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REVIEW ARTICLE

A review on the Indian summer monsoon rainfall, variability and its association with ENSO and IOD

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Abstract

The Indian summer monsoon rainfall (ISMR) during June to September contributes most of the annual rainfall over India and plays an important role in Indian agriculture and thus the economy. It exhibits high spatio-temporal variabilities forced from both internal and external factors, which are important for better understanding and prediction of ISMR. Since the internal factors, mainly in the form of intraseasonal oscillations set a limit to the predictability, the major focus is given to the external forcing factors including the coupled air–sea interactions, sea surface temperature variations, snow cover, etc. This paper mainly aims to review the results of recent research analysis on ISMR variability and the major climate factors that determine the variability. Focus is given on the contributions from the coupled ocean–atmosphere processes in the Indian and Pacific Oceans to the ISMR variability [(primarily the El Niño Southern Oscillation (ENSO)] and Indian Ocean Dipole (IOD). Several studies were carried out in recent decades to explore the ISMR variabilities and their influences from tropical oceans. The studies, which focused the impact of ENSO and IOD on the ISMR variability have been considered in exploring their relationships and observed changes in recent decades. In the backdrop of varying relationship of ISMR with ENSO and IOD in the regional scale, it is important to study further the regional teleconnection of ISMR variabilities with oceanic factors, especially from the Indian and Pacific Ocean basin.

1 Introduction

The Asian monsoon system is considered as a large-scale coupled ocean–atmosphere phenomenon and it is associated with distinct seasonal precipitation and circulation patterns (Wang and Fan 1999; Meehl 1994; Hu et al. 2000; Wang 2006; Hernandez et al. 2015). The Indian summer monsoon rainfall (ISMR) or Southwest monsoon rainfall during June to September is a component of Asian monsoon system (Ghosh et al. 2009), which accounts for 70–90% of annual precipitation in India (Shukla and Haung 2016). The ISMR exhibits high temporal as well as spatial variations. The temporal variation of rainfall includes variabilities ranging from diurnal to multidecadal time scales. The spatial variability of summer monsoon rainfall in India is associated with variations in precipitation from one region to another. During this season, large-scale precipitation is observed along the west coast and northeast regions of India, while the precipitation values are minima over the northwest and southeast regions (Fig. 2). The amount of rainfall during the southwest monsoon varies spatially from 160 to 1800 mm year^{-1} from the northwest to the northeast and from the far north to the extreme south (Kishore et al. 2015). The information on spatial and temporal variations of rainfall is important to understand the hydrological balance on a global/regional scale (Rajeevan et al. 2006). The summer monsoon rainfall is also associated with the synoptic-scale convective systems generating over warm oceans that surround the Indian subcontinent, which propagates into the land mass (Gadgil 2003). The ocean–atmosphere coupling affects the global circulation patterns (Varikoden and Babu 2015) and hence the climate variability in the regional and large scale.

Therefore, it is highly relevant to understand the impact of different coupled ocean–atmosphere processes in the tropical oceans on the variability of ISMR. The El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Atlantic multidecadal oscillation (AMO), Atlantic zonal mode

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(AZM), Pacific decadal oscillation (PDO), etc., are widely recognized as the major climate drivers of ISMR as well as the rainfall of other tropical areas (Ashok et al. 2001; Yun et al. 2018; Nair et al. 2018; Sabeerali et al 2019). Many researchers have studied the link of these climate drivers with ISMR and observed that the most significant drivers of ISMR are ENSO and IOD (Krishnaswami et al. 2015). Previous studies have focused on the relationships of ISMR with ENSO and IOD and provided clear evidences regarding how the sea surface temperature (SST) conditions and circulation features over the Indo-Pacific domain affect the variability of ISMR. Therefore, in the present review, we have mainly focused on the contributions from ENSO and IOD to the monsoon variability. In this review, we focused the studies carried out over the last few years on ISMR variability, the different forcing mechanisms, primarily ENSO and IOD, their causes and applications.

2 Spatio-temporal variability of ISMR

Southwest monsoon rainfall in India is contributed by the propagation of synoptic-scale convective systems from the surrounded warm oceans. The low-pressure systems from the Bay of Bengal propagating along the monsoon core zone substantially contributes to the total rainfall (Gadgil 2003). It exhibits variability in all time scales ranging from diurnal to multidecadal (Guhathakurtha et al. 2014) as well as in regional scale. The mechanisms behind these variabilities include internal dynamics, influence of land and oceans, and teleconnections to climate variability in other regions (Krishnamurhy and Kinter 2002). The predictability of the mean seasonal rainfall depends mainly on the interannual variability of the ISMR (Goswami et al. 2006a; Pillai and Chowdary 2016), which is related to the fluctuations associated with the regional Hadley circulation**.** The interannual variability of ISMR is mainly contributed by an externally forced component and an internal intraseasonal component (Krishnamurthy and Shukla 2000, 2007). Several studies have been conducted to explore the intraseasonal oscillations and its relation with monsoon rainfall (Goswami and Ajayamohan 2001a; Sengupta et al. 2001; Goswami and Xavier 2005; Suhas et al. 2012). The intraseasonal variability is associated with active (periods of high rainfall) and break (periods of deficient rainfall) spells during the season (Goswami et al. 2006a; Sinha et al. 2011; Taraphdar et al. 2010). The intraseasonal variations are mainly composed of oscillations on 10–20 days (Chatterjee and Goswami 2004; Goswami 2005) and 30–60 days time scales (Annamalai and Slingo 2001; Suhas and Goswami 2008). The 10–20-day oscillation is associated with the westward propagating modes entering the Indian region from the Bay of Bengal and the 30–60-day oscillation is associated with the northward propagation of cloudiness and rainfall to the Indian region from the equatorial Indian Ocean (Achuthavarier and Krishnamurthy 2011). The intraseasonal variability plays an important role in agriculture, economy and water resource management, so the prediction of active and break spells, their duration and intensities are highly relevant (Maharana and Dimri 2015). However, the interannual variability mainly depends upon the number of active and break days (Rajeevan et al. 2010). It is also shown that the monsoon rainfall is significantly negatively (positively) correlated with the number of break (active) days (Gadgil and Joseph 2003).

The ratio between the internal and external variabilities of ISMR was observed to be close to one over the Indian monsoon region which indicates that both the variabilities are equally contributing to the interannual ISMR variations (Goswami and Ajayamohan 2001b). They reported that the internal variability arises from the interaction between the intraseasonal oscillations and the annual cycle. Moreover, the intraseasonal and interannual variabilities are governed by a common mode of spatial variability. Hence, they reported that the poor predictability of ISMR is due to interannual variability by the internal low-frequency variations. A clear understanding of mechanisms responsible for the internal interannual variability is useful for improving seasonal mean prediction (Goswami and Xavier 2005), which remains as a challenging problem since the mechanisms behind the low-frequency internal variations have not been fully understood.

Considering the case of regional variations in summer monsoon rainfall, it is well known that the rainfall in India exhibits high spatial variability, i.e., some regions are covered with surplus rainfall and some other regions are with deficit rainfall, which leads to flood and drought conditions, respectively. During the summer monsoon season, the west coast and northeast regions of India receive maximum amount of rainfall, while the southeast and northwest regions receive minimum rainfall (Rajeevan et al. 2006; Kishore et al. 2015). Figure 1 shows the meteorological subdivisions of India as classified by the Indian Meteorological Department (IMD) and Fig. 2 is the rainfall climatology and its standard deviation during the summer monsoon period 1901–2015.

The regional variations of ISMR are closely related to the variations in the trends of means and extremes. So the analysis of the spatial variations of means and extremes of ISMR and its causes are of great importance and were carried out in several studies. (Goswami et al. 2006b; Rajeevan et al. 2008; Guhathakurta et al. 2014; Cash et al. 2015; Varikoden et al. 2013; Oza and Kishtawal 2014; Sinha et al. 2014; Kothawale and Rajeevan 2017; Mohapatra et al. 2018; Varikoden and Revadekar 2019; Fukushima et al. 2019). It is important to note that the number of studies to understand

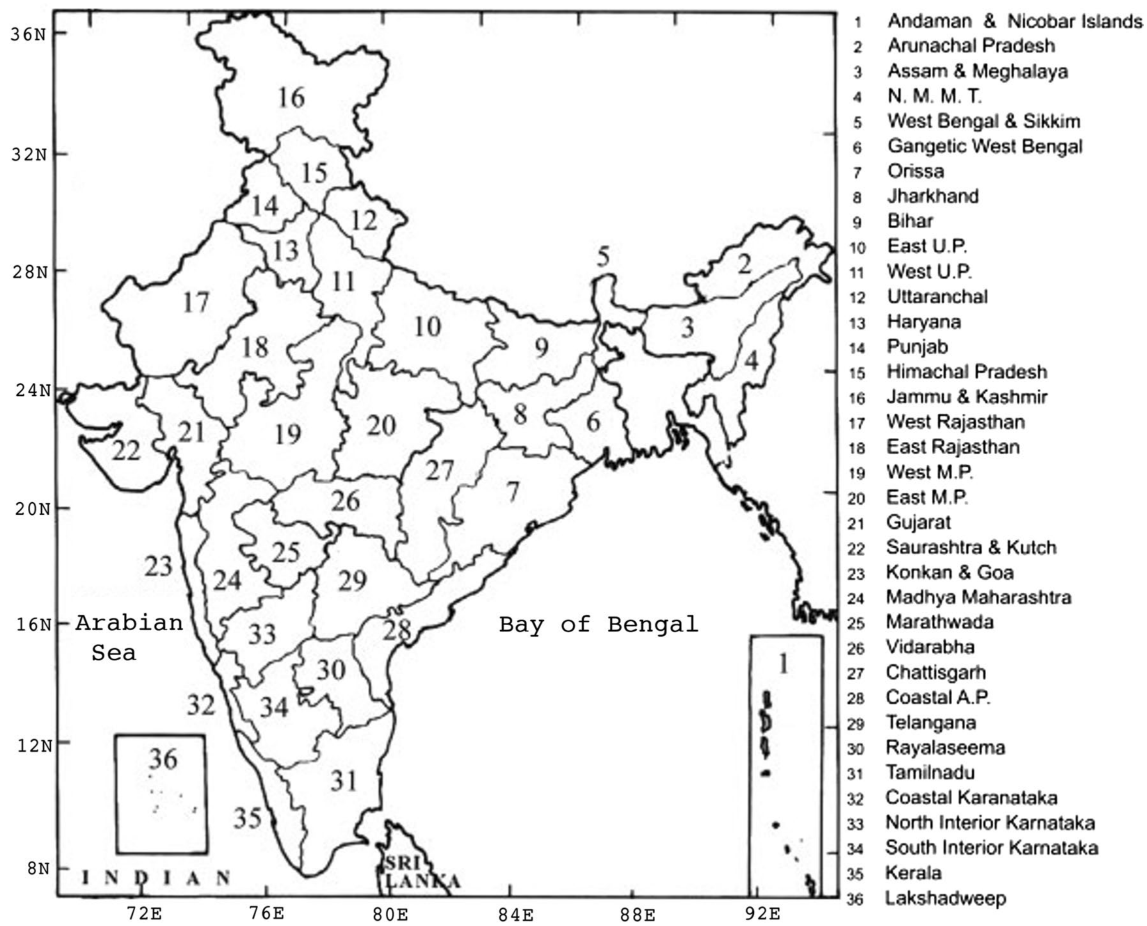

Fig. 1 36 meteorological subdivisions of India as classified by the Indian Meteorological Department (IMD)

the regional distribution of ISMR and its mechanisms are relatively fewer than the studies on the temporal variations of ISMR especially in interannual and intraseasonal time scales.

While studying the regional variations of ISMR, it is important to examine the characteristics of rainfall in different homogenous zones in India separately rather than considering the country as a whole since it does not reveal the regional characteristics (Dash et al. 2009; Nair et al. 2018). The variations in rainfall over four different regions in India namely Western Ghats, the Ganges basin, the Bay of Bengal and Bangladesh–northeastern India was studied by Cash et al. (2015). They reported that the rainfall varies independently in these four regions since the correlations in rainfall between the regions are not significant. A similar analysis was carried out by Kishore et al. (2015), but the regions considered were West Coast, East Coast, interior peninsula, Northeast, North Central, Northwest and the Western Himalayas. They also reported significant incoherent variabilities from region to region. After constructing a newly homogeneous rainfall data set of 36 meteorological subdivisions of India (Fig. 1) for the period 1901–2003, Guhathakurtha and Rajeevan (2008) showed that ISMR did not show any significant trend but there are large variations in regional scale. A significant decreasing trend in rainfall patterns was observed over three subdivisions (Jharkhand, Chhattisgarh and Kerala) and increasing trends over eight subdivisions (Gangetic West Bengal, western Uttar Pradesh, Jammu and Kashmir, Konkan and Goa, Madhya Maharashtra, Rayalaseema, coastal Andhra Pradesh, and north Interior Karnataka). They further reported that there is a major shift in the rainfall pattern in India spatially and temporally during the recent years. A similar study by Guhathakurtha et al. (2014) found multidecadal variability in rainfall over four homogenous regions (Northwest India, Central India, Northeast India and Penisular India) and found that their phases are different. Konwar et al. (2012) observed asymmetry in trends of monsoon rainfall over western (eastern) parts of India and found that the trends of low and moderate rainfall events are increasing (decreasing) in recent decades. They suggested that the increasing trend of low and medium rainfall events in western part is due to the enhanced vertically integrated

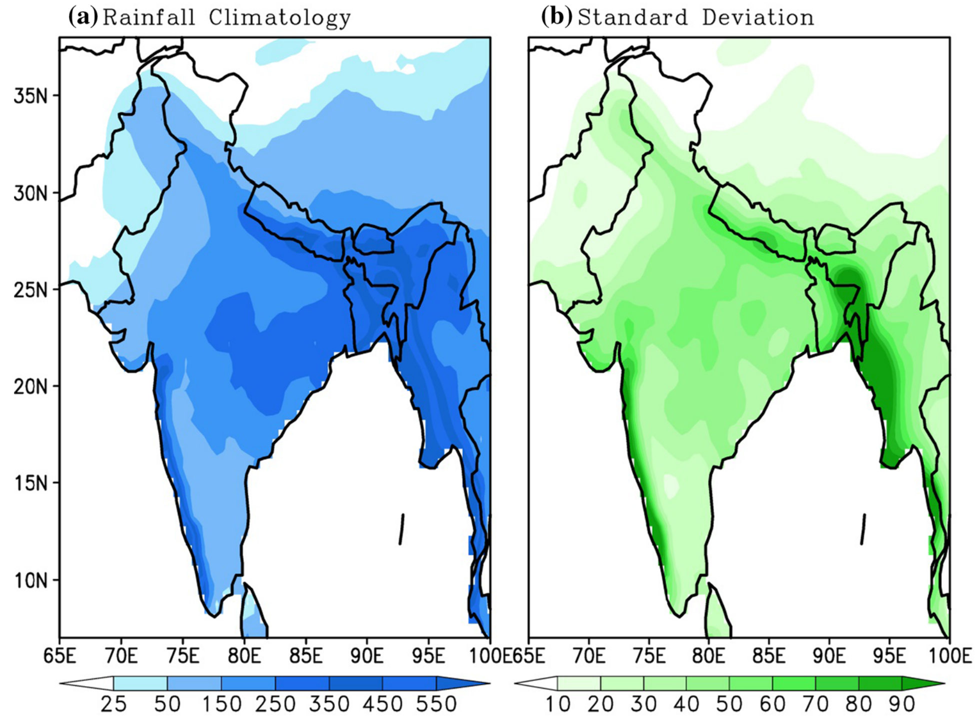

Fig. 2 **a** Rainfall climatology (mm month^{-1}) and **b** standard deviation of rainfall during the period 1901–2015 (115 years)

moisture transport (VIMT) over the Arabian Sea and the decreasing trend in the eastern parts is due to the decreased VIMT over the Bay of Bengal.

The trends in extreme rain events over Central India for the period 1951–2000 were analyzed by Goswami et al. (2006b) and found that the temporal variation of daily rainfall over Central India is increasing. Further, they stated that the seasonal rainfall did not show any significant trend but there is an increase in frequency and magnitude of extreme rainfall events in Central India. However, the study was confined only to the Central India by considering it as a spatially homogeneous region and they excluded large variabilities of rainfall from other regions. The study of Ghosh et al. (2009) observed that the trends are highly variable over the spatial domain based on finer resolution data set. Hence, they argued that the trend analysis at a finer scale is more useful and reliable, which was in contrast to the studies of Goswami et al. (2006b), who carried out the analysis based on relatively larger spatial resolution data set. A threefold rise of extreme rainfall events in Central India was found (Roxy et al. 2017) and this increase is due to the increase in westerlies from the Arabian Sea which provides moisture supply to the central Indian region. Using a high-resolution gridded data for the period 1901–2004, the variability and long-term trends of extreme rain events over central India were analyzed by Rajeevan et al. (2008). They reported that the frequency of extreme rain events showed interannual and interdecadal variations during their study period, which is modulated by the sea surface temperature (SST) variations over the tropical Indian Ocean. Varikoden et al. (2019) found an increasing (decreasing) trend in summer monsoon rainfall in the northern (southern) Western Ghats. They attributed that this contrasting trend is basically due to the shift of low level westerlies over the region. A study by Ghosh et al. (2016) showed that the spatial variability of mean and extreme of the ISMR exhibits opposite trends. The trend in the spatial variability of mean summer monsoon rainfall is decreasing but that of extremes showed an increase. Ghosh et al. (2011) found the spatial coverage of rainfall extremes is increasing trend, but with lack of spatial uniformity, which indicates the regional dominance in rainfall characteristics. The northeast regions of India showed an increase in high-intensity rain events and a decrease in low-intensity rain events based on TRMM (Tropical Rainfall Measuring Mission) rainfall data set (Varikoden and Revadekar 2019). The duration and spatial coverage of ISMR are decreasing even though there is an expansion of monsoon season over a wider area which has larger socioeconomic impacts (Ramesh and Goswami 2007). Ramesh and Goswami (2007) further reported a decreasing trend in summer monsoon rainfall over India and an increasing trend in pre-monsoon and post-monsoon rainfall. The study of Das et al. (2014) on the spatial patterns in the trends of summer monsoon rainfall and rainy days found that the southern region of the Indian peninsula covering the Deccan plateau and east coast shows positive trends both in rainfall and rainy days. A negative trend is observed in both the parameters over west coast (Kerala, coastal Karnataka), the eastern part

(Jharkhand, Arunachal Pradesh) and western desert region (east and west Rajasthan).

The above furnished analyses outlined some of the observed characteristics and trends of spatio-temporal variability of ISMR. While studying these variabilities, it is important to analyze the major external factors that determine the variabilities. The coupled ocean–atmosphere interactions and SST variations of the Indian and Pacific Oceans influence the Indian monsoon variability (Krishnamurthy and Kinter 2002). So understanding the links between the convection over these oceans and the Indian monsoon variability remains as a very challenging problem (Gadgil 2003).

3 Role of Indo-Pacific Ocean on ISMR variability

3.1 Ocean–atmosphere interactions

Tropical oceans play an important role in maintaining the world climate variability and different coupled ocean–atmosphere phenomena generated in tropical oceans affect the global circulation changes and thus the regional climate variability (Yamagata et al. 2004). The impact of tropical Pacific Ocean SST conditions on the ISMR variability can be studied through the relationship between ENSO and ISMR, since the ENSO is known as the strongest driver of the ISMR variability (Yun et al. 2018). The ENSO is considered as the most important coupled ocean–atmosphere phenomenon in the tropical Pacific and has a major impact on the interannual variability of ISM rainfall. It does not mean that the ENSO is the only driver of ISMR variability but the existence of ENSO as a major coupled ocean–atmosphere phenomenon in the tropical Pacific and its strong impact on ISMR variability are widely accepted.

Even though ENSO originates in the tropical Pacific Ocean, it affects global climate and weather events (Guilyardi et al. 2009) and may be influenced by the ocean–atmosphere processes in other tropical oceans and extratropics (Liu and Alexander 2007). Several studies have been undertaken in the last few years to understand ENSO and its impacts on ISMR variability (Slingo and Annamalai 2000; Lau and Nath 2000; Annamalai and Liu 2005; Guilyardi 2006; Xavier et al. 2007; Mishra et al. 2012; Ashok et al. 2019). El Niño (positive phase of ENSO) events are accompanied by a reduced Indian summer monsoon rainfall due to anomalous subsidence associated with a shift in zonal Walker circulation (Ummerhofer et al. 2011) and on the other hand, La Niña (negative phase of ENSO) events are associated with excess rainfall conditions in the Indian region as evidenced by Fig. 3. Since the interannual variability of ISMR depends on the contributions from both the external forcings and the internal intraseasonal oscillations, whether ENSO (which is an external forcing) could modulate the intraseasonal oscillations of ISMR is a relevant question. In a study carried out by Joseph et al. (2011), it is reported that during an El Niño year is dominated with the typical break phase, whereas the La Niña year is with the typical active phase. The study further reported that the El Niño–break relationship is independent of ENSO–monsoon relationship and La Niña–active relationship is interlinked with ENSO–monsoon relationship. Several other studies (e.g., Teng and Wang 2003; Yoo

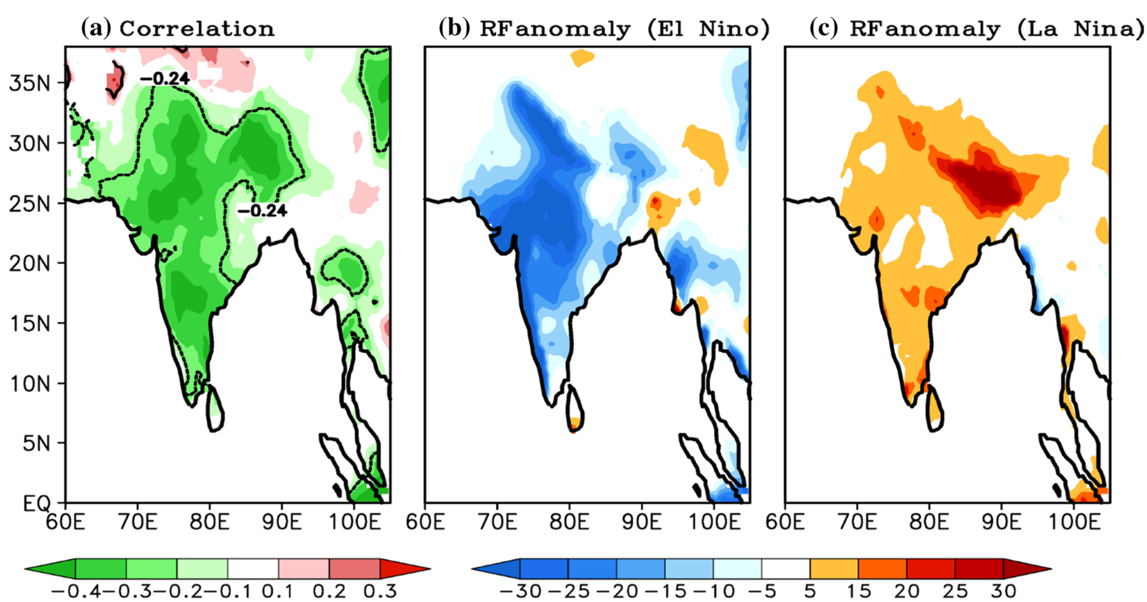

Fig. 3 **a** Spatial correlation between ISM rainfall and Niño 3.4 index, **b** composite of rainfall anomaly associated El Niño years, **c** same as that of **b** but for La Niña years. The contour in the **a** shows the confidence at 5% significant level

et al. 2010) were also performed to explore the different aspects of relationship between ENSO and internal intraseasonal oscillations and to establish a link between the internal and external forcings of ISMR.

It is well observed that the changes in the Walker and Hadley circulations are linked to ENSO (Power and Smith 2007; Stachnik and Schumacher 2011). Figure 4 shows the variations in equatorial Walker circulation over the Indo-Pacific sector and regional Hadley circulations over Indian domain during the El Niño and La Niña events for the period 1948–2016. The Walker and Hadley circulations were plotted using the zonal, meridional and vertical wind components at different vertical levels. The ISMR is controlled by tropical Pacific SST through equatorial zonal circulation called the Walker circulation (Shukla and Paolino 1983) and regional meridional circulation over south Asian domain called Hadley circulation. The Walker circulation is an east–west circulation in the vertical plane of the troposphere with ascending (descending) regions of air over the western (eastern) Pacific Ocean. On the other hand, Hadley circulation is manifested as the meridional overturning circulations in which heated air rises at the equatorial region and moves poleward and when it cools, sinks and moves towards the equator.

The ENSO affects Indian monsoon through an interaction between the equatorial Walker circulation and the regional Hadley circulation, which are considered as the world's two prominent and important atmospheric zonal and meridional circulations, respectively. Webster et al. (1998) reported that anomalies produced by ENSO causes large-scale descent over the Indian monsoon region to modulate ISMR. Multiple studies (e.g., Ju and Slingo 1995; Soman and Slingo 1997; Dai and Wigley 2000; Ashok et al. 2004b, a) through observation and models demonstrated that the tropical Pacific SST anomalies associated with ENSO relate the ISM through modulation of zonal circulation cells as indicated in Fig. 4a, c. In most of the studies, ENSO–monsoon relationship has been studied by connecting the regional anomalous monsoon rainfall to the SST anomalies over the tropical Pacific (Wang et al. 2003), since the SST anomalies act as intermediate to ocean–atmosphere coupling (Rao et al. 2002). In general, large-scale circulation changes due to spatial shift in the zonal direction of the ascending/descending limbs of Walker circulation influence the monsoon circulation over Indian domain. Moreover, coupled air–sea feedback in the regional scale in the Indian Ocean is suggested to alter the meridional overturning circulation during the ENSO phases, which impacts on the ISMR (Wu and Kirtman 2004). The modulation during ENSO period as manifested by circulation anomalies over the south Asian domain is given in Fig. 4b, d.

The observed inverse relationship between ENSO and monsoon was found to be weakening after 1980s (Kumar et al. 1999). They proposed two possible reasons for this weakened ENSO–monsoon relationship. One is the southeastward shift in the Walker circulation anomalies during ENSO events which produce normal summer monsoon rainfall in Indian region even during a strong ENSO event. The

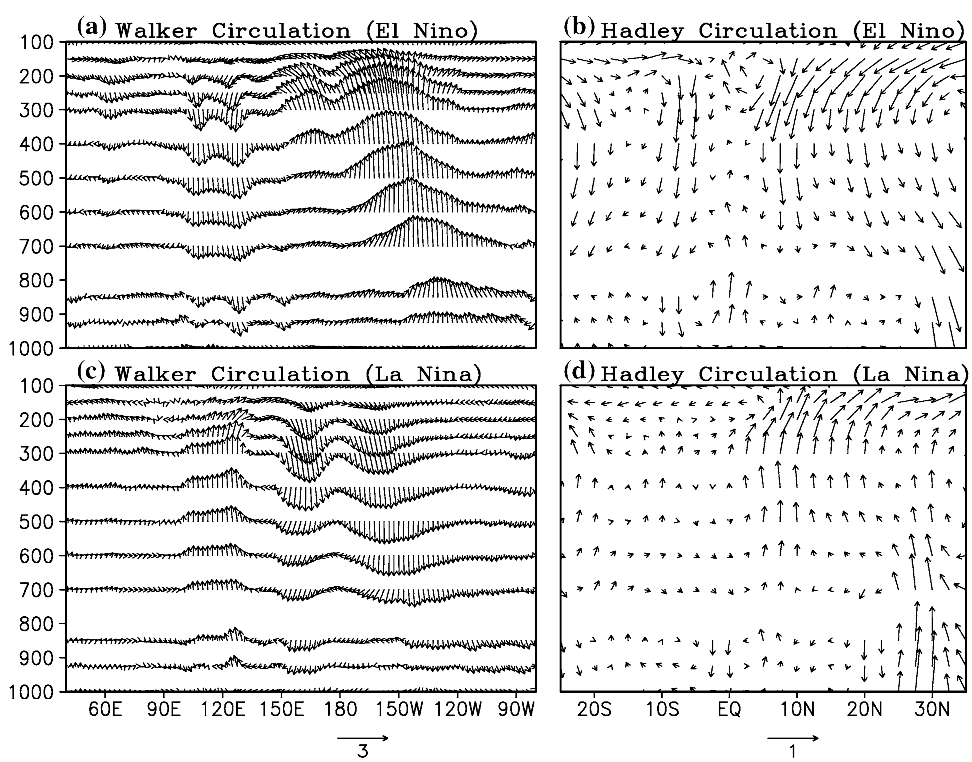

Fig. 4 **a** Walker circulation anomalies over the Indo-Pacific sector during El Niño and **c** that for La Niña. **b**, **d** are the Hadley circulation anomalies for El Niño and La Niña years, respectively. The base period is considered from 1948 and 2016

second reason is the increased surface temperatures over Eurasia during the winter and spring which enhances the land–sea gradients favorable to a strong monsoon. A similar conclusion of weakening ENSO–monsoon relationship was made by Ashrit et al. (2001); however, they attributed the enhanced concentration of greenhouse gases. Another possible reason was found as the enhanced impact of Indian Ocean dipole (Saji et al. 1999; Webster et al. 1999; Ashok et al. 2001, 2004a). A significant change to the observed El Niño–ISMR relationship was clearly observed during the El Niño events of 1997 and 2002 (Gadgil et al. 2004). They reported that during the strongest El Niño event of the century in 1997, the ISMR was higher than normal and during 2002, a deficit in rainfall was observed in the peak monsoon month of July. So, even though all the El Niño events have not always produced severe droughts, severe droughts in the Indian region are predominantly accompanied by El Niño events (Kumar et al. 2006; Varikoden et al 2015). The study of Kumar et al. (2006) showed that India is more prone to drought when the El Niño events shifted westward in the tropical Pacific. Also, they found that the El Niño events with the warmest SST in the central equatorial Pacific are associated with Indian droughts than the events with the warmest SST in the eastern equatorial Pacific. In a similar type of analysis carried out by Ratnam et al. (2010), the role of Pacific SSTs on the ISM failure during 2009 was explored. They reported that the unusual warming of the central Pacific modified the Walker circulation over tropical and subtropical Pacific lead to deficit rainfall in Indian region. Roy et al. (2019) studied the ENSO–ISMR relationship using CMIP5 models over central India and reported a negative correlation in all the models. The negative correlation was found to hold up for both the canonical and Modoki ENSO events. All these analyses indicate the inevitable role of Pacific Ocean SST on the modulation of ISMR variability, since ENSO plays an important modulator of ISMR variability even though their relationship is in the weakening stage during the recent decades. Figure 5 represents a schematic diagram indicating the ENSO–monsoon relationship by summarizing the major conclusions of this section.

3.2 The Indian Ocean dynamics on ISMR variability

In contrast to the Pacific Ocean, the Indian Ocean is bounded by the Asian land mass in north so that the heating of land during the boreal summer monsoon season produces a strong meridional pressure gradient which drives the summer monsoon (Han et al. 2014). The deep convection over the equatorial Indian Ocean is critical for monsoon, since the cloud bands generated over the equatorial Indian Ocean propagate northward and cause precipitation in India during the summer monsoon (Gadgil et al. 2003). However, the role of the tropical Indian Ocean on the rainfall variability is still unclear (Chowdary et al. 2015), even though it is an important modulator of tropical climate variability (Ashok et al. 2003). Apart from Pacific Ocean SSTs, SST in the Indian Ocean also plays a major role in ISMR variability (Ummerhofer et al. 2011). The moisture availability in the Indian region is related to the ocean–atmosphere interactions over the Indian Ocean (Ajayamohan and Rao 2008). So analyzing the convective systems and the ocean–atmosphere variability in the Indian Ocean are also important as much as in the Pacific to determine the variability of ISMR.

The ENSO phenomenon was considered as the most important driver of ISMR variability and the major focus of scientific community was to explore the mechanisms behind ENSO until a dipole mode was discovered in the Indian Ocean called Indian Ocean Dipole (IOD) (Saji et al. 1999; Webster et al. 1999). After the discovery of IOD, it was recognized that the coupled ocean–atmosphere processes in the

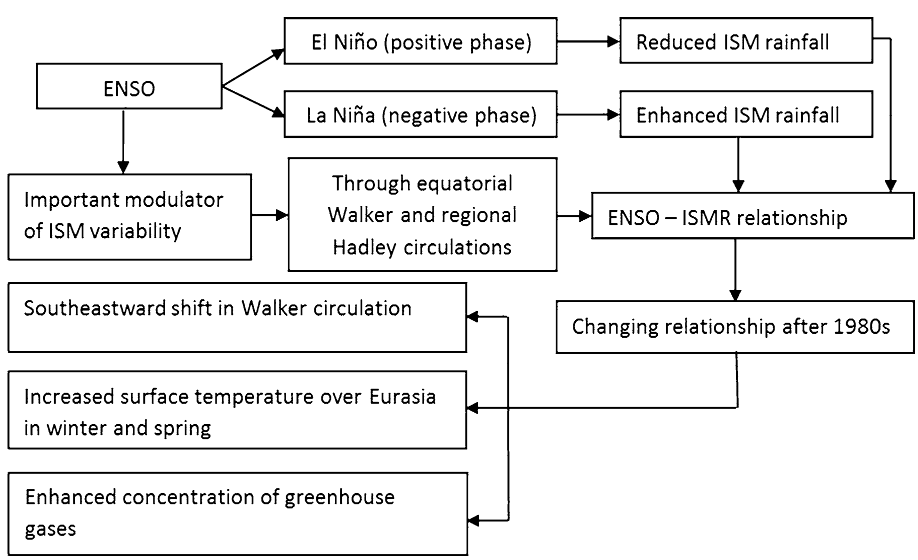

Fig. 5 Schematic diagram representing the ENSO–monsoon relationship

Indian Ocean can also make significant climate fluctuations (Han et al. 2014). Saji et al. (1999) reported that the intensity of IOD is associated with the east–west SST gradients and zonal wind anomalies in the equatorial Indian Ocean. They showed that this mode is seasonally phase locked, inherent over the Indian Ocean and independent of ENSO. The positive IOD event in the Indian Ocean is characterized by warm (cold) SST anomalies in the west (southeast) equatorial Indian Ocean and the conditions are reversed for a negative IOD event (Saji et al. 1999; Vinayachandran et al. 2002; Rao et al. 2006). After the discovery of IOD, several studies were conducted to explore its characteristics, relationship with ISMR, ENSO, and with the climate of other tropical regions (Ashok et al 2001; Yamagata et al. 2004; Behera et al. 2005; Ashok et al. 2007; Abram et al. 2008; Luo et al. 2010). Figure 6 shows the spatial correlation between ISMR and IOD index, the rainfall anomaly associated with positive IOD years and rainfall anomaly associated with negative IOD years during the period 1948–2016. The figure clearly indicates the significant relationship between the IOD and rainfall during the summer monsoon season.

Ashok et al (2001) pointed out that surplus rainfall over monsoon core zone is associated with positive IOD and a negative IOD events leads to weakening the rainfall. It can also modulate the number of extreme rain events in India by transporting moisture from the south eastern equatorial Indian Ocean to the Bay of Bengal (Ajayamohan and Rao 2008). The study of Ajayamohan and Rao (2008) suggested that the ongoing warming of the Indian Ocean in recent decades enhances the occurrence of extreme events in central India. The warming trend of Indian Ocean SSTs in recent decades was also reported by Ihara et al. (2008). Thus the IOD have an important role in seasonal and interannual climate variations (Yamagata et al. 2004). The IOD also shown its impacts over several remote regions apart from the Indian Ocean such as Europe, North and South America, South Africa, Australia, etc. (Saji and Yamagata 2003a). A positive IOD causes surplus rainfall in India, Africa, Bangladesh and Vietnam; however, it causes deficit rainfall in Indonesia (Yamagata et al. 2004).

3.3 Impact of Indian Ocean on ENSO and ISMR

It is important to check the linkage of ocean–atmosphere phenomenon between the Indian and Pacific Ocean basins, since the Indian and Pacific Ocean variabilities are interlinked (Ummerhofen et al. 2011). The impact of the monsoon on the ENSO is absent without the air–sea coupling and difficult to capture the observed ENSO–monsoon relationship. Since the ocean–atmosphere phenomenon in other tropical oceans influence the evolution of ENSO, numerous studies have been carried out to study the impact of Indian Ocean on ENSO features. The ENSO–monsoon relationship can be explained using the atmospheric conditions over the Indian Ocean (Ihara et al. 2007). Wu and Kirtman (2004) found that the existing out-of-phase relationship of ENSO–monsoon is reversed to in-phase relationship when the Indian Ocean is de-coupled from the atmosphere. Hence they claimed that the air–sea interaction in the Indian Ocean is an integral component in the simulation of ENSO–monsoon relationship. The Indian Ocean variability is related to ENSO variability and the lagged correlation between

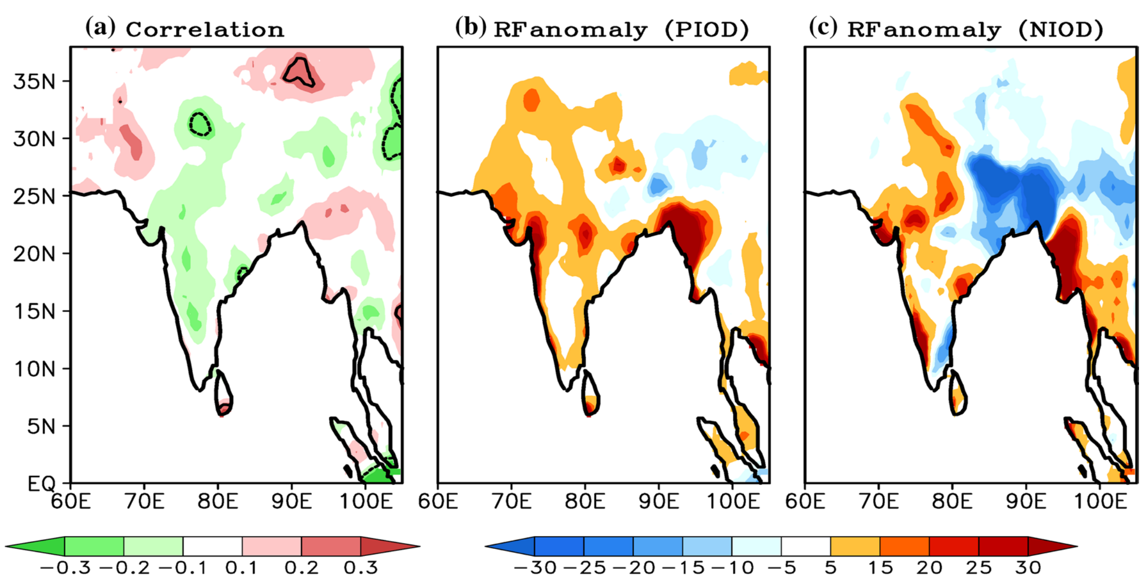

Fig. 6 **a** Spatial correlation between ISM rainfall and IOD index. **b** Rainfall anomaly composite during positive pure IOD years and **c** same as that of **b** but for the negative pure IOD years during the period 1948–2016

monsoon and ENSO may be mediated by air–sea interactions in the Indian Ocean (Krishnamurthy and Kirtman 2003) and the strength of the relationship varies on interdecadal time scale (Krishnamurthy and Goswami 2000). In a study carried out by Goswami and Jayavelu (2001), the impact of ISMR on ENSO was analyzed. It was found that ISMR is unlikely to influence the ENSO since it could not induce surface wind anomalies in the active regions of the central and eastern equatorial Pacific. But in a study by Wu and Kirtman (2003) reported that monsoon can make significant modulations on an ongoing warm event through surface zonal wind anomalies in the equatorial western central Pacific.

Influence of the Indian Ocean on the ENSO events in the Pacific can be mainly associated with the relationship between IOD and ENSO events. Even though IOD was discovered as an independent mode in the Indian Ocean apart from the ENSO in the Pacific (Saji et al. 1999), the interconnection between the two processes and their individual and combined effect on ISM were widely studied. Figure 7 represents a schematic diagram indicating the observed IOD–ENSO and IOD–ISM relationships.

Ashok et al. (2001) found that IOD and ENSO have complimentary impacts on ISM rainfall. They found that during a positive IOD event, an anomalous convergent flow is observed over the Bay of Bengal and Indian region, which provides excess rainfall over the Indian region. Also, the ENSO-induced subsidence over the Indian region during a pure ENSO (ENSO events that occur without IOD events) year is replaced by the IOD-induced convergence and causes normal summer monsoon rainfall even during a strong El Niño year. Similarly, the negative IOD events can reduce

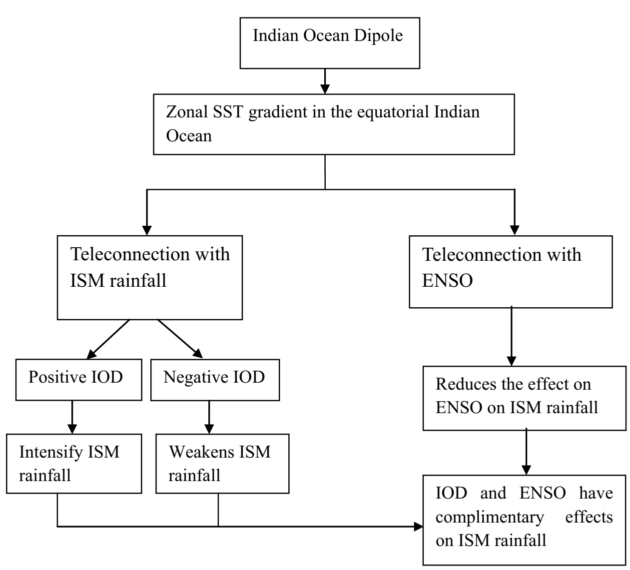

Fig. 7 Schematic diagram representing the IOD–ISM and IOD–ENSO relationships

the impact of La Niña on ISM rainfall and provide deficit monsoon rainfall. They reported that the co-occurrence of IOD with ENSO reduces the impacts of ENSO on ISMR. In a similar study carried out by Ashok et al. (2003), the existence of IOD as a physical entity was examined. They showed that IOD is an independent mode unique to the Indian Ocean and tropical Indian Ocean can sustain strong IOD events without the support from external forcings. IOD was also found to have an influence on the atmospheric pressure variations of the Indo-Pacific sector (Behera and Yamagata 2003). A significant correlation between IOD and Darwin index was obtained in the study of Behera and Yamagata (2003), which implied the role of IOD in the pressure swings of the Asia-Pacific sector. In contrast, Li et al. (2003) reported that ENSO is one of the forcing mechanisms that trigger the IOD events. It was supported by Behera et al. (2006), who carried out a GCM study to find out the interactions between IOD and ENSO and obtained a different result that interannual variability of IOD events are affected by the changes in the Walker circulation induced by the ENSO in the tropical Pacific. Another study carried out by Saji and Yamagata (2003b) reported that the IOD events are equally strong whether or not it is co-occurred with ENSO. They pointed out that IOD events arise from the coupled air–sea interactions inherent to the tropical Indian Ocean and it occurs independent of ENSO. Cretat et al (2017) studied the impact of the Indian Ocean on ISMR by removing the influences from the Pacific using model studies and found that the ISMR variability is barely modified by the Indian Ocean and it did not force the monsoon circulation in the absence of ENSO. In addition, Krishnaswami et al. (2015) found that the influence of IOD on mean ISMR and extreme rainfall events is strengthening but that of ENSO is weakening in recent decades. While the IOD–ISMR relation is mainly confined in the summer and autumn seasons, on the other hand, ENSO–monsoon relation extends beyond these seasons (Cherchi and Navarra 2013). However, the study of Chowdary et al. (2015) explains the air–sea interactions in the tropical Indian Ocean that opposes the impact of the Pacific on ISMR even in the absence of IOD. Even though a positive IOD event is associated with above normal rainfall in most of the Indian region, an unusual case occurred in the summer monsoon season of 2008 in which the Central Indian region witnessed a below normal rainfall (Rao et al. 2010). Rao et al. (2010) reported that during the summer monsoon period of 2008, abnormal SST warming was observed in the southern tropical Indian Ocean, which resulted in enhanced convection over the southern tropical Indian Ocean and anti-cyclonic circulation over the Bay of Bengal and Central India, which led to a suppressed rainfall over this region. Since the warming is so strong it nullified the influence of IOD on the Indian monsoon rainfall. This work provided important evidence that the combined

Indian Ocean warming and IOD-related warming can have an impact on ISMR. All the above-mentioned studies mainly focused on the contributions from IOD and ENSO to summer monsoon rainfall and its variability. The impact of ENSO and IOD on the regional variability of ISMR was investigated by Ashok and Saji (2007) and they found that the ENSO has significant impact on the rainfall variability of 19 sub-divisions, while IOD has impact on the rainfall variability of 8 sub-divisions out of 29 sub-divisions considered. They showed that the impact of ENSO is distributed more widely, since the correlation between ENSO and regional rainfall is stronger than that of IOD. Even though there have been several different arguments put forward by the scientific community regarding the existence of IOD, especially its dependence on ENSO and ISMR. The research on IOD has raised a new possibility in the prediction of seasonal and interannual climate variations originating from the tropics (Yamagata et al. 2003, 2004).

3.4 Interdecadal variability of ENSO and IOD

Apart from interannual and intraseasonal variations, the observed ENSO–monsoon relationship showed considerable fluctuations also in decadal and interdecadal times scales (Yun et al. 2018). The decadal variability of the ENSO–monsoon teleconnection for the period 1958–2008 was explored in a study carried out by Feba et al. (2018). They found that a shift in the ISMR, which is associated with surface wind circulations over the Indo-Pacific region that weakens the El Niño transfer mechanisms in recent decades. Using a coupled general circulation model, the influence of southern Pacific on the decadal ENSO-like variations was studied by Luo et al. (2003). They showed that the decadal variability of this ENSO-like variation can be used for the potential prediction of global warming. In the case of IOD, the decadal variations of IOD for the period 1950–1999 were given by Ashok et al. (2004b). They stated that the decadal modulation of IOD events was related with the modulation of IOD in the interannual time scale or the changes are due to the scale interactions. They further explored that there are strong decadal IOD events for the chosen period but they are not well correlated with the decadal ENSO events during the same period. A different type of analysis was carried out by Ham et al. (2017) in which the reason for the weakening of the coupling between ENSO and IOD events in recent decades was examined. They found that the weakening of the ENSO–IOD coupling in recent decades is associated with the different spatial patterns in the ENSO evolution during the boreal spring and summer season. Seetha et al (2020) also found the considerable variations in the teleconnections between the ENSO and ISMR on multidecadal times scales. They argued that these variations are due to the changes in the equatorial Walker and regional Hadley circulations that modify the monsoon low level circulation and hence the moisture supply to alter the rainfall pattern over the Indian subcontinents.

3.5 Impact of other coupled ocean–atmosphere processes on ISMR

Apart from ENSO and IOD, other coupled ocean–atmosphere phenomena in the tropical Oceans (such as Atlantic multidecadal oscillation, Pacific decadal oscillation, etc.) also play important roles in determining the spatio-temporal variability of ISMR. Atlantic multidecadal oscillation (AMO) is considered as a basin-wide oscillation of north Atlantic SST, with a period of about 65–80 years (Kerr 2000). A positive (warm) phase of AMO is associated with the enhanced SST over the North Atlantic, which strengthens the low level jets and thus the monsoon circulation over the Indian region (Li et al. 2008). It can also affect the variability of ISMR by inducing changes in the tropospheric temperature over Eurasia (Goswami et al. 2006c; Lu et al. 2006), i.e., positive (negative) AMO can produce stronger (weaker) ISMR by inducing positive (negative) tropospheric temperature over Eurasia. The study of Feng and Hu (2008) reported that the north Atlantic SST affects the surface temperature of the Tibetan Plateau, which creates meridional temperature gradient to drive the monsoon circulation over the Indian region. Another important driver of ISMR in the Atlantic is the Atlantic zonal mode (AZM; Kucharski et al. 2008; Nair et al. 2018; Sabeerali et al. 2019). These studies reported that the summer monsoon rainfall over different regions of India is influenced by the AZM variability. Sabeerali et al. (2019) showed that the observed inverse relationship between ISMR and AZM has strengthened in recent decades due to the increased eastern equatorial Atlantic Ocean SST in recent decades. Apart from Atlantic Ocean, an another important external forcing factor of ISMR variability is the Pacific Decadal Oscillation (PDO), which is an important mode of climate variability in the North Pacific Ocean (Krishnan and Sugi, 2003; Vishnu et al. 2018). It is inversely linked to the ISMR, with the warm (cold) phases related to the decrease (increase) of rainfall over the Indian subcontinent (Krishnan and Sugi 2003). It can also amplify the impact of ENSO on ISMR (Roy et al. 2003). When El Niño events co-occur with the positive phase of PDO, drought conditions are likely to occur over the Indian region. On the other hand, Indian region is wet condition when La Niña events co-occur with negative phase of PDO.

3.6 Future scope of the study

In last few decades, ENSO–ISMR and IOD–ISMR teleconnection studies are mainly focused on temporal variations, however, the regional variability or the teleconnection of regional patterns are very limited. Since the regional rainfall patterns over the Indian region have been showing a changing trend (e.g., Varikoden et al. 2019) and therefore it has been a topic of current research. Even though, studies are being carried out to study the regional characteristics of ISMR, its influences from the coupled ocean–atmosphere phenomena are not fully explored. Additionally, most of the works explaining the link between the interactions of ocean–atmosphere phenomena with Indian monsoon is focused by considering the monsoon season as whole from June to September. The teleconnection of ENSO–ISMR and IDO–ISMR needs to be studied by considering the different facets of monsoon such as onset phase, peak monsoon phase and withdrawal phase. The association of Indo-Pacific SSTs with active break cycle of monsoon is also a wide topic to be covered for further research, especially in the backdrop of climate change.

4 Conclusions

This review is an attempt of describing early research related to Indian summer monsoon rainfall variability and their association with ENSO in the Pacific and IOD in the Indian Ocean. The literature considered in this work is mainly published after the year 2000 and therefore, it can be treated as review work of relatively new articles. Considering the dependence of summer monsoon rainfall on agriculture and economy of the country, the study on the spatial and temporal variabilities of rainfall and the different climate factors that determine the variability have received more attention in recent decades. The ISMR is generally considered as a seasonal migration of intertropical convergence zone (ITCZ), therefore the convective systems and coupled ocean–atmosphere phenomenon in the tropical Indo-Pacific domain play an important role in determining the spatial and temporal variations of ISMR. The ENSO phenomenon is widely accepted and studied coupled ocean–atmosphere interaction in the Pacific Ocean. The positive (El Niño) and negative (La Niña) phases of ENSO affect the Indian monsoon by providing deficit and excess rainfall, respectively. But this negative relationship between the Indian summer monsoon and ENSO was found to be weakened after 1980s. Several explanations were given by the scientific community to this weakened ENSO–monsoon relationship such as global warming. However, a reliable explanation was given after the discovery of IOD in the Indian Ocean. The discovery of IOD provided a new concept that the coupled ocean–atmosphere phenomenon in the Indian Ocean can also make a significant impact on the monsoon variability of India and other countries. A positive (negative) IOD event is usually associated with excess (deficit) rainfall in India and it can reduce the impact of ENSO on the ISMR when the two events co-occur. The discovery of IOD has raised new possibilities of climate predictions in tropical areas.

Several studies have been carried out in recent years to understand the influence of the Indian and Pacific Oceans on ISMR variability. Most of the studies were carried out in such a way that it connects the climate conditions on the Indo-Pacific sector to the interannual/intraseasonal variability of the monsoon rainfall. Since the summer monsoon in India shows high variations in regional precipitation and they are related to the regional water management and agricultural activities of the country. Therefore, it is important to understand the major external forcings that constitute the regional variability. The important factors/mechanisms that contribute to regional distribution of ISMR and how the coupled ocean–atmosphere phenomena in the Indo-Pacific sector influence the regional variations of rainfall are highly relevant problems which need to be explored further through in-depth research.

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