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Regime shift of Indian summer monsoon rainfall to a persistent arid state: external forcing versus internal variability

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Abstract The high propensity of deficient monsoon rainfall over the Indian sub-continent in the recent 3 decades (seven deficient monsoons against 3 excess monsoon years) compared to the prior 3 decades has serious implications on the food and water resources in the country. Motivated by the need to understand the high occurrence of deficient monsoon during this period, we examine the change in predictability of the Indian summer monsoon (ISM) and its teleconnections with Indo-Pacific sea surface temperatures between the two periods. The shift in the tropical climate in the late 1970s appears to be one of the major reasons behind this. We find an increased predictability of the ISM in the recent 3 decades owing to reduced 'internal' interannual variability (IAV) due to the high-frequency modes, while the 'external' IAV arising from the low-frequency modes has remained largely the same. The Indian Ocean Dipole–ISM teleconnection has become positive during the monsoon season in the recent period thereby compensating for the weakened ENSO–ISM teleconnection. The central Pacific El-Niño and the Indian Ocean (IO) warming during the recent 3 decades are working together to realise enhanced ascending motion in the equatorial IO between 70°E and 100°E, preconditioning the Indian monsoon system prone to a deficient state.

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1 Introduction

More than 75% of the annual rainfall received by the Indian sub-continent occurs during a short span of 4 months during the southwest monsoon season (June–September, JJAS) (Turner and Annamalai 2012). The sowing of major cereal crops in India is largely dependent on the onset of the southwest monsoon, and the crops are sustained mostly by the rainfall that the sub-continent receives during the monsoon season (Rajeevan 2013). Fluctuations in monsoon onset or the quantum of rainfall during the monsoon season can affect the quantity and the quality of the harvest (Rajeevan 2013), and, consequently, the country's Gross Domestic Product (Gadgil and Gadgil 2006; Kumar et al. 2004). Furthermore, the interannual variability of the monsoon can exert stress on the already strained water resources of the country. There is an increased demand of fresh water due to agricultural expansion, rapid urbanization, and increasing population. Therefore, the prediction of the seasonal mean rainfall over the Indian continent is crucial for policy makers to prepare the country for food security during possible large-scale droughts and floods, and to provide safeguards against scarcity of fresh and potable water (Guhathakurta and Rajeevan 2008). The usefulness of reliable seasonal forecasts of monsoon rainfall has been exemplified during 2014 and 2015 when the country could overcome two consecutive deficient monsoons without serious food crisis and food inflation due to better management of water resources based on reliable forecasts from India Meteorological Department and the Indian Institute of Tropical Meteorology (IITM, Pai et al. 2015; Srivastava et al. 2015).

The predictability of the tropical seasonal climate, in general, including the Indian summer monsoon rainfall (ISMR) arises from the fact that the tropical seasonal climate is modulated by the slowly varying climate modes like

the El-Niño and Southern Oscillation (ENSO), the Indian Ocean Dipole Mode (IOD), the Pacific Decadal Oscillation (PDO), the Atlantic Multi-decadal Oscillations (AMO), etc. (Charney and Shukla 1981; Goswami and Shukla 1991; Krishnamurthy and Krishnamurthy 2014a, b; Lau et al. 2002, 2004; Nigam et al. 2011; Shukla 1998), and is limited by 'internal' interannual variability generated by higher frequency processes such as the monsoon intra-seasonal oscillations (MISOs, Goswami and Ajayamohan 2000; Goswami and Xavier 2005; Goswami 1998). Numerous studies have documented the important role of eastern-central Pacific sea surface temperatures (SSTs) in modulating the interannual variability of the ISM (e.g., Sikka and Gadgil 1980; Shukla and Paolino 1983; Rasmusson et al. 1983; Nigam 1994; Slingo and Annamalai 2000; Annamalai and Liu 2005). The seasonal mean monsoon variability is largely explained by the ENSO and the ENSO–monsoon teleconnection forms an integral part of the tropical ocean atmosphere low-frequency coupled response (Shukla 1987; Walker 1918; Webster 1987; Webster et al. 1998). In most of the general circulation models, the teleconnection between the SSTs specified in the Pacific and the ISM is too strong (Sperber and Palmer 1996), and hence, most of the predictability of the ISM comes from them. Similarly, the Indian Ocean Dipole (IOD) has been reported to be a major player in the coupled ocean–atmosphere dynamics of the tropical Indian Ocean (Saji et al. 1999; Webster et al. 1999). The IOD plays an important role in modulating the ISMR and also affects the relationship between ENSO and monsoon (Ashok et al. 2001). In a recent study by Chattopadhyay et al. (2015a), it has been demonstrated that slow variations of the northern hemispheric extra-tropical SSTs act as a potential source of seasonal predictability of the south Asian monsoon. The characteristics of the interannual variability of the ISMR, therefore, can be influenced by changes in the teleconnections between the ISMR and other slowly varying modes as well as by the relative contributions of the 'internal' variability to 'external' variability arising from the slowly varying forcing. The teleconnections or the physical linkages through which the SSTs over the Indian Ocean, the Pacific Ocean, or the Atlantic Ocean modulates the ISM rainfall depend on the background mean climate. The Indian Monsoon is known to have a multi-decadal oscillation associated with it. For example, 1901–1930 was a dry period followed by a wet period of 30 years (1931–1960) and the again by a dry period (1961–1990) (Guhathakurta and Rajeevan 2008). An examination of the climate for the past 6 decades indicates that there has been a major shift of the tropical climate in mid-1970s (Nitta and Yamada 1989; Trenberth and Hurrell 1994, Graham 1994). Notwithstanding the fact that this 'shift' could be part of a multi-decadal variability of the tropical climate, it represents a significant change in the mean background climate relative to the previous period of

say 3 decades. We also note that the character of the interannual variability of the ISM rainfall (Fig. 1b) has changed significantly during the recent 31 years (1985–2015) compared to the previous 31 years or other similar 31 year periods
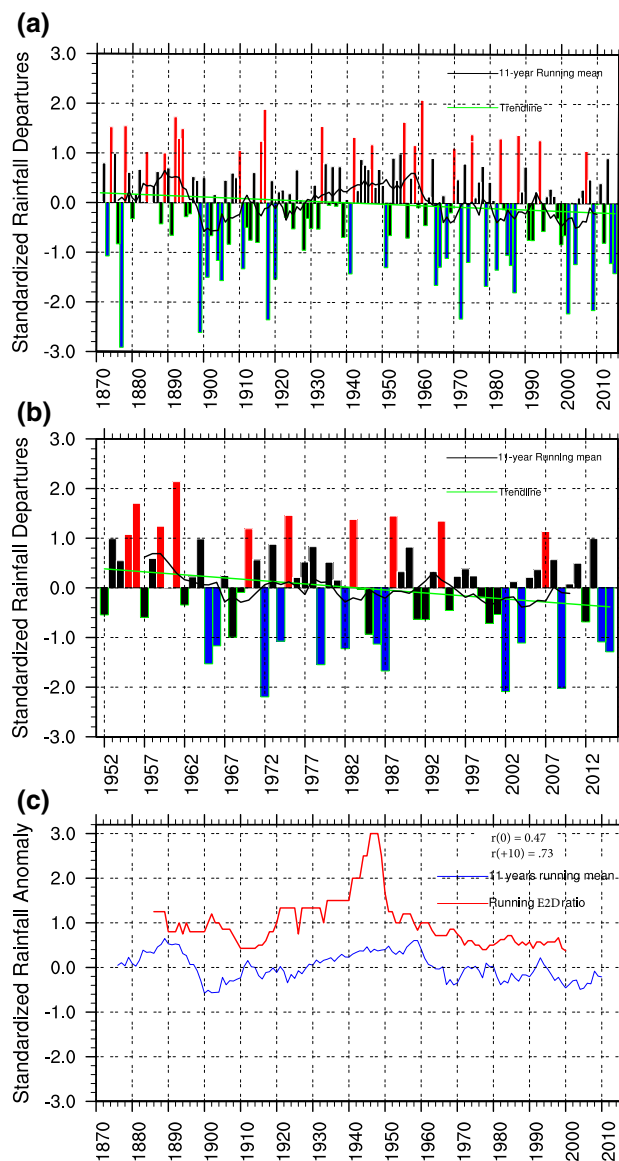

Fig. 1 a Time series evolution of standardized AISMR anomalies, expressed as percentage departures from its mean. The red bars represent excess monsoon years, when the standardized AISMR anomaly was greater than + 1 standard deviation (SD), and, the blue bars represent deficit monsoon years, where the anomaly was less than − 1 SD, while the black bars are neither flood nor drought years. The black curve indicates the 11-year running mean, and the green curve indicates the trendline. Trendline shown is significant at 90% confidence level. **b** Same as **a** but for the period 1952–2015, and, **c** blue curve indicates a 11-year running mean of the standardized AISMR anomalies and the red curve indicates Excess-to-Deficit monsoon years' ratio (E2D) in a moving window of 31 years. The correlation between the time series is 0.47 and that at lag + 10 of F2D time series is 0.73

in the past (Fig. 1a). For example, the ratio between number of excess monsoon years (normalized ISMR > 1) and deficient monsoon years (normalized ISMR < − 1) during this period (E2D) is 0.38 (3/8), less than half the value during the previous 31 years (1954–1984) when it was 0.86 (6/7). It may be argued that this may be due to the general decreasing trend of ISMR between 1951 and 2015 (Rao et al. 2010, 2012; Bollasina et al. 2011; Saha et al. 2014; Roxy et al. 2015). However, even after removing the trend, the difference in E2D during the two periods remains almost the same. Thus, there is a genuine increase in propensity of large-scale-deficient monsoons compared to excess monsoons during the recent 3 decades compared to 3 previous decades. In fact, the E2D remained significantly higher than the present period during two other 31-year periods namely, 1923–1953 and 1892–1922 when it was 1.5 (3/2) and 0.86 (6/7), respectively. To investigate the dependence of the E2D on the choice of the 31-year window, the ratio is calculated with a 31-year moving window starting from 1871 (Fig. 1c). It is interesting to note that the current very low value of the E2D occurred only once in the past instrumented records of ISMR centred around 1912, while highest value of the E2D occurred centred around 1945. It is also interesting to note that the variation of the E2D has a strong relationship with the multi-decadal variation of the ISMR, as shown by the 11-year running mean of ISMR in Fig. 1b. While both the very low values of the E2D happened soon after the peak negative phases of the ISMR multi-decadal oscillation, the highest ratio occurred a few years before the peak positive phase of the ISMR multi-decadal oscillation. Very low value of E2D during the current 3 decades represents a persistent aridity in the country with serious implications on water resources and food production in the country and socio-economic disasters that are associated with them. In addition, it is to be noted that the natural multi-decadal variability of the monsoon system would have pushed the system to a wet phase in 1991–2020 period. However, Fig. 1a suggests that the system is witnessing a persistent dry state since 1960s. Thus, indeed, there is a change in the nature of the IAV of ISMR in the recent 3 decades. To strengthen our claim further, we computed the probability distribution function (PDF) of the seasonal mean departures of rainfall for the period 1949–2016 and are shown in Fig. 2. It is interesting to note that this shift in the AISMR is corroborated by a shift in the probability distribution function (PDF) of the AISMR time series in the recent decades (Fig. 2). The PDF has become more symmetric in recent decades as compared to earlier decades, which implies a lesser probability of having a good monsoon year. To prepare for and to mitigate against the potential disasters due to droughts, it is imperative to improve the skill of simulation and prediction of monsoon droughts by dynamical models. For improving the skill of the dynamical models, it is critical to understand
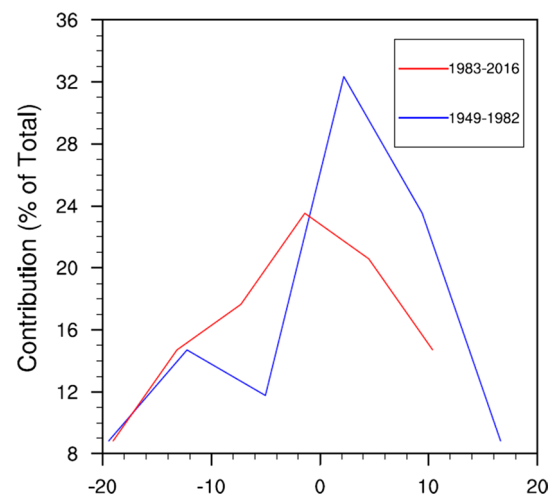

Fig. 2 Probability distribution function (PDF) for seasonal (JJAS) mean rainfall departures over Indian landmass for the two different time periods

the changes in the predictability of the system and the associated teleconnections. The present study is intended to identify the changes in the monsoon system, and is organized as follows. The data used and methodologies are discussed in Sect. 2. The results are presented in Sect. 3, where we examine whether the interannual variance explained by 'internal' dynamics relative to that explained by 'external' forcing has changed. We also examine whether the teleconnections between Indo-Pacific SST and Indian monsoon have changed during these two epochs. Furthermore, we try to understand how the changes in the background mean flow lead to the changes in physical linages responsible for these teleconnections. The conclusions are listed in Sect. 4.

2 Data and methodology

For examining the interannual variability of the Indian summer monsoon rainfall (ISMR), we use monthly rainfall data prepared by IITM based on fixed 306 stations uniformly distributed in the country (Parthasarathy et al. 1994) for the period 1871–2015. The data can be downloaded from the website of the institute using the link (ftp://www.tropmet.res.in/pub/data/rain/iitm-regionrf.txt). The National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay et al. 1996), the monthly NOAA Extended Reconstructed SST version 4 (ERSST v4, Huang et al. 2015; Liu et al. 2015), have also been used for the same period. We have used some other reanalysis data such as the Japanese 55-year reanalysis (JRA-55, Ebita et al. 2011; Kobayashi et al. 2015) to verify the

robustness of the results presented in this study. The signatures of these changes are present in those reanalysis products too.

To examine the changes in the teleconnection of ISMR with ENSO and IOD, we split the time period 1952–2013 in two halves, viz., 1952–1982 (T1) and 1983–2013 (T2) of 31 years each. The recent period is the period when the E2D ratio is very small and happens to be on a low negative phase of ISMR multi-decadal oscillation, while the earlier period is representative of the positive and transition phase of the ISMR multi-decadal variability (Fig. 1c). It may also be noted that the two periods are roughly on two sides of the climate shift in the late 70s. However, the results presented are not much sensitive to modest changes to the time periods. For examining the interannual variability during the two periods, anomalies of dynamic and thermodynamic atmospheric and oceanic fields are constructed with respect to the climatologies of the fields for the two different epochs, respectively. Furthermore, the statistical significance of composite anomalies has been calculated using a two-tailed t test, the null hypothesis being the sample means are from the same population. An F-ratio is used as an estimate of predictability computed using the methodology described by Ajayamohan and Goswami (2003). The methodology is described in supplementary information of this article.

3 Results

It is well known that the interannual variability of the monsoon system is strongly controlled by the slowly varying modes of tropical variability such as ENSO and IOD. Furthermore, the intraseasonal oscillations and synoptic scale systems can also strongly influence the seasonal mean (Goswami and Ajayamohan 2000; Krishnamurthy and Ajayamohan 2010; Srivastava et al. 2017). These high-frequency components can limit the influence of the slowly varying modes and, hence, also control the nature of the interannual variability. This brings in the concept of predictability. The low-frequency components can be predicted months in advance (seasonal time scales) on account of their slowly evolving nature. However, the high-frequency components have predictability only on short and extended ranges. Thus, the predictability of the seasonal mean monsoon is limited by these high-frequency components. Predictability on seasonal scales may basically be defined as the signal-to-noise ratio, the signal being the low-frequency component and the noise being the synoptic and intraseasonal time scales. Since both of them contribute to the seasonal mean, we will first look into any changes in the variabilities of these two time scales.

3.1 Changes in potential predictability

The character of interannual variability (IAV) of ISMR could be influenced by the relative contributions of 'internal' IAV compared to the 'external' forced IAV, the 'internal' IAV being the high-frequency component and the 'external' IAV is the low-frequency component. Before examining the change in teleconnections, therefore, we examine the relative contributions of these two components of IAV to the total IAV of the ISMR. For this purpose, we estimate the total IAV as the JJAS mean zonal winds at each grid point for each 31-year period from NCEP/NCAR reanalysis. The 'forced' and 'internal' components of the IAV are estimated by the method described by Ajayamohan and Goswami (2003). An F-ratio is defined by the ratio of total variance and variance of 'internal' IAV (detailed methodology is given in supplementary information). The F-ratios for the two periods are shown in Fig. 3. It is clear from the figures that there is an increase in the F-ratio over the Asian monsoon region in the recent epoch compared to the earlier epoch. Averaged over the extended Indian monsoon rainfall (EIMR, 70°E–100°E, 10°N–30°N, Goswami et al. 1999) region, the F-ratio increased to 4.8 in the recent epoch from 3.4 in the previous epoch. This indicates that although the mean rainfall has decreased and droughts have become more frequent, the potential predictability of the seasonal mean ISMR has increased appreciably during the recent period compared to the earlier period. This increased predictability has arisen due a decreased 'internal' variability in the recent epoch compared to the earlier epoch, while the 'external' variability has remained almost the same during the two epochs (figure not shown). To test whether this result is robust, the calculation of the F-ratio was repeated using the JRA-55 reanalysis for slightly different periods and shown in Fig. 3c, d. It is seen that the F-ratio has increased over the EIMR region to 4.2 in the recent epoch (1986–2012) from 3.0 in the previous epoch (1958–1985). Studies have reported a decreasing trend in the observed frequency of MDs in the recent decades (Patwardhan and Bhalme 2001; Rajendra Kumar and Dash 2001; Mandke and Bhide 2003). Prajeesh et al. (2013) suggested that the decreasing trend in the frequency of occurrence of MD could be associated with the declining trend in mid-tropospheric relative humidity. Vishnu et al. (2016) have shown that the reduction in the mid-tropospheric relative humidity due to weakening on monsoon low-level jet is responsible for the decrease in the number of monsoon depressions. Interestingly, Vishnu et al. (2016) also report a strong discontinuity in the number of monsoon depressions in post-1980s which roughly matches the period of enhanced predictability. Zveryaev (2002) had shown that in response to sea surface warming and associated enhanced convection, the 30–60-day (low-frequency) ISO mode became stronger over the equatorial central and
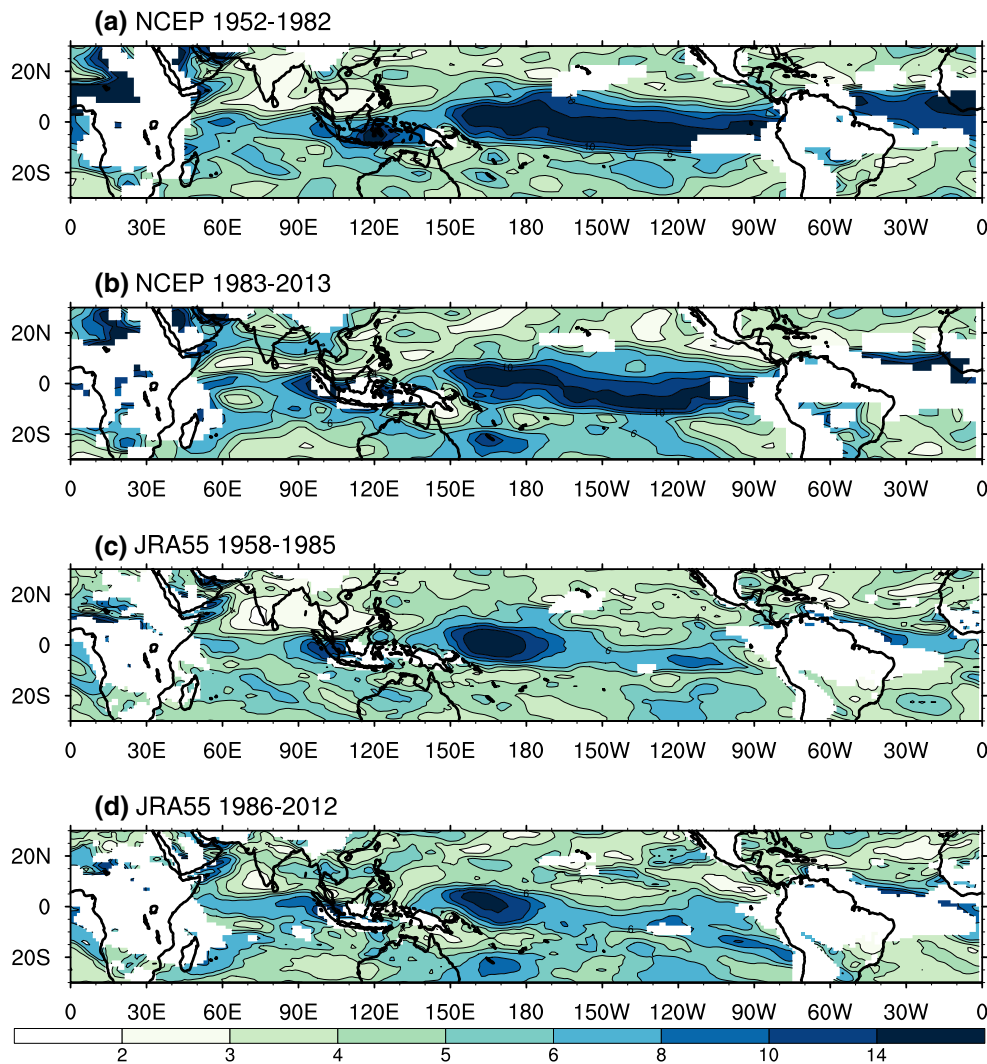
Fig. 3 Estimates of "*F*" ratios for zonal winds at 850 hPa for all NH summer months (JJAS) for **a** NCEP reanalysis for 1952–1982, **b** same as **a** but for 1983–2013; **c** and **d** same as **a** and **b** but for JRA55 reanalysis, respectively

western Indian Ocean and the South China Sea, and weaker over the Indian sub-continent. More importantly, the study has shown that the regime shift had occurred in the late 1970s, which again matches with the second time period of our study. The low-frequency ISO variance exhibits lowest values in post-1980 period. Furthermore, Karmakar et al. (2015) have shown that the relative strength of the northward-propagating low-frequency ISO (20–60 days) modes has had a significant decreasing trend during the past 6 decades, possibly due to the weakening of large-scale circulation in the region during monsoon season.

The declining trend in the low-frequency ISO mode superimposes on the declining trend in the number of monsoon depressions. Both these phenomena have epochal changes after the 1980s. The combined effect has resulted in decreased 'internal' component of variability, 'external' variability remaining largely the same. The result is

enhanced predictability of the seasonal mean monsoon. Thus, it appears that the increased potential predictability in the recent years is a robust conclusion.

3.2 Changes in teleconnections

It is important for the dynamical models to properly capture the dominant teleconnections which modulate the monsoon. Numerous studies have evaluated the important role of the ENSO–monsoon teleconnection in governing the seasonal prediction skill in dynamical models (Gadgil and Sajani 1998; Kang et al. 2002; Wang et al. 2004; Bracco et al. 2007; Rajeevan and Nanjundiah 2009; Rajeevan et al. 2012). IOD also plays an important role in controlling the rainfall over India (Ashok et al. 2001; Krishnamurthy and Kirtman 2003; Saji and Yamagata 2003; Ajayamohan and Rao 2008; Ajayamohan et al. 2009; Rao et al. 2010; Krishnan et al.

2011; Chattopadhyay et al. 2015b). Thus, it becomes vital to study any changes in the teleconnections due to these two models in light of the climate shift in 1977. They can be represented by a lead–lag correlation between a monthly index of ENSO such as the Niño3.4 index and the ISMR index and between a monthly index of IOD and the ISMR index. Considering ISMR index to be centred on the month of July, such lead–lag correlations are calculated between Niño3.4 index and ISMR during the two periods (Fig. 4a). The characteristic feature of this teleconnection is that the correlations between ISMR and Niño3.4 are maximum after the monsoon season in the months of October–November (as in the case for the period 1982–2012) (Fig. 4a, Kirtman and Shukla 2000; Krishnamurthy and Kirtman 2003; Wu and Kirtman 2003). However, it is noted that the correlations are generally weaker compared to those during the previous 3 decades consistent with weakening of the teleconnection indicated in some previous studies (Kumar et al. 1999; Torrence and Webster 1999). It is interesting to note that during the previous period not only the correlations during and after the monsoon season were stronger, it peaked within the monsoon season towards the end of the season (Fig. 4a). This means that ENSO affected the latter half (August–September) of the monsoon more vigorously in the previous decades, whereas the ENSO effect during the July–August–September months in the recent decades is almost the same. Thus, even though the ENSO–monsoon

teleconnection might have weakened, the peak effects are present throughout the JAS months. Therefore, it is clear that there has been not only a change in strength of the teleconnection but also in phasing of the teleconnection between the ENSO and ISMR during the two epochs. Furthermore, we have made a La-Nina minus El-Niño composite, as shown in Fig. 6. Roxy et al. (2014) have reported an asymmetry in the ENSO forcing wherein the number and intensity of El-Niño events have increased. This is evident from Fig. 6 where 10 El-Niño years (ENY) occurred as compared to a meagre three La-Nina years (LNY). Keeping in mind the skewness of El-Niño events, we note a shift in the teleconnections associated with the ENSO to eastern-central Pacific as has been reported by earlier studies (Ashok et al. 2007; Kumar et al. 2006). The cooling (warming) signal in the Arabian Sea associated with a La-Nina (El-Niño) event has become weak and insignificant in the recent epoch.

However, the largest change in teleconnection between the two epochs has occurred in the teleconnection between the IOD and the ISMR (Fig. 6b–d). Earlier studies have shown that strong monsoons result in enhanced cooling of the Arabian Sea (Shukla and Misra 1977; Weare 1979). Thus, a negative correlation of the SSTs in the western pole of the IOD (10°S–10°N, 50°E–70°E) with the ISMR is observed in T1 (Fig. 4c). However, in the recent 3 decades, a cooling signal in the Arabian Sea due to a strong monsoon is absent and is replaced by weak and simultaneous positive
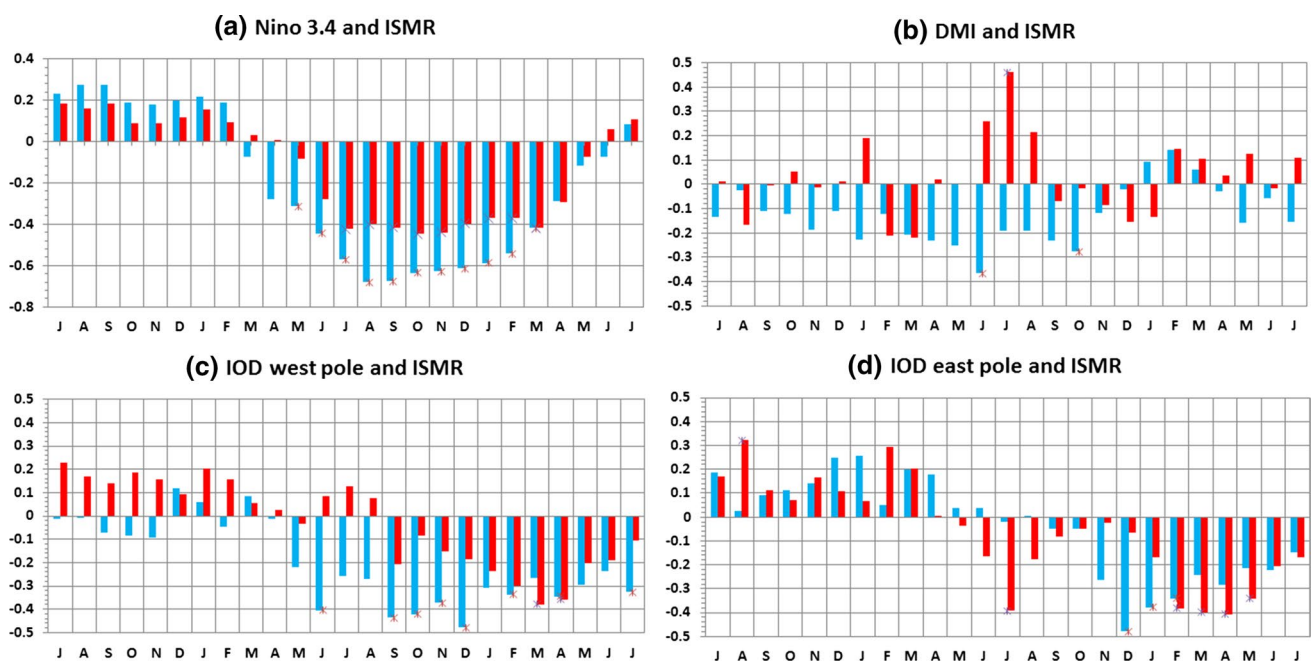

Fig. 4 Lag correlations of monthly **a** Nino 3.4 index, **b** DMI index, **c** IOD west pole index, and **d** IOD east pole index with seasonal mean monsoon rainfall over Indian Landmass for the two different epochs. Blue bars denote the earlier time period (1952–1982) and red bars denote the recent years (1983–2013). Zero lag indicates corresponding July index correlated with JJAS mean rainfall. Correlations significant at 90% confidence level are marked with asterisks

correlations of SST with ISMR. IOD east pole (10°S–0°, 90°E–110°E) does not have a simultaneous association with the ISMR in the earlier epoch, but in the recent epoch, a strong monsoon is governed by cool SSTs in the eastern equatorial IO. The net effect is that the correlation between IOD and ISMR which is weakly negative and peaks following the monsoon season during the earlier epoch; positive correlation occurs simultaneously during the monsoon season in the recent epoch (Fig. 4b). We have also made a good monsoon (standardized ISMR > 1) minus bad monsoon (standardized ISMR < − 1) composite of SST anomalies and is shown in Fig. 5. To have a good sample size and equal number of good and bad monsoon years (GMY and BMY, respectively) in a given time period, we have suitably relaxed the criterion for selecting the GMY and BMY. The cooling of SSTs in the western IO is a characteristic signature of a good monsoon which is associated with strong cross-equatorial westerlies. Such a signature can be easily discerned in the earlier epoch, but the recent epoch shows warm anomalies in the western Indian Ocean. In a study by Rao et al. (2012), it has been pointed out that the tropical IO SSTs have been warming at a rate unparalleled by any other region in the tropical basins. It is also known that these warmer SSTs induce enhanced convection over the

IO, thereby inducing frequent IOD events (Ajayamohan and Rao 2008; Rao et al. 2010, 2012). From the composite of Fig. 5, it is evident that, indeed, the GMY in the recent decades are associated with a simultaneous positive IOD-type signal with warming in the western IO and cool anomalies along the Java-Sumatra coast. The simultaneous occurrence of positive IOD signal with the monsoon may partly be attributed to the IO warming in the recent decades. Similar changes in the IOD–ISMR teleconnections have been observed in a recent study by Pradhan et al. (2016) on a seasonal time scale, though they did not look at the phasing of IOD teleconnections with the ISMR. They argue that the tropical Indian Ocean (TIO) was relatively passive during the earlier 3 decades and thus was basically controlled by the atmospheric fluxes; the ocean–atmosphere coupled dynamics were less significant. A strong cross-equatorial flow during the boreal summer resulted in cooling of SSTs in the western IO and gave good rainfall over India. These negative correlations between ISMR and western IO SSTs are evident in Fig. 4c during the recent period. These negative correlations have become slightly positive during the JJA months in recent period which means that SSTs are not driven only by the winds in WIO. The westward propagating Rossby wave response to the relatively "active" ocean–atmosphere system
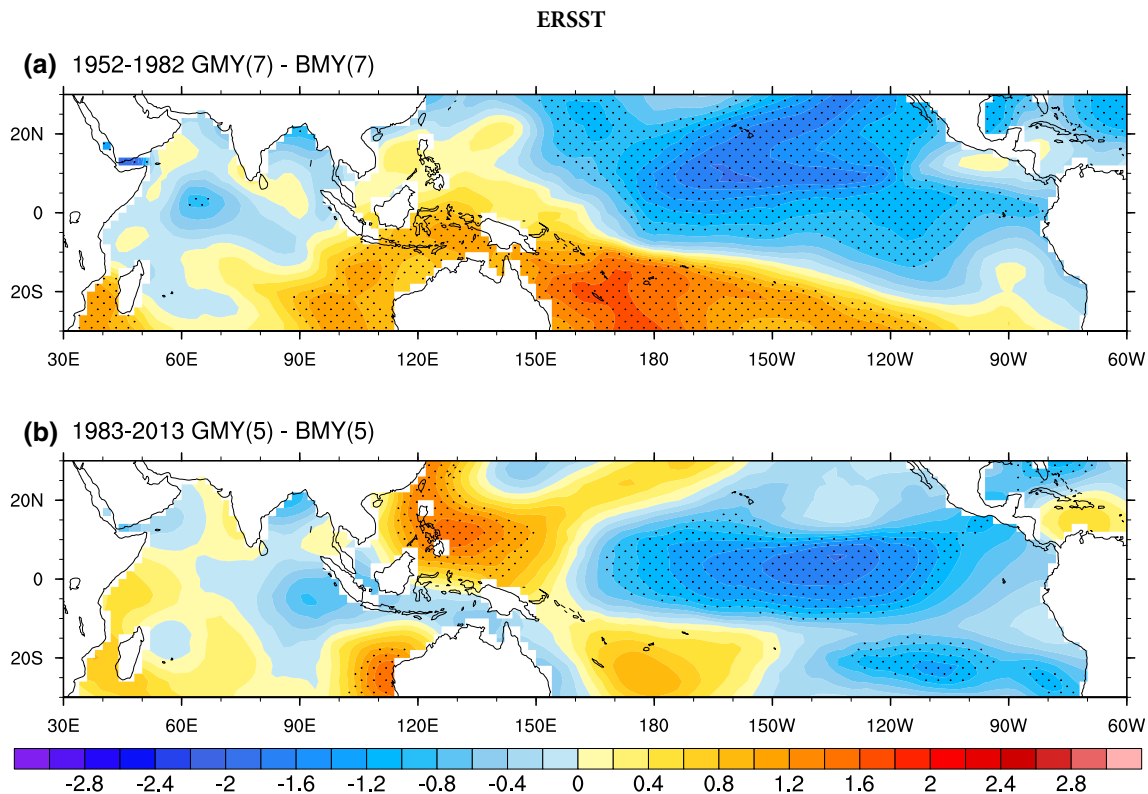
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Fig. 5 Difference in seasonal (JJAS) mean SST anomaly composites (in °C) for **a** good monsoon years (GMY) and bad monsoon years (BMY) for the period 1952–1982; and **b** GMY and BMY for the period 1983–2013. The number of GMY and BMY is indicated in square brackets. Anomalies significant at 90% confidence level are stippled
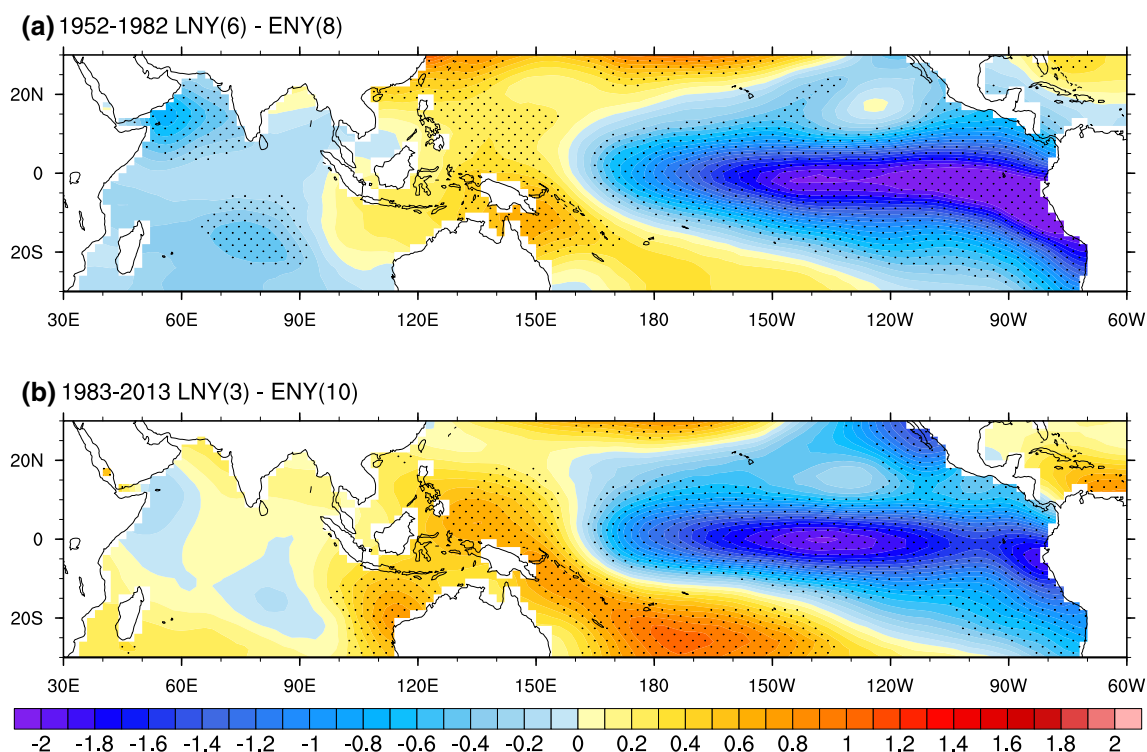
Fig. 6 Difference in seasonal (JJAS) mean SST anomaly composites (in °C) for **a** La-Nina years (LNY) and El-Nino years (ENY) for the period 1952–1982; and **b** LNY and ENY for the period 1983–2013. The number of LNY and ENY is indicated in square brackets. Anomalies significant at 90% confidence level are stippled

in T2 causes piling up of warm waters in the western tropical IO. The resultant upwelling Kelvin wave response will cause cooling in the eastern tropical IO. The associated changes in regional Hadley circulation will lead to a good monsoon due to these cold SSTs. It is interesting to note that these coupled phenomena occur during the JJAS season in T2 as compared to the post monsoon season in T1. Small changes in the IOD east pole SSTs cause significant changes in air–sea interaction processes which might be partly responsible for an increased frequency of IOD events (Ajayamohan and Rao 2008). This is a major change in the Indian Ocean SST teleconnection with the ISMR and has made the Indian Ocean (IO) as important as or more important than the ENSO in determining the interannual variability of ISMR. Using generalized additive models, Krishnaswamy et al. (2015) have shown that the impact of IOD on extreme rainfall events and ISMR is strengthening in the recent decades, and the relationship grows steeply after 1980. In conjunction to their study, the physical mechanisms mentioned above contribute to this enhanced relationship, and have a vital role to play with regard to monsoon predictability. The competing and opposing influence of the IO and the ENSO may also be responsible for the weakening ENSO–monsoon relationship during the recent decades. The concurrence of IOD-type signal during the boreal summer in T2 may also serve as a

predictability source for ISMR. Thus, despite the weakened ENSO–monsoon teleconnection, the Indian Ocean is serving as an important source of predictability in the recent 3 decades. This makes it essential for the coupled dynamical models to capture these changes in IO teleconnections to exploit this source of predictability.

3.3 Changes in zonal Walker circulation

Since the changes in SSTs over the tropical Indo-Pacific region largely manifest themselves as changes in Walker circulation, hence, we examine the seasonal mean anomalous Walker circulation averaged over 5°N–5°S based on GMY and BMY along with the climatological circulation for the two epochs (Fig. 7). It is interesting to note that there has been a large-scale shift in the atmospheric heat sources. The ascending branch of the Walker circulation which is used to extend well beyond the dateline up to 150°W (Fig. 7g) is now restricted only up to the dateline (Fig. 7h). Thus, the ascending branch is now restricted to a smaller range of longitudes, starting from about 60°E extending up to the dateline and the ascending motions have now become much stronger in the climatological mean sense as compared to the earlier period. The GMY composite in T2 (Fig. 7c) and the GMY composite difference (T2–T1,
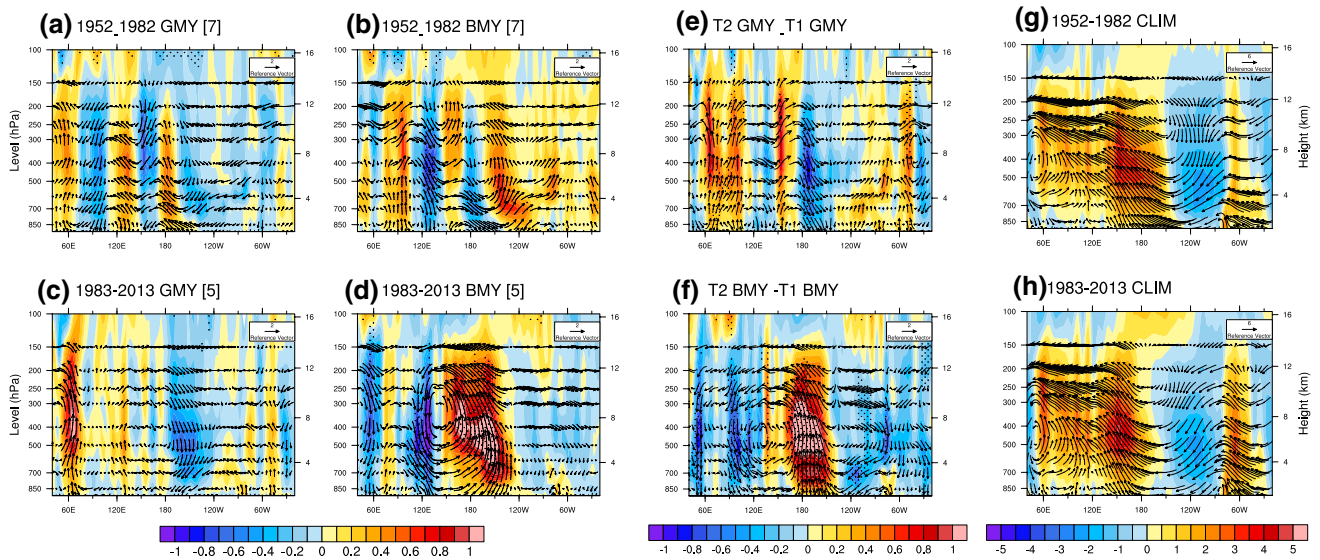
Fig. 7 Composite zonal–vertical profile (Walker Cell) of anomalous seasonal mean state (JJAS) averaged over 5°S–5°N (vectors) and the diabatic heating (K day^{-1}; shaded) during **a** GMY: 1952–1982, **b** GMY: 1983–2013, **c** BMY: 1952–1982, **d** BMY: 1983–2013, **e** difference between GMY for the two time periods (T2–T1), and **f** difference between BMY for the two time periods (T2–T1). Pressure velocity has been scaled by a factor of − 200 to elucidate the vertical motion; Q1 anomalies significant at 80% confidence level are stippled. **g**, **h** Climatologies for the respective periods

Fig. 7e) shows enhanced updraft over the equatorial IO, particularly stronger around 60°E, which is consistent with the findings of Roxy et al. (2014) that the western tropical IO has been warming rapidly compared to other regions. The results suggest enhanced convective activity over the said region. The BMY composite (Fig. 7d, f) suggests a vigorous single-celled Walker circulation anomaly largely associated with the central Pacific El-Niño (Ashok et al. 2007; Kumar et al. 2006).

3.4 Changes in meridional Hadley circulation

In addition to modulating the zonal Walker circulation, the SSTs in the IO also impact the regional Hadley circulation. Thus, we examine the seasonal mean anomalous Hadley circulation averaged over 60°E–95°E (Fig. 8) based on GMY and BMY. In T1, GMY (BMY) are associated with an anomalous Hadley circulation with clear ascending (descending) motion over the north (10°N–30°N) and south (10°S–30°S) with descending (ascending) motion over the equatorial Indian Ocean (10°S–10°N). The associated Q1 shows a positive anomaly over the landmass extending over the entire troposphere. This deep ascending motion over the landmass is a characteristic signature of the ISM and brings rainfall to the landmass. However, in T2, the anomalous Hadley cells during GMY or BMY are distinctly different from the two cell symmetric structure seen during T1. In GMYs, during T2, there are two competing ascending branches, one that is associated with the heating of the Indian landmass and

the other which is present between 10°S and 10°N. This is mainly caused by the weakening of the climatological mean background state, wherein the positive Q1 anomaly between 10°N and 20°N has considerably weakened and that between 10°S and 10°N has relatively strengthened. The anomalous Hadley circulation during BMYs is roughly reversed as compared to that during GMYs except that a weak ascending motion still persists close to the equator. It appears that the IO warming is playing a crucial role in producing stronger and persistent ascending motion around the equatorial IO and affecting the monsoon variability.

3.5 Moisture transport

Moisture availability is an important factor which determines the quantum of rainfall over land regions. A normal monsoon year is associated with strong moisture divergence from the Mascarene High with convergence over the Indian landmass and the head Bay of Bengal. This moisture transport is largely governed by the strong heating of the Indian landmass during boreal summer. The warming of the tropical SSTs of the IO basin can hinder the passage of the moisture transport towards the Indian landmass. To investigate this aspect, we compute the divergent component of anomalous moisture transport following the methodology as discussed in the previous studies (Behera et al. 1999; Chen 1985; Rao et al. 2010; Sabeerali et al. 2014). The GMY and BMY difference composites for the two periods are shown in Fig. 9 along with the associated
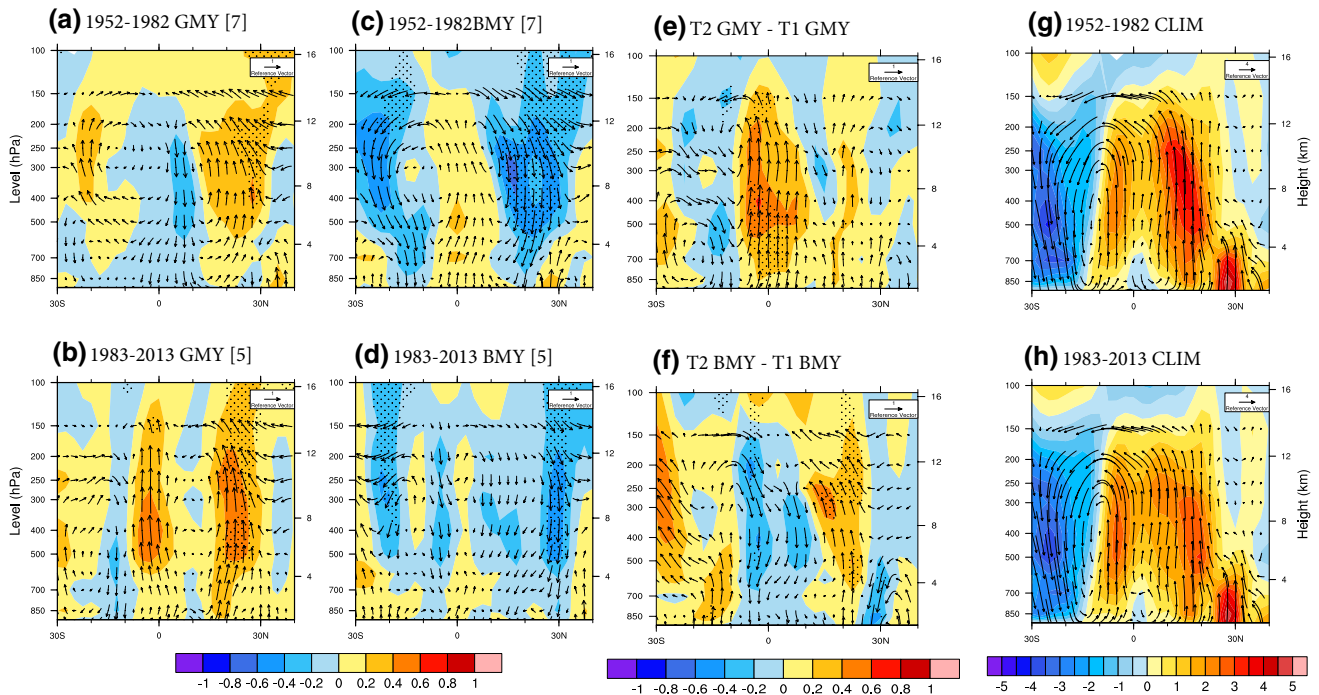
Fig. 8 Composite meridional–vertical profile (Hadley Cell) of anomalous seasonal mean state (JJAS) averaged over 65°E–95°E (vectors) and the diabatic heating (K day⁻¹; shaded) during **a** GMY: 1952–1982, **b** GMY: 1983–2013, **c** BMY: 1952–1982, **d** BMY: 1983–2013, **e** difference between GMY for the two time periods (T2–T1), and **f** difference between BMY for the two time periods (T2–T1). Pressure velocity has been scaled by a factor of − 200 to elucidate the vertical motion; Q1 anomalies significant at 80% confidence level are stippled. **g**, **h** Climatologies for the respective periods
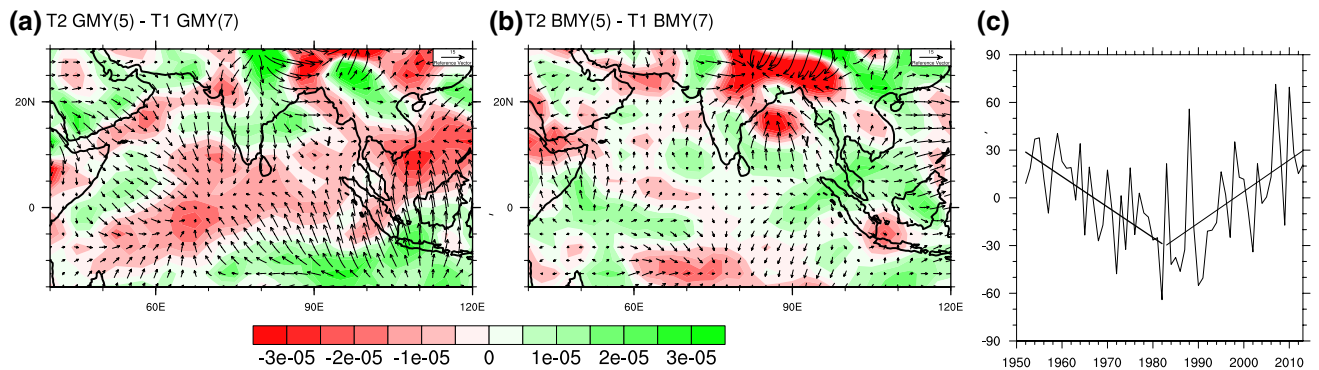

Fig. 9 Difference in boreal summer (JJAS) divergent component of moisture transport (10^6, kg s⁻¹ m⁻¹) and the related moisture transport vectors for GMY and BMY for **a** 1952–1982 and **b** 1983–2013. The number of GMY and BMY is indicated in brackets. **c** Divergent component of moisture transport averaged over 0°N–20°N, 50°E–75°E. The trend lines shown are significant at 90% confidence level

moisture transport vectors. Also shown is the average divergent component of moisture transport over the Arabian Sea (0°N–20°N, 50°E–75°E). The warming of SSTs in the western tropical IO causes the centre of moisture convergence to shift from central India to over the equatorial IO during GMY in T2 (Fig. 9a). During BMY in T2, there appears to be no significant change over Arabian Sea; however, there is increased moisture flux over the Bay of

Bengal (Fig. 9b). The clear increasing trend in the moisture availability over Arabian Sea in the recent decades is evident in Fig. 9c. This increasing trend coincides with the warming trend that has been seen in the western tropical Indian Ocean in the recent decades. This SST warming has caused displacement in the centres of moisture transport over the Indian monsoon region. The associated anomalous moisture transport vectors seen in Fig. 9a converge

over the Arabian Sea rather than the central Indian land-mass reducing the quantum of rainfall over India.

4 Conclusions and Discussion

The ISM has undergone a significant change in the nature of its interannual variability in the sense that there is an increased tendency of the occurrence of large-scale deficient monsoons compared to large-scale excess monsoons in the recent 3 decades compared to the prior 3 decades, which can have serious implications for the food and water resources of the country. We argue that the shift in the mean background climate in the late 1970s has strong implications for this change. We find that the 'internal' IAV of the monsoon system has reduced in the recent decades, the 'external' forced IAV remaining similar. Thus, a reduction in the contribution of high-frequency weather and sub-seasonal oscillations to the overall IAV of the seasonal mean has resulted in an increased predictability of the ISM despite the weakening of the ENSO–monsoon teleconnection. This reduction in the ENSO–monsoon relationship is also complemented by the simultaneous positive correlations of ISMR with the IOD during the monsoon season which used to be weak and negative during the earlier epoch. The unparalleled warming of the equatorial IO might be partly responsible for the increased IOD–monsoon teleconnection.

Studies have reported that dynamical models exhibit low skill in predicting the ISMR (Wang et al. 2004, 2015; Preethi et al. 2010; Rajeevan et al. 2012, and many more). However, coupled models have now started to exhibit moderate prediction skill for ISMR (Srivastava et al. 2015; Ramu et al. 2016, 2017). Pradhan et al. (2016) have shown that the state-of-the-art models are unable to capture the shift in mean state after the climate shift in 1977 and they simulate unrealistic overtly strong air–sea coupling which might be responsible for reduced model skill in recent years despite an increase in predictability. In addition, improvements in the coupled dynamics of the IO are needed to increase the skill of coupled models in predicting the ISMR (George et al. 2015; Srivastava et al. 2017). Thus, it becomes imperative for the models to capture the shift in mean state and the associated teleconnections to augment the enhanced predictability of the monsoon system.

We have also documented changes in the climatological mean Walker circulation. The ascending branch has become narrower (restricted up to the dateline) and has invigorated, and the signatures of western tropical IO warming are evident during the GMY where there is increased updraft over the corresponding longitudes. Much more interesting is the fact that the single-celled Hadley circulation during GMY has now split up into two competing ascending branches largely owing to the significant changes in the atmospheric heat sources. The rapid warming of the western tropical IO is bound to affect the pathway of moisture towards the Indian landmass, thereby reducing the moisture availability during GMY.

The changes in the boundary conditions during the recent 3 decades compared to the earlier 3 decades such as the IO warming and shift towards central Pacific El-Niño occurrence are forcing the Indian monsoon to go to a more frequent drought state. Close similarity in the SST pattern in the Pacific in Figs. 5b and 6b indicates that CP El-Niños are controlling the monsoon variability more strongly during this period. In conjunction with the CP El-Niños, the Indian ocean warming is creating anomalous Walker circulation in such a way that the descending motion between 70°E and 100°E during GMY (Fig. 7a) in T1 is replaced by ascending motion over the region in T2 (Fig. 7c). Furthermore, the centre of moisture convergence during GMY in T2 is over the Arabian Sea, thereby reducing the moisture availability over the Indian landmass. The enhanced and persistent ascending motion in the equatorial IO and western IO is resulting in enhanced subsidence over the continent and an increased tendency for a deficient monsoon condition.

The future monsoon predictions using models must take into account the changes in the monsoon teleconnections and the significant role that the Indian Ocean teleconnections have to play in modifying the monsoon circulation. Realistic simulation of the changes in monsoon teleconnections will enable the models to exploit the increased predictability of the monsoon system in recent decades. In addition to this, models must realistically reproduce the shift in the mean background state to provide reliable forecasts of the global weather systems.

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