



Recent changes in the trend, prominent modes, and the interannual variability of Indian summer monsoon rainfall centered on the early twenty-first century

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Abstract

In this study, the recent changes in rainfall trend, prominent modes, and interannual variability of Indian summer monsoon rainfall (ISMR) for the period 1980–2014 is investigated. Rainfall observations showed a decreasing trend during 1980–2000 (period 1) which changed to a significant increasing mode for the period 2001–2014 (period 2). The analysis shows that two prominent changes in the second period can induce the recent increasing trend of ISMR. The first one is the increased easterly wind anomalies from the equatorial Pacific associated with recent cooling in the eastern Pacific, and the second one is the increased cross-equatorial flow in the Indian Ocean as a result of increased land-sea thermal contrast. During the period 2, the dominant mode of ISMR variability increased and the connection with boundary forcing has intensified. The first mode of ISMR became strongly related to central and east Pacific SST (El Niño Southern Oscillation (ENSO)) anomalies after 2000, while its relationship with major SST indices was weak before that. The second mode contributed to around 14% of variability after the 2000s and is strongly related to Indian Ocean Dipole mode. These modes represent the interannual variability of ISMR during both the periods, and it increases considerably in the second period. Another significant difference between the two periods is that during period 1, many of the severe monsoon events are independent of ENSO; contrary during period 2, many were associated with that. Thus along with the significant change in trend, ISMR has stronger interannual variability, which is the prominent mode of Indian summer monsoon rainfall in the recent period.

1 Introduction

Rainfall during the four months of June to September over the Indian land region (Indian summer monsoon rainfall (ISMR)) is the major source of water for the millions of people and their livelihood (Webster et al. 1998). The interannual variability (IAV) of ISMR is relatively weak, with a standard deviation of around 10% of the summer mean rainfall (Shukla and Moolay 1987), but is associated with flood/drought-like situation over the Indian subcontinent, which can determine the socio-economic situations of the country. The IAV of ISMR largely depends on major slowly varying boundary forcing such as sea surface temperature (SST) in the Indo-Pacific region,

Eurasian snow cover/extent, soil moisture variability, etc. (Charney and Shukla 1981; Webster et al. 1998; Krishnamurthy and Kinter III 2003). Among these boundary forcing, variability in the Pacific Ocean associated with El Niño Southern Oscillation (ENSO) (Walker 1924; Rasmusson and Carpenter 1983; Webster et al. 1998) and Indian Ocean Dipole (IOD, Saji et al. 1999; Ashok et al. 2001, 2003; Behera et al. 2006) is the mostly studied factor. The positive phase of ENSO (El Niño) is associated with the eastward extension of the western Pacific warm pool to central equatorial Pacific and thus weakening the mean Walker circulation (Rasmusson and Carpenter 1983). This will induce anomalous descend over western Pacific and the eastern Indian Ocean extending to Indian landmasses and accounts for the below normal ISMR (Rasmusson and Carpenter 1983; Lau and Nath 2000; Pillai and Annamalai 2012). The opposite situation is associated with the negative phase of ENSO (La Niña). IOD, which has warm (cool) western equatorial Indian Ocean and cool (warm) eastern equatorial Indian Ocean during its positive (negative) phase, influences the

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ISMR through the modification of local Hadley circulation (Behera et al. 2006).

Meanwhile, studies like Krishna Kumar et al. (1999, 2006) have shown that ISMR interannual variability and its relationship with external SST forcing have changed with time. The strong simultaneous relationship between ENSO and ISMR weakened during the later part of twentieth century, while the weak ISMR-IOD relationship gained significant strength (Ashok et al. 2004) resulting in decadal modulation of ISMR-tropical SST relationship (IOD and ENSO). Nevertheless, ISMR also observed to have alternating epochs of above-normal and below-normal conditions, each lasting about two to three decades (Parthasarathy et al. 1994; Kripalani and Kulkarni 1997; Krishnamurthy and Goswami 2000). For example, the study by Kripalani and Kulkarni (1997) showed that the ISMR time series remained below normal during 1901–1930 and 1961–1990 period and above normal during 1871–1900 and 1931–1960 period. If this decadal modulation is natural, ISMR should be in an above-normal epoch after the 1990s, but reverse situation occurred in nature.

However, studies on the ISMR variability in the recent global warming period have different views. Wang et al. (2013) showed that the northern hemisphere summer monsoon rainfall and large-scale circulations intensify after 1978. Goswami et al. (2006) also pointed out that global warming will result in the increased frequency of extreme rainfall events over the Asian region. Model intercomparison study of Turner and Annamalai (2012) reported that monsoon rainfall in India is likely to increase in the future. However, studies like Zhou et al. (2008), Guhathakurta and Rajeevan (2008), Tokinaga et al. (2012), and Krishnan et al. (2013) indicated that the monsoon rainfall and large-scale circulations are weakening over the South Asian region since the 1950s. It is also showed that even though the extreme rainfall events have increased over some regions (Goswami et al. 2006), the frequency of moderate-to-heavy rainfall events has decreased over the subcontinent (Krishnan et al. 2013). Besides, several recent studies based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) indicate a significant weakening of the large-scale Asian summer monsoon circulation, especially in the middle to the upper atmosphere (Ma and Yu 2014).

Many recent studies discuss the coupled relationship between the Indian Ocean and monsoon, which can be a potential reason for the recent weakening of ISMR in the late twentieth century (Swapna et al. 2014; Roxy et al. 2015). Roxy et al. (2015) showed that recent warming in the Indian Ocean played a major role in the weakening of the monsoon circulation and rainfall over central Indian subcontinent. But Swapna et al. (2014) earlier showed opposite relationship as the weakened monsoon in the recent period is the cause for the recent warming in the tropical Indian Ocean. They argued that the weakening of the summer monsoon cross-equatorial flow

increased the SST warming in the central equatorial Indian Ocean. Another recent study by Arora et al. (2016) showed that in the recent period after 2000, Indian Ocean warming is responsible for the hiatus in the Pacific Ocean SST, which leads to decreased SST in the tropical east Pacific regions. Recently, Jin and Wang (2017) using different types of observed summer rainfall data showed that ISMR had weakening trend in the last period of twentieth century, while in the early twenty-first century, the trend is changed to increasing trend and they proposed the moisture changes in the pre-monsoon season as the reason for the increasing trend.

The present study is built on these previous observational studies (Jin and Wang 2017; Arora et al. 2016; Swapna et al. 2014). Major purpose of this study is to investigate the mechanism behind this increasing trend in summer monsoon rainfall observed over the Indian region in the recent period and relate it to the similar changes in the tropical ocean-atmosphere system. Also, the present study analyzes the changes in the prominent mode and interannual variability of ISMR during these two epochs of different ISMR trend and highlights the reason behind these changes.

2 Data and methodology

The present study uses Indian land region rainfall data from the University of Delaware (Willmott and Matsuura 2001) and the India Meteorological Department (IMD) (Rajeevan et al. 2006). As these datasets have only land rainfall, Global Precipitation Climatology Project (GPCP) monthly rainfall dataset (Adler et al. 2003) is also used in the study. The study also uses the Met Office Hadley Centre's sea ice and sea surface temperature dataset (HadISST1) (Rayner et al. 2003), NCEP/NCAR Reanalysis1 specific humidity data and datasets at 850 hPa for zonal (u) and meridional (v) components (Kalnay et al. 1996), and the University of Delaware Air Temperature data (Willmott and Matsuura 2001). All the datasets are used for the summer monsoon season (JJAS) from 1980 to 2014. The study period is further subdivided into two distinct periods. The first period is from 1980 to 2000 (period 1), and the second period is from 2001 to 2014 (period 2).

Trend analysis of monthly precipitation anomaly over the Indian region for the two periods is carried out, and the results are analyzed. The trend of SST and wind anomalies was depicted over Indo-Pacific region (30° N–0° S, 40° E–90° W). The composite analysis is done using GPCP rainfall data, SST, and wind datasets over the same region. This can be quite useful for exploring the large-scale impacts of teleconnections from modes of atmospheric variability such as El Niño. To study the prominent patterns of ISMR, empirical orthogonal function (EOF) analysis (principal component analysis) has been done. The correlation of PC values of ISMR with Niño3 index (5° N–5° S, 150° W–90° W, Trenberth 1997)

and EMI index ($EMI = [SSTA]_A - 0.5 \times [SSTA]_R - 0.5 \times [SSTA]_C$, where the brackets in the equation represent the area-averaged SST anomaly over each of the region A (10° S– 10° N, 165° E– 140° W), B (15° S– 5° N, 110° W– 70° W), and C (10° S– 20° N, 125° E– 145° E), respectively (Ashok et al. 2007), and the Indian Ocean Dipole Mode Index (IODMI) (SSTA difference between the western (10° S– 10° N, 50° E– 70° E) and southeastern (10° S to equator, 90° E– 110° E) regions of the tropical Indian Ocean (Saji et al. 1999) are calculated. These results are used to assess the influence of canonical ENSO, Modoki, and IOD on ISMR pattern in the two periods. The PC values of rainfall are regressed with SST anomalies, GPCP rainfall, and wind anomalies to identify the large-scale ocean-atmosphere patterns associated with ISMR.

3 Results and discussion

3.1 Observed trend of ISMR and other variables before and after 2000

In the present section, we try to understand the observed trend of ISMR and try to relate it to the other variables, such as Indo-Pacific Ocean SST, land-sea temperature difference, lower level circulation, and moisture availability, which are related to the ISMR variability on an interannual timescale. Figure 1 a and b show the anomaly time series of ISMR with two periods from 1980 to 2000 (period 1) and 2001 to 2014 (period 2), respectively, with linear trend marked in each figure. ISMR has a decreasing trend with a value of 0.05 per year during first phase, and in the second period, the rainfall is showing an increasing trend of 0.12 per year, which is in accordance with Jin and Wang (2017). Figure 1 c and d show the time series of JJAS SST anomaly over the tropical Indian Ocean (30° S– 30° N, 40° E– 120° E) and Pacific Ocean (30° S– 30° N, 130° E– 270° E) for the two epochs, respectively. Both the tropical Indian Ocean and the Pacific Ocean had a weak increasing trend in period 1 (Fig. 1c, 0.008 and 0.010 per year, respectively). Meanwhile, after 2000, the drastic change occurred in the SST over the two oceans (Fig. 1d), in which the Pacific Ocean is having a significant decreasing trend (0.005 per year) whereas the Indian Ocean is heating rapidly (increasing trend of 0.011 per year). Thus, the warming tendency of tropical Indian Ocean increased, and the Pacific Ocean attained a cooling trend after 2000. These ocean changes probably affect ISMR through circulation. Figure 2 shows surface temperature over the Indian Ocean and Indian land region (10° N– 35° N, 70° E– 95° E) and 850-hPa wind trend over the Indo-Pacific region (30° N– 30° S, 40° E– 90° W), along with specific humidity over Indian region (10° N– 35° N, 70° E– 95° E) for the two epochs under investigation. Land temperature over the Indian monsoon region has similar warming trend (0.005 per year) as the Indian Ocean during 1980–2000

time (Fig. 2a), while it has more warming trend (0.025 per year) compared with the Indian Ocean warming in period 2 (Fig. 2b). Thus after 2000, Indian land surface warms more compared with the Indian Ocean providing a notable land-sea thermal contrast and drives the circulation towards the monsoon region. The spatial trend of 850-hPa wind in both the periods indicates that in period 1, there is weak easterly trend in the western Pacific Ocean and easterlies in the equatorial Indian Ocean (Fig. 2c), whereas in the next period, there is strong easterly trend in the Pacific and extending to monsoon region with strong cross-equatorial trend from the Indian Ocean to Indian land region (Fig. 2d). Associated with these wind patterns, moisture advection and moisture convergence over the monsoon region are found to be increased in period 2 (the trend is 0.023 per year) compared with earlier period (decreasing trend of 0.014 per year) (Fig. 2e, f).

Thus, we can arrive at the possible cause for these two different trends of ISMR during the two periods. During the first period, SST over the Indian Ocean is high and the land temperature is relatively low. This leads to a reduction in land-sea thermal contrast and weakens the wind flow towards the land region. SST over the Pacific Ocean is also having an increasing trend, which is responsible for the reduction in easterly flow from there. Since there is a huge reduction in moisture supply from both the Indian Ocean and the Pacific Ocean to the Indian land region, ISMR is having a decreasing trend in the first period. However, both SST and air temperature over the Indian region are having a highly positive trend and significant meridional gradient also during the second period. This enhances the cross-equatorial flow from the Indian Ocean to monsoon region, providing a sufficient amount of moisture. SST trend over the Pacific is being reduced and is favoring the circulation from the eastern Pacific to monsoon region. Due to the combined effect of these changes in the Indo-Pacific region, ISMR is showing a significant increasing trend during the second period. Hence, we can evidently conclude that the temperature gradient and strong cooling over the Pacific Ocean are the two most important mechanisms behind the increased ISMR during the second period.

3.2 Recent changes to the prominent modes of ISMR

The above analysis confirmed that the change in ISMR trend is associated with ocean-atmospheric changes in the tropical Indo-Pacific region. An earlier study by Pillai et al. (2019) has shown that major modes of tropical Pacific SST have undergone changes around the period 1998 reducing the co-occurrence of ENSO and IOD. Thus as the two periods considered for this study are also fairly matched with the changes, the variability of the prominent mode of ISMR and their interannual variability in the two epochs are discussed here.

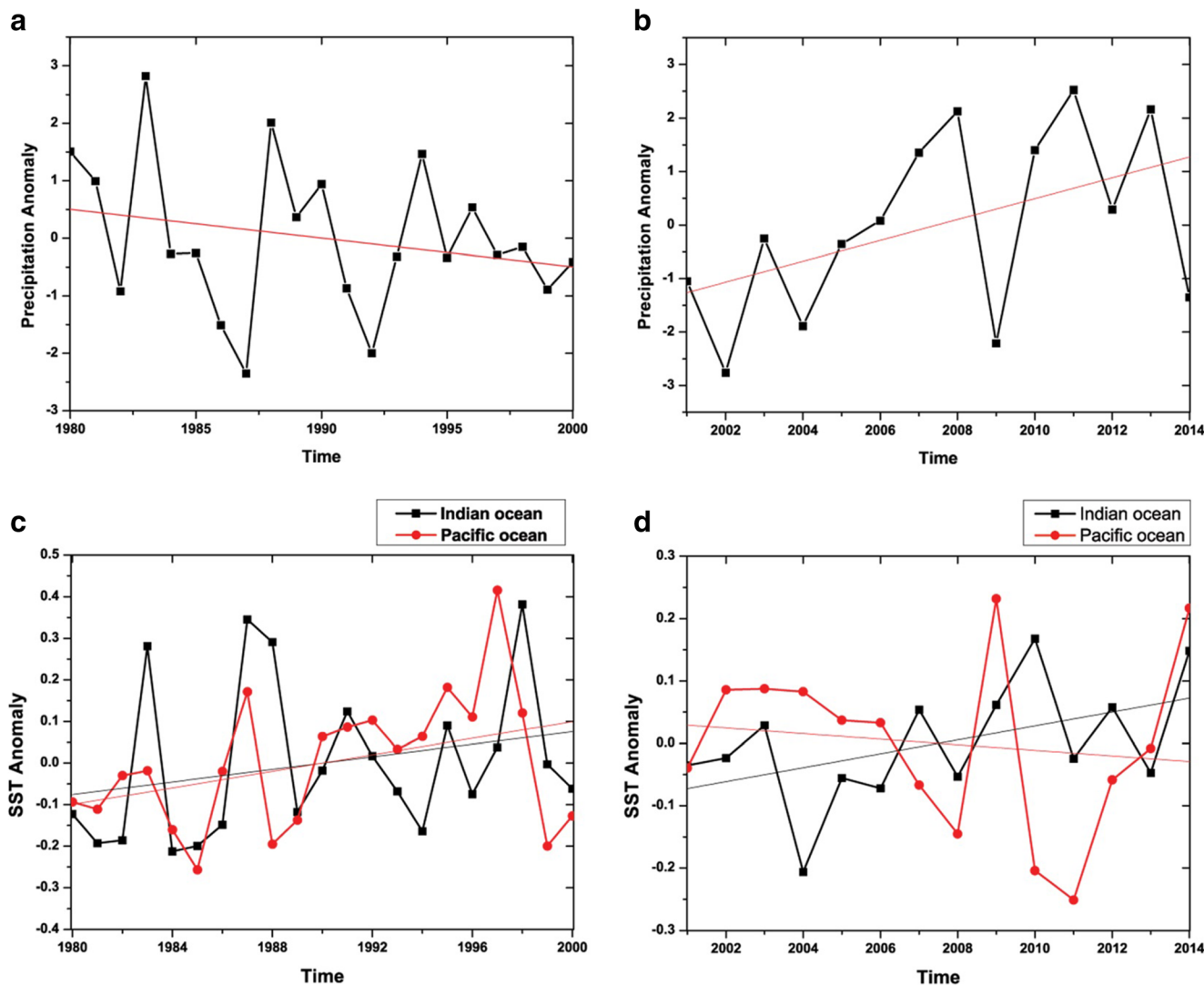


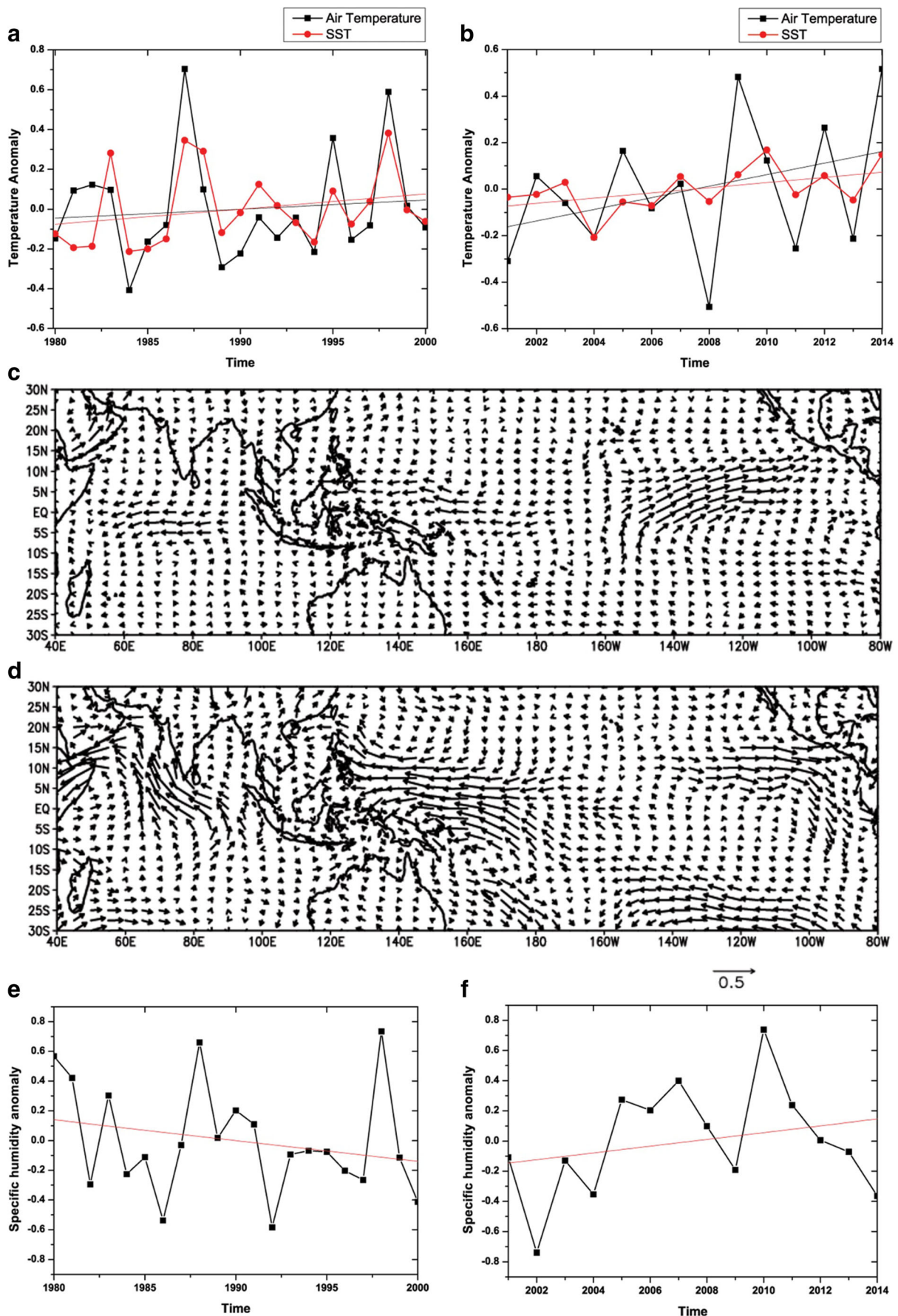
Fig. 1 Standardized anomalies of ISMR (mm/day) for **a** 1980–2000 period and **b** 2001–2014 period. **c** and **d** same as **a** and **b**, respectively, but for SST (°C) averaged over tropical Indian Ocean (black line) and Pacific

Ocean (red line). The straight line in each panel indicates the linear trend corresponding to the respective time period

To understand the prominent patterns of ISMR, EOF analysis of the land rainfall over the Indian region is performed for the two selected study periods and is provided in Fig. 3. During period 1, EOF1 with 19% of total variability has positive loading in the western part and negative loading in the eastern central part of India (Fig. 3a). Meanwhile, in period 2, variability increases to 26% with positive loading over the majority of Indian land region (Fig. 3b). The EOF time series (PC1) is strongly related to EMI ($cc = 0.60$) and Niño3 ($cc = 0.51$), and the correlation with IOD index is 0.36 in period 2, while the relationship with tropical SST was weak during the first period (Table 1). At the same time, EOF2 (11% variability) with positive loading in the central and southern Indian region (Fig. 3c) also has not much relationship with the SST indices up to 2000. During 2001–2014 period, its variability increases to 14% with dipole loading (Fig. 3d) and a correlation of 0.53 with IOD index. EOF3 with north–south dipole

rainfall loading explains around 10% variability in both the periods (Fig. 3e, f) and has a correlation of 0.47 with EMI index after 2000. EOF4 with 8% of total variability has a correlation of 0.56 with IOD in period 1 (Fig. 3g) and 0.35 with Niño3 in period 2 (Fig. 3h). Thus in period 1, major variability of ISMR (EOF1 and EOF2) has not much relationship with tropical SST anomalies, while in period 2, EOF1 is related to ENSO flavors and EOF2 to Indian Ocean SST anomalies. The ocean-atmospheric variations associated with these prominent modes are discussed below.

Fig. 2 Time series of standardized anomalies of surface temperature (°C) over Indian land region (black line) and over tropical Indian Ocean (red line) for **a** period 1 and **b** period 2. **c** and **d** are the spatial pattern of linear trend of 850-hPa wind (m/s) during these periods, respectively. **e** and **f** are same as **a** and **b**, but for specific humidity averaged over Indian land region



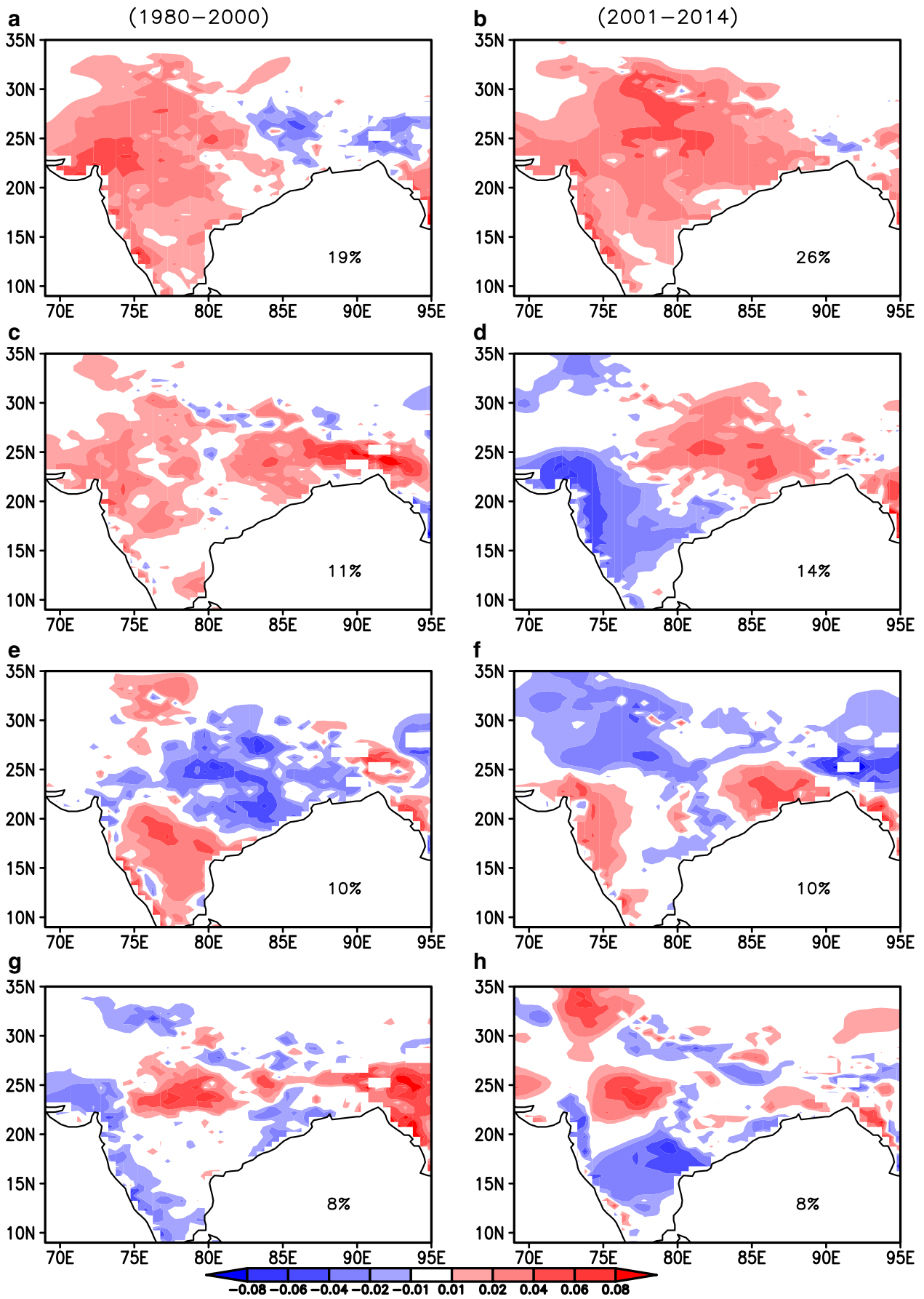


Fig. 3 Spatial loading of prominent modes (EOFs) of JJAS ISMR **a** EOF1 for first period and **b** same for second period. **c** and **d** are same as **a** and **b**, but for EOF2, **e** and **f** for EOF3 and **g** and **h** for EOF4. The percentage value in bottom right corner of each panel represents the variability explained by that EOF during the period

3.3 SST and circulation changes associated with major modes of ISMR

Figure 4 shows the spatial pattern of SST, rainfall, and 850-hPa wind anomalies obtained by the regression of ISMR PC1 of both the periods. Table 1 also shows the correlation of these PCs with different SST indices over the Indo-Pacific region. During first period, the SST anomalies were weakly negative in the central Pacific and warm in the entire tropical Indian Ocean and western Pacific (Fig. 4a). Thus, the SST relationship with PC1 is non-significant for all the SST indices in Table 1. The associated wind pattern has easterly anomalies in the central Pacific and cyclonic circulation in the western Indian Ocean region. The cyclonic circulation in the western Indian Ocean is associated with increased rainfall over the western and southern parts of the country, and there is negative rainfall in the northeastern part of the country (Fig. 4c). Meanwhile, during second epoch, the cold SST anomalies in the central Pacific are stronger and extend both eastward and northward. Indian Ocean SST anomalies have opposite phase in both the periods (Fig. 4a, b). There are increased easterly wind anomalies from central Pacific to Indian land region and have increased cross-equatorial flow in the Indian Ocean leading to increased convection over the monsoon region (Fig. 4d). Thus as seen from Table 1, latter period is associated with SST anomalies in the tropical Pacific and Indian Ocean with strong La Niña like wind from the Pacific and cross-equatorial flow from the monsoon region leading to stronger ISMR.

The ocean-atmosphere parameters associated with PC2 of ISMR for both the periods are provided in Fig. 5. Here, there are weak SST anomalies (Fig. 5a) and circulation during period 1 with weak convection over monsoon region (Fig. 5c). But in

period 2, there is strong cooling in the eastern Indian Ocean (Fig. 5b) with easterly wind anomalies converging in the central Indian Ocean and northeastern part of India, making strong north–south dipole rainfall pattern over the monsoon region (Fig. 5d). The corresponding wind also has easterly wind anomalies in the eastern Indian Ocean converging in the south-central region, indicating the formation of dipole like SST and rainfall anomalies over the Indian Ocean and dipole anomalies over the monsoon region as indicated by the significant PC2-IOD correlation during the second period.

Thus, it is clear that the major modes of Indian summer monsoon rainfall are weakly related to SST anomalies during 1980–2000 period, while during the second period, EOF1 is strongly linked with central and east Pacific SST anomalies and PC2 is linked to Indian Ocean SST anomalies. The time series of PC1 coincides with the strong and weak monsoon years based on the JJAS ISMR index. To confirm the major mode of ISMR, a strong minus weak monsoon year composite of rainfall, 850-hPa wind, and corresponding SST anomalies are plotted in Fig. 6. The corresponding SST pattern has cool SST anomalies in the central Pacific during period 1 (Fig. 6a), and it extends to the eastern Pacific in the second period (Fig. 6b). Thus in the second period, the easterly wind anomalies from the central Pacific are stronger (Fig. 6d), and both the periods have increased rainfall over the monsoon region. The strong-weak rainfall composite and corresponding SST and circulation anomalies have close resemblance with the spatial pattern of rainfall, SST, and circulation induced by the first prominent mode of ISMR in both the periods, indicating that extreme events are also modified in both the epochs, with ISMR having stronger dependence on central and east Pacific SST in period 2 compared with period 1.

The standard deviation (SD) of ISMR indicates that ISMR interannual variability increased by around 42% in the recent period (SD of ISMR is 1.32 in period 1 and 1.74 in period 2). Moreover, the ISMR interannual variability is strongly associated with SST anomalies in the tropical Pacific during this time. The correlation between ISMR and Niño3 index is increased from -0.22 of 1980–2000 to -0.76 in the 2001–2014 periods. It is also known from the years used for the composite in Fig. 6 that, during 1980–2000 period, out of the four weak years (1982, 1985, 1986, and 1987), only 1982 and 1987 are associated with El Niño and in the four strong years (1983, 1988, 1990, and 1994), only 1988 is associated with La Niña. Meanwhile, in the second period, weak years such as 2002 and 2009 are with strong El Niño and 2004 and 2014 are with weak El Niño in the Pacific and in the strong years such as 2007 and 2010 are with La Niña and 2006 and 2013 are independent of La Niña in the Pacific. Thus, more number of extreme ISMR years is associated with ENSO in the Pacific confirming the EOF1 pattern and the composite pattern in Fig. 6. Thus along with the increase in ISMR trend, major modes of ISMR variability and its relationship with SST boundary forcing are increased in the present decade. But the number of strong and weak ISMR years is almost

Table 1 Correlation of time series of prominent modes (PCs) of ISMR with EMI, IOD, and Niño3 indices during the periods 1980–2000 and 2001–2014

Period	Correlation with			
		EMI	IOD	Niño3
1980–2000	EOF1	0.23	0.06	0.1
	EOF2	0.17	0.08	0.09
	EOF3	0.24	0.03	0.16
	EOF4	0.06	0.56	0.47
2001–2014	EOF1	0.6	0.36	0.51
	EOF2	0.09	0.53	0.22
	EOF3	0.47	0.15	0.13
	EOF4	0.07	0.06	0.35

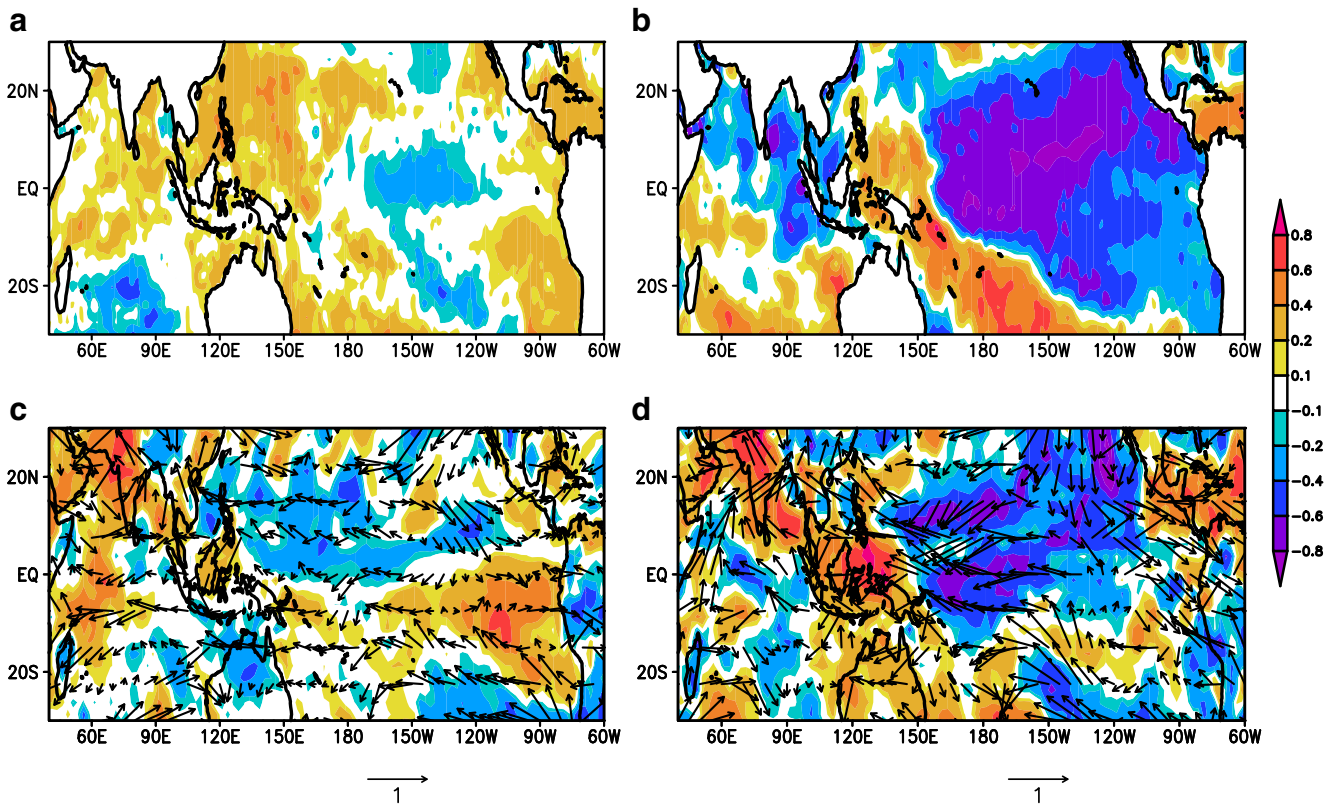


Fig. 4 JJAS season anomalies obtained by regression of first mode of ISMR (PC1) of a SST (°C) during period 1, b same as a, but for period 2, c rainfall (mm/day, shaded) and 850-hPa wind (m/s, vector) for period 1, d same as c, but for 2001–2014 period

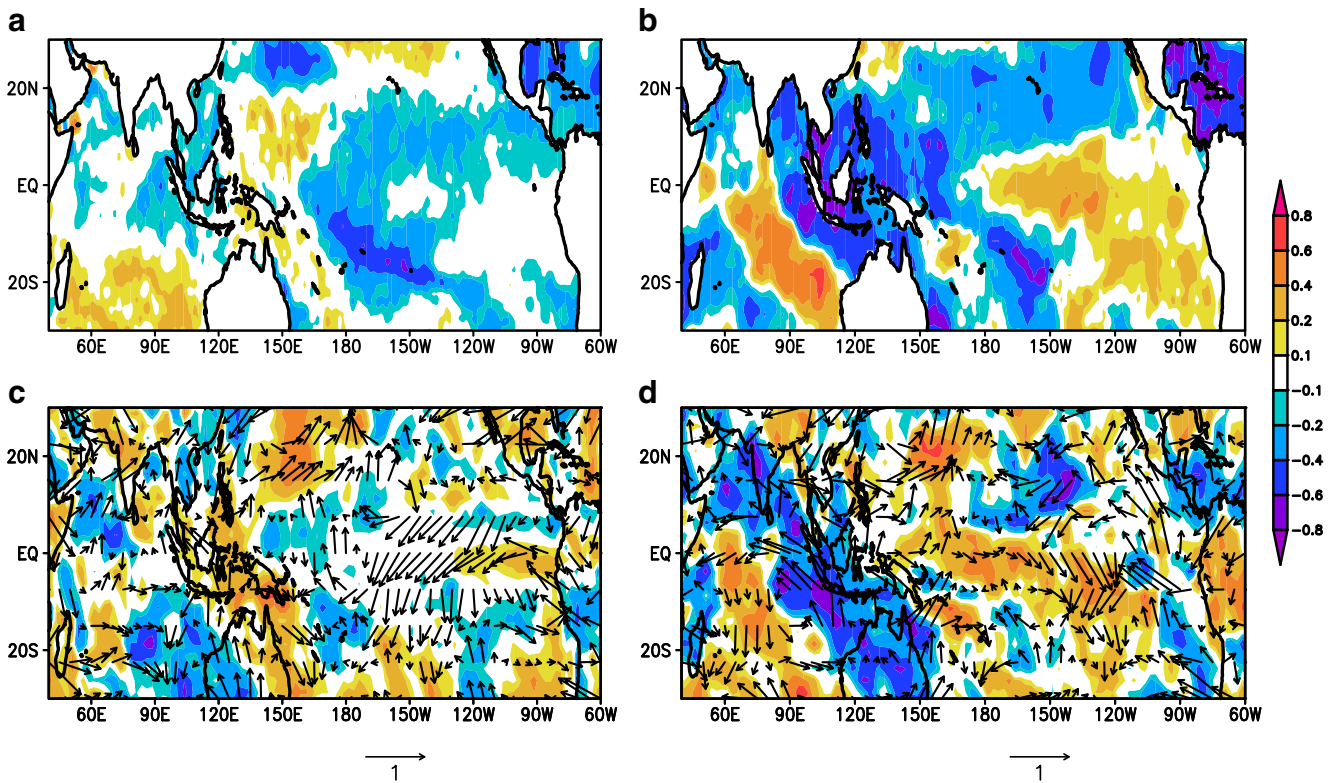


Fig. 5 JJAS seasonal anomalies of regression of second mode of ISMR (PC2) of SST (°C) a during 1980–2000 and b during 2001–2014. c Rainfall (mm/day, shaded) and 850-hPa wind (m/s, vector) for 1980–2000, d same as c, but for 2001–2014 period obtained by regression of second mode of ISMR (PC2) during these two periods

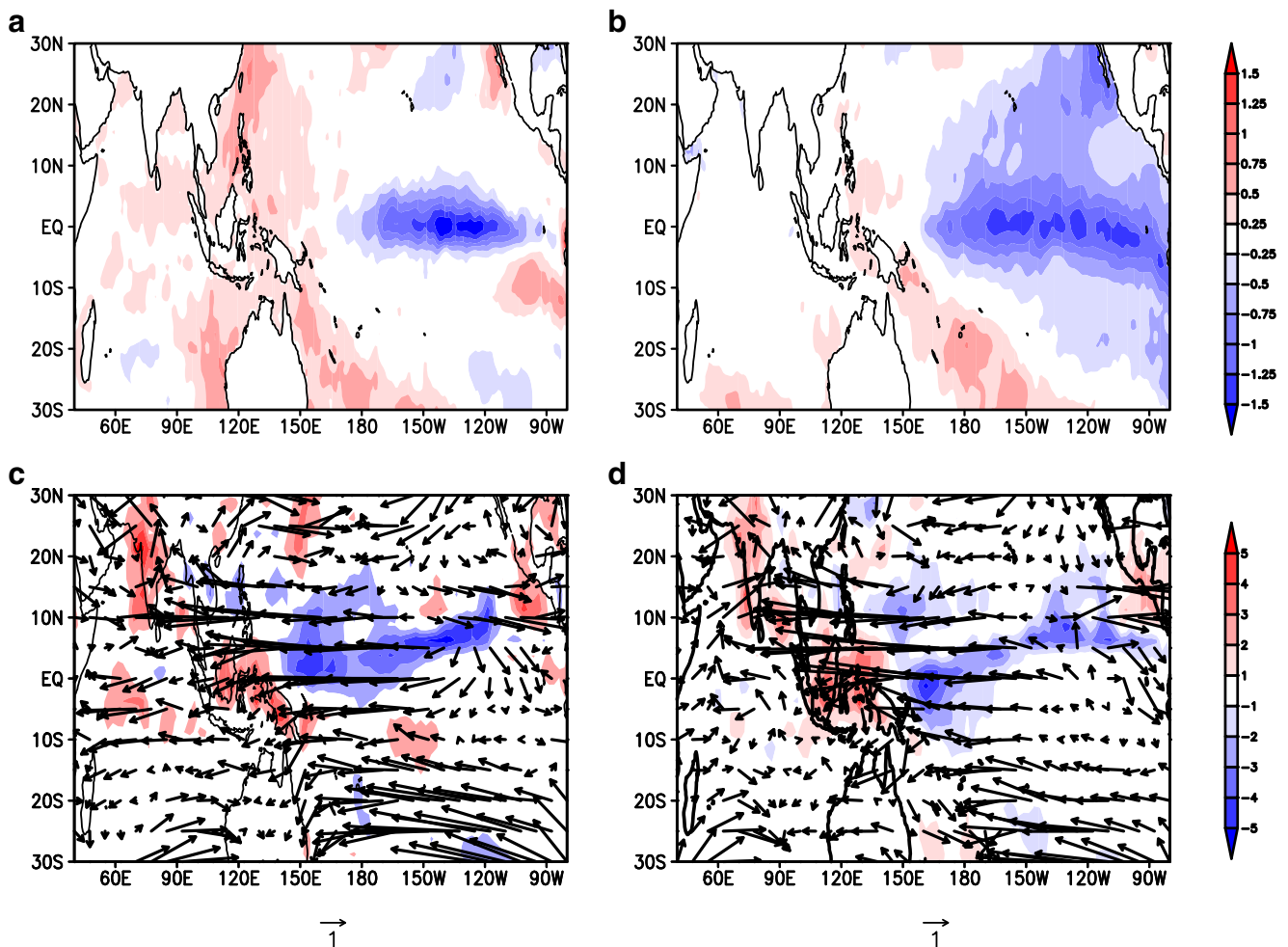


Fig. 6 Strong minus weak Indian summer monsoon year composite anomaly of SST ($^{\circ}\text{C}$) during **a** period 1 and **b** period 2. **c** and **d** are rainfall (mm/day, shaded) and 850-hPa wind (m/s, vector) corresponding to 1980–2000 and 2001–2014 periods, respectively

equal in both the epochs, even with the positive trend in the second period. But in the second period, as ISMR relationship with Niño3 increases and the east Pacific itself has La Niña like background change, it may positively contribute to an above-normal condition for ISMR.

4 Summary and conclusion

The present study verifies the reported change in ISMR trend centered on the beginning of twenty-first century (Jin and Wang 2017) and confirms the similar changes occurred in the processes controlling the interannual variability of ISMR. The study points out that equatorial Pacific SST reversed to a cooling trend from the early 2000s, while the warming trend in the equatorial Indian Ocean is intensified. These changes induced an easterly wind trend in the equatorial central Pacific to monsoon region and cross-equatorial flow during period 2. In the second period, Indian land surface is warming faster than the Indian Ocean region inducing a strong land-sea thermal contrast associated with stronger cross-equatorial wind towards the monsoon region.

All these changes favor the increased monsoon trend during the second period compared with the first period, and thus, the study verifies the increasing trend of ISMR in the recent period.

The changes in major variability of ISMR and the factors responsible for that are also analyzed in the study. The major two modes have increased variability in the period 2 with EOF1 strongly controlled by SST anomalies in the central and eastern Pacific and EOF2 by the dipole anomalies of equatorial Indian Ocean. Meanwhile, the role of SST anomaly in EOF1 and EOF2 was limited in period 1 with EOF1 having a weak correlation with central Pacific SST anomalies. The EOF1 of ISMR is associated with weak SST anomalies in the central Pacific and weak circulation over the monsoon region. Meanwhile, during period 2, EOF is strongly dependent on central and east Pacific SST with strong wind anomalies from both the Pacific and Indian Ocean region with stronger variability. EOF2 has strong dipole pattern of SST in the Indian Ocean after 2000, and so, the major modes depend more on the tropical SST forcing during that time. Further analysis confirms that EOF1 pattern corresponds to strong and weak ISMR rainfall and corresponding SST and circulation features, and the interannual variability of ISMR is also

modified during both the periods and is stronger in the period 2 compared with period 1. Thus, the present study accounts the observed trend, changes in major modes of ISMR variability and its interannual variability during the last period of twentieth century and early twenty-first century, and it confirms that these changes are dependent on the changes in the association of ISMR with other external forcing factors in both the periods.

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References

- Adler RF et al (2003) The Version 2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979–Present). *J Hydrometeorol* 4:1147–1167
- Arora A, Rao SA, Chattopadhyay R, Goswami T, George G, Sabeerali CT (2016) Role of Indian Ocean SST variability on the recent global warming hiatus. *Glob Planet Chang* 143:21
- Ashok K, Guan Z, Yamagata T (2001) Impact of the Indian Ocean Dipole on the relationship between the Indian monsoon rainfall and ENSO. *Geophys Res Lett* 28:4499–4502
- Ashok K, Guan Z, Yamagata T (2003) A look at the relationship between the ENSO and the Indian Ocean Dipole. *J Meteor Soc Jpn* 81:41–56
- Ashok K, Chan WL, Motoi T, Yamagata T (2004) Decadal variability of the Indian Ocean Dipole. *Geophys Res Lett* 31:L24207
- Ashok K, Behera SK, Rao SA, Weng HY, Yamagata T (2007) El Niño Modoki and its possible teleconnection. *J Geophys Res* 112:C11007
- Behera SK, Luo JJ, Masson S, Rao SA, Sakuma H, Yamagata T (2006) A CGCM study on the interaction between IOD and ENSO. *J Clim* 19:1688–1705
- Charney JG, Shukla J (1981) Predictability of monsoons. *Monsoon Dynamics*. Cambridge University Press, pp 99–109
- Goswami BN, Venugopal V, Sengupta D, Madhusoodanan MS, Xavier PK (2006) Increasing trend of extreme rain events over India in a warming environment. *Science* 103:1442
- Guhathakurta P, Rajeevan M (2008) Trends in the rainfall pattern over India. *Int J Climatol* 28:1453–1469
- Jin Q, Wang C (2017) A revival of Indian summer monsoon rainfall since 2002. *Nat Clim Chang* 7:587–594
- Kalnay et al. (1996) The NCEP/NCAR 40-year reanalysis project. *Bull Am Meteorol Soc* 77:437–470
- Kripalani RH, Kulkarni AA (1997) Rainfall variability over south-east Asia—connections with Indian monsoon and ENSO extremes: new perspectives. *Int J Climatol* 17:1155–1168
- Krishna Kumar K, Rajagopalan B, Cane A (1999) On the weakening relationship between the Indian monsoon and ENSO. *Science* 284:2156
- Krishna Kumar K, Rajagopalan B, Hoerling M, Bates G, Cane M (2006) Unraveling the mystery of Indian monsoon failure during El Niño. *Nature* 314:115–119
- Krishnamurthy V, Goswami BN (2000) Indian monsoon–ENSO relationship on interdecadal timescale. *J Clim* 13(3):579
- Krishnamurthy V, Kinter JL III (2003) The Indian monsoon and its relation to global climate variability. *Global Climate, X Rodó and FA Comin, Eds., Springer-Verlag*, 186
- Krishnan R, Sabin TP, Ayantika DC, Kitoh A, Sugi M, Murakami H, Turner AG, Slingo JM, Rajendran K (2013) Will the South Asian monsoon overturning circulation stabilize any further? *Clim Dyn* 40:187–211
- Lau NC, Nath MJ (2000) Impact of ENSO on the variability of the Asian–Australian monsoons as simulated in GCM experiments. *J Clim* 13:4287–4309
- Ma J, Yu JY (2014) Paradox in South Asian summer monsoon circulation change: lower tropospheric strengthening and upper tropospheric weakening. *Geophys Res Lett* 41:2934–2940
- Parthasarathy B, Munot AA, Kothawale DR (1994) All India monthly and seasonal rainfall series 1871–1993. *Theor Appl Climatol* 49:217–224
- Pillai PA, Annamalai H (2012) Moist dynamics of severe monsoons over south Asia: role of the tropical SST. *J Atmos Sci* 69:97–115
- Pillai PA, Nair RC, Vidhya CV (2019) Recent changes in the prominent modes of Indian Ocean Dipole in response to the tropical Pacific Ocean SST patterns. *Theoretical and Applied Climatology* (online)
- Rajeevan M, Bhate J, Kale JD, Lal B (2006) High resolution daily gridded rainfall data for Indian region: analysis of break and active monsoon spells. *Curr Sci* 9(3):296–306
- Rasmusson EM, Carpenter TH (1983) The relationship between eastern equatorial Pacific sea surface temperatures and rainfall over India and Sri Lanka. *Mort Weather Rev* 111:517–528
- Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J Geophys Res* 108:4407
- Roxy MK, Ritika K, Terray P, Murtugudde R, Ashok K, Goswami BN (2015) Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land–sea thermal gradient. *Nat Commun* 6:7423
- Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian Ocean. *Nature* 401:360
- Shukla J, Moolay DA (1987) Empirical prediction of summer monsoon rainfall over India. *Mo Wea Rev* 115:695–703
- Swapna P, Krishnan R, Wallace JM (2014) Indian Ocean and monsoon coupled interactions in a warming environment. *Clim Dyn* 42:2439
- Tokinaga H, Xie SP, Deser C, Kosaka Y, Okumura YM (2012) Slowdown of the Walker circulation driven by tropical Indo-Pacific warming. *Nature* 491:439–443
- Trenberth K (1997) The definition of El Niño. *Bull Am Meteorol Soc* 78:2771–2777
- Turner AG, Annamalai H (2012) Climate change and the South Asian summer monsoon. *Nat Clim Chang* 2:587
- Walker GT (1924) Correlation in seasonal variations of weather IX: a further study of world weather. *Memoirs of the Indian Meteorological Department* 24:225–232
- Wang B, Liu J, Hyung-Jin K, Webster PJ, So-Young Y, Xiang B (2013) Northern Hemisphere summer monsoon intensified by mega-El Niño/southern oscillation and Atlantic multidecadal oscillation. *Proc Natl Acad Sci U S A* 110:5347–5352
- Webster PJ, Magana VO, Palmer TN, Shukla J, Tomas RA, Yanai M, Yasunari T (1998) Monsoons: processes, predictability, and the prospects for prediction. *J Geophys Res* 103:14451
- Willmott CJ, Matsuura K (2001) Terrestrial air temperature and precipitation: monthly and annual time series (1950–1999), (http://climate.geog.udel.edu/~climate/html_pages/download.html)
- Zhou T, Zhang L, Li H (2008) Changes in global land monsoon area and total rainfall accumulation over the last half century. *Geophys Res Lett* 35:L16707

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