of southeastern equatorial Indian Ocean on the same has overshadowed the Pacific influence during the recent years (Fig. 6e, f). In order to assess the relative influence of the tropical Pacific versus the tropical Indian Ocean SST on the withdrawal dates, a suite of AGCM experiments with ECHAM5 is performed, as summarized in Table 1. The SST anomalies in the month of September–October are superimposed on the climatological SSTs in tropical Indian and Pacific basins separately to represent various heat sources (Fig. 12a–d). The SST anomalies corresponding to a late (early) withdrawal are related to a negative (positive) IOD event in the Indian Ocean basin and a La Niña (El Niño) pattern in the tropical Pacific (Fig. 12a–d).

In the model, the earliest (latest) withdrawal of the Indian summer monsoon occurs when we force the model

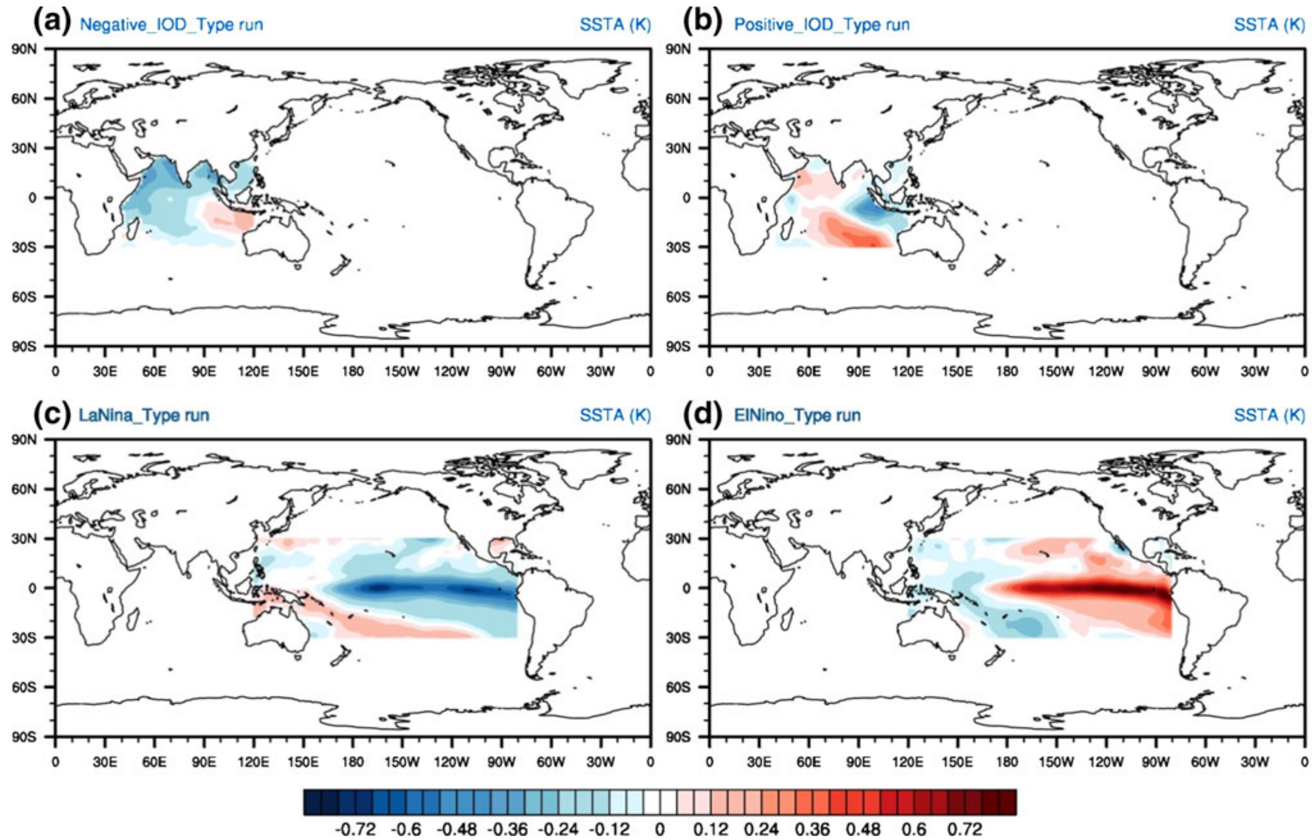

Fig. 12 SST anomalies (°C) superimposed on the climatological SST used in the CTL run for various sensitivity experiments; **a** PRE76 late withdrawal years' composite SST anomalies over tropical Indian Ocean (30°S–30°N, 40°E–120°E), **b** POST76 early withdrawal years' composite SST anomalies over tropical Indian Ocean. **c** and **d** same as **a** and **b** respectively, but over tropical Pacific (30°S–30°N, 120°E–80°W)

with SST anomalies in September–October similar to a positive IOD over the Indian Ocean and a La Niña over the Pacific basin (Fig. 13). This suggests that while the positive IOD conditions lead to early withdrawal, La Niña conditions lead to late withdrawal of the Indian summer monsoon. It is also found that the El Niño forcing or the negative IOD forcing do not lead to much a deviation in the withdrawal date compared to the CTL run withdrawal date (Fig. 13).

The upper tropospheric temperature gradient clearly plays a key role in the withdrawal of the Indian summer monsoon as pointed out in the previous studies (Goswami and Xavier 2005; Xavier et al. 2007; Syroka and Toumi 2004). In an earlier study, Flohn (1957) showed the importance of Tibetan Plateau in generating the tropospheric temperature gradient. It is found that the seasonal heating of elevated surface of the Tibetan Plateau produces the seasonal reversal of tropospheric temperature gradient and thereby changes the monsoon circulation over Asia. Recent studies noted that after the monsoon onset, the warm tropospheric temperature over Asian land mass is maintained by the latent heat release from the South Asian

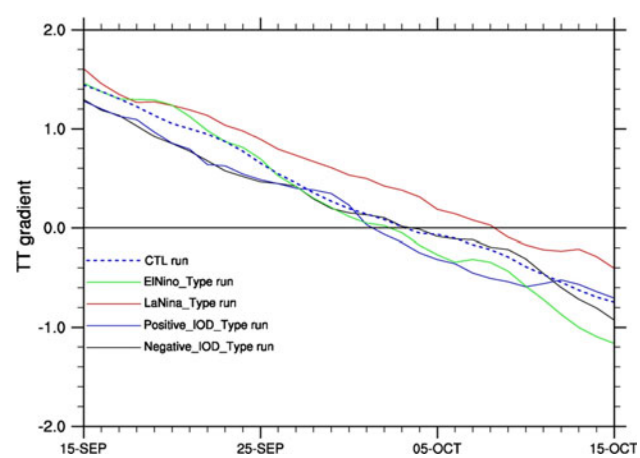

Fig. 13 The meridional gradient of *upper* tropospheric temperature (averaged between 200 and 700 hPa pressure levels) from 15th September to 15th October for various sensitivity experiments. The day when the meridional tropospheric temperature gradient changes sign from positive to negative is defined as the withdrawal date

Monsoon (Goswami and Xavier 2005; Goswami et al. 2006b). The UTT gradient determines the monsoon circulation and its sustainability over Indian summer

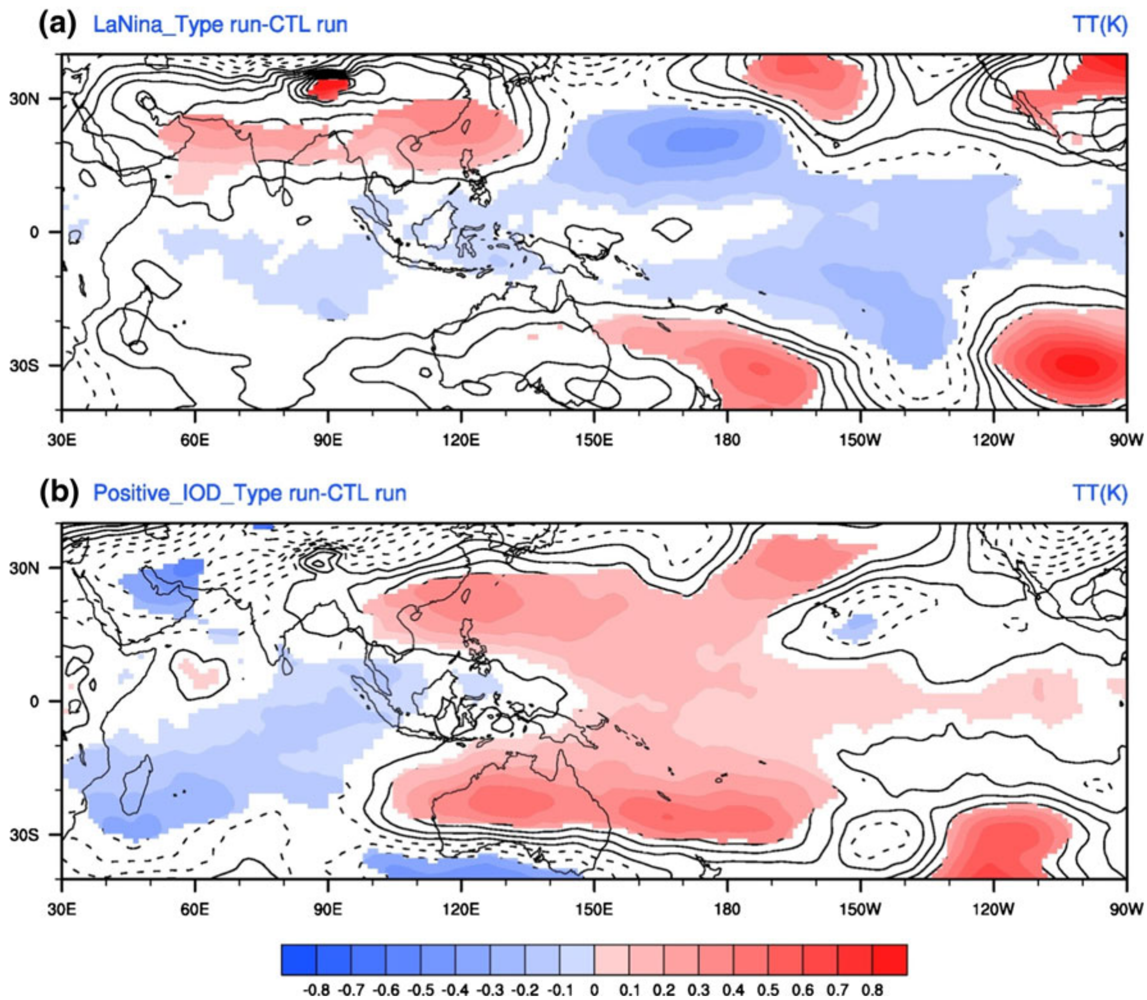

Fig. 14 **a** The difference in the *upper* tropospheric temperature (averaged between 200 and 700 hPa pressure levels) between the LaNiña_Type run and CTL run. **b** same as **a** but the difference between Positive_IOD_Type run and CTL run (units °K). The *shaded* regions represent the values exceeding 90% confidence level. The contour interval is 0.1°K

monsoon region, and during the withdrawal time UTT gradient changes sign from positive to negative (Goswami and Xavier 2005). So the model response to Indo-Pacific SST anomalies on the tropospheric temperature gradient is of great importance. We found from observations that the upper tropospheric temperature gradient over the dominant monsoon region (15°S–35°N, 30°E–110°E) has decreased and the relative influence of Indian Ocean SST variability on the withdrawal of Indian summer monsoon has increased in recent years. The model reproduces this increased (decreased) upper tropospheric temperature gradient in the La Niña (Positive IOD) forcing (Fig. 14a, b), thereby supporting our observational evidence that SST anomalies corresponding to a La Niña (a positive IOD) in the Pacific (Indian) Ocean will increase (decrease) the upper tropospheric temperature and will facilitate a late (early) withdrawal of the Indian summer monsoon. The cold SST anomaly in the tropical eastern/central Pacific and warm SST anomaly in tropical western Pacific in the La Niña type run (Fig. 12c) produces convection in the western tropical Pacific, and as a forced Rossby wave response to this convection (Matsuno 1966; Gill 1980), an anomalous cyclonic circulation on either side of the equator is evident (Similar to Fig. 9a in observation) over Asian monsoon region during the late summer monsoon season (September–October). Since northern cyclonic cell is stronger, probably due to the presence of easterly vertical shear (Xie and Wang 1996), than the southern counterpart (similar to Fig. 9a in observation), it enhances the vertical motion over Asian land mass, and thus releases more latent heat and increases the tropospheric temperature over the land mass and finally leads to stronger UTT gradient. The increased UTT gradient strengthens the monsoon circulation and thus facilitates the late withdrawal of the Indian summer monsoon. The entire process is given in the schematic diagram (Fig. 15a). This is consistent with the

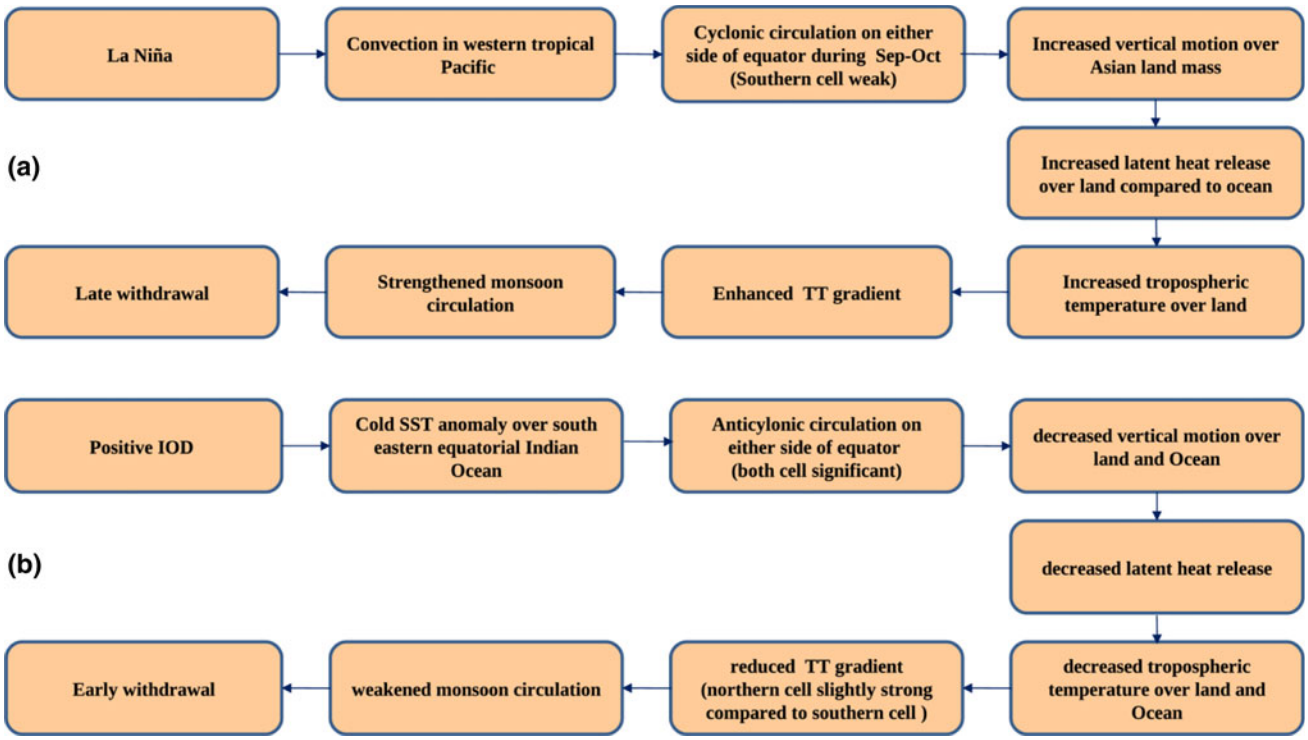

Fig. 15 Schematic representation of the mechanism proposed for the changes in tropospheric temperature gradient during the late summer monsoon period (September–October) **a** La Niña condition (pre 76 scenario), **b** positive IOD condition (post 76 scenario)

previous study of (Syroka and Toumi 2004), which shows that a quasi-stationary response to heating anomalies over Indonesian region may enhance the upper tropospheric temperature gradient during La Niña and thereby facilitate a late withdrawal of the Indian summer monsoon.

In the Positive IOD type run, we force the model with cold SST anomalies over south-eastern equatorial Indian Ocean and warm SST anomalies in western tropical Indian Ocean (Fig. 12b). The quasi-stationary response to this cold SST anomaly over south-eastern equatorial Indian Ocean produces anomalous anticyclonic circulations on either side of the equator (Matsuno 1966; Gill 1980) over Asian monsoon region during the late monsoon period (Similar to Fig. 9b in observation). The presence of southeastern equatorial Indian Ocean heat sink (i.e., close to the equator) makes both the anticyclonic circulations to be more symmetric around the equator, which leads to suppressed convection on both sides of the equator and thus the reduced latent heat release, which anomalously cools the upper troposphere. Even though both anticyclones are significant, the northern cell is slightly stronger compared to southern counterpart and thus reduces the UTT gradient. The reduced UTT gradient weakens the monsoon circulation and facilitates the early withdrawal of the Indian summer monsoon. The whole process is explained in schematic diagram (Fig. 15b).

5 Summary and discussion

In this study, we used criteria based on the upper tropospheric temperature gradient to define the Indian summer monsoon onset and withdrawal (TT index withdrawal) dates. The length of rainy season is defined as the difference between withdrawal date and onset date. A tendency for early withdrawal date and shortening of the length of the rainy season is observed during the recent decades. Prior to (after) the 1976/1977 climate shift, in majority of the years, the withdrawal of monsoon is late (early). But we find no long term trend in the onset date. So the change in the length of rainy season is mainly determined by variability in withdrawal dates. In this context, withdrawal of monsoon and associated teleconnection patterns are of significance. The change in the relationship between the Indian summer monsoon withdrawal date and the Indo-Pacific SST before and after 1976/1977 climate shift are investigated using the NCEP/NCAR reanalysis data and forced-AGCM experiments.

The correlations of withdrawal date and LRS with September–October mean SST show a significant difference between the PRE76 and POST76 periods. In the first epoch, the influence of eastern equatorial Pacific Ocean and Arabian sea SST on both withdrawal and LRS was strong. During the second period, the influence of eastern equatorial Pacific Ocean SST appears to have decreased and surprisingly, the influence of the Arabian Sea SST is almost non-existent. On the other hand, the influence of the south eastern equatorial Indian Ocean SST has increased significantly. Similarly, the correlation between the onset date and the May–June averaged SST anomaly also shows a dramatic change between PRE76 and POST76. Significant positive SST anomalies prevail over both the central and western Pacific and the northern IO in the POST76 period compared to the PRE76 period. The southeastern equatorial Indian Ocean SST variability does not seem to play a role in the onset of the Indian summer monsoon in either the PRE76 or the POST76 period as IOD is in its infant stages during May–June. The correlation between May and June SST anomalies and LRS show no significant difference between two epochs. Thus, it appears that the LRS shortening in the recent years seems to be borne out of the SST anomalies over the Indo-Pacific Oceans during the withdrawal phase.

The composite of September–October mean low level wind anomalies corresponding to late and early withdrawal years, and the correlation between withdrawal date and upper tropospheric temperature show a Rossby wave signal during both epochs. This Rossby wave structure is more symmetric during POST76 compared to PRE76, which is due to the change in position of the heat source (SST anomaly pattern) in the latter years. For the northern Rossby-like vortex, the wind at its southern side strengthens the cross equatorial monsoon flow into the Indian domain during the years when a late withdrawal is observed. But during the early withdrawal years, both the Rossby-like vortices contribute to the weakening of cross equatorial flow which should favor the early withdrawal of the Indian summer monsoon. Also during PRE76, the upper tropospheric temperature gradient is stronger compared to POST76, which also facilitates the late withdrawal of the monsoon and causes the lengthening of rainy season during PRE76. But after 1976, due to a change in position of the heat source (southeastern equatorial IO SSTA), the upper tropospheric temperature gradient decreases, which is favorable for an early withdrawal of the Indian summer monsoon and a shortening of the rainy season. In short, the recent shortening of the rainy season is mainly due to the change in anomalous SST forcing over Indo-Pacific during the withdrawal. Several model sensitivity experiments with an AGCM, each consisting of a 5 member ensemble are also carried out to confirm these causative links. These experiments essentially re-inforce the relative role of the tropical Pacific and Indian Ocean SST variability in the withdrawal of the Indian summer monsoon in PRE76 and POST76 periods. In a coupled climate system, there is obviously a feedback between the atmospheric variability and the SST response and using observed SST anomalies as forcing does not deconvolve the coupled feedback that produce the original SST patterns nor quantify the role of the forced atmospheric response on the subsequent evolution of the SST patterns. However, such model sensitivity studies are indeed instructive in understanding the causative links and the links we have found here should further process understanding leading to improved monsoon and ENSO forecasts.

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