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ORIGINAL PAPER

Impact of Southern Oscillation and Indian Ocean Dipole on rainfall variability over India: trends and interlinkages during 1871–2017

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Abstract

This investigation highlights changes and various facets of inter-connections between rainfall over India and its prominent drivers such as Southern Oscillation (SO) and Indian Ocean Dipole (IOD). As the monsoon rainfall over majority of sub-divisions from Northeast India (NEI) and Central Northeast India regions (53% area) exhibits declining trend, which are reflected in annual rainfall (AR) as well. On the contrary, during the post-1971 period, the post-monsoon rainfall is observed to be decreasing over all the regions, except Peninsular India (PI). Moreover, the contradictory trends in monsoon and post-monsoon rainfall are registered over the PI, Northwest India (NWI) and West Central India regions. The significant increase in IOD (warming over Arabian Sea) is observed with a swift rise after 1960. Under changing climate conditions, a decline in rainfall and an increase in IOD Index (IODI) may aggravate the water scarcity challenge in semi-arid regions. More than 70% of sub-divisions has positive and negative relationship of SO with monsoon and post-monsoon rainfall, respectively. This contradiction is particularly observed over PI Region, which led to weaker SO-AR relationship. As compared to SO-rainfall relationship, almost opposite picture is observed in the case of sub-divisional and regional rainfall (monsoon and post-monsoon)-IOD relationship. The SO-AR relationship displays epochs of weak (1941–1970 and 1995–2016) and strong (1871–1941 and 1970–1995) connections. Interestingly, the strengthening of the IOD-AR relationship is responsible for the weakening of SO-AR and vice-versa, especially during the post-1970 period. It is evident that the strengthening of SO-IOD relationship results in good rainfall over India, as it shows a significant positive relationship and explains about 6 to 38% variations in regional and All-India annual rainfall.

1 Introduction

Identification of rainfall trends is of vital importance, as almost all the water-related plans are formulated based on available water resources and are of considerable interest in planning and management of water resources projects, ecological planning, environmental systems management, agriculture and irrigation planning, forestry, public health engineering, etc. (Kundzewicz and Robson 2000). Indian agriculture is primarily influenced by the year-to-year variations in monsoon rainfall (Kumar et al. 2013; Todmal 2022). As about 70% of the rural population of the country depends on the agriculture and allied sectors for their livelihood, changes in rainfall amount considerably affect the Indian Economy (GoI 2020). The previous studies (Singh et al. 2005, 2008; Guhathakurta and Rajeevan 2008; Kumar et al. 2010; Kumar and Jain 2011; Pal and All-Tabbaa 2011) have shown considerable spatial variability in trends in rainfall over India. There are studies (Annamalai et al. 2013; Bollasina et al. 2011; Kulkarni 2012; Roxy et al. 2015) that reported a notable reduction in rainfall over some regions in India, particularly during the post-1950 period. Moreover, it is reported that South Asia is highly vulnerable to adverse climatic changes (CDKN 2014). Therefore, the regional changes in rainfall along with temperature rise over India may increase agricultural distress through the intensification of the water scarcity problem (Kumar et al. 2010).

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The SO and IOD are the two dominant modes of the coupled ocean–atmosphere interactions in the Indo-Pacific sector and are considered to be drivers of the Indian Summer Monsoon Rainfall (ISMR) (Hrudya et al. 2021; Ham et al. 2017; Krishnaswami et al. 2015; Ashok et al. 2001; Lacombe and McCartney 2014). Therefore, the mutual connections of IOD, ENSO and the ISMR form an important and complex aspect of the tropical climate (Saji et al. 1999). Generally, the El Niño (La Niña) events are mainly responsible for the below-average (above-average) precipitation over India (Kripalani and Kulkarni 1997; Kumar et al. 2006a, 2006b; Varikoden et al. 2015). Recent studies (Feba et al. 2019; Krishnamurthy and Kirtman 2003) have highlighted the weakening relationship during the last few decades and provided justifications (Ashrit et al. 2001; Feba et al. 2019). The increasing greenhouse gas concentrations cause warming over the Indo-Pacific Ocean, diminishing rainfall during the La Niña years (Samanta et al. 2020), and affect the predictability of rainfall over India. IOD is another important driver of the Indian monsoon. The sea surface anomalies between south-eastern (90°E–110°E, 10°S) and western (50°E–70°E, 10°S–10°N) regions of tropical Indian Ocean are considered as IOD Index (Saji et al. 1999). The active phase of IOD (positive phase) has a connection with below-average rainfall over the majority of parts of India (Saha et al. 2021). The recent human-induced warming (Du and Xie 2008) and geophysical processes (Dong et al. 2016; Mayer et al. 2013) increase the frequency of the positive phase of the IOD, which adversely affects the rainfall over the Indian Sub-continent. Although the positive phase of IOD reduces the intensity of El Niño-induced droughts over India (Ashok et al. 2004a), it has a connection with a long-term increase in drought-affected areas in a country (Kumar et al. 2013).

Numerous studies have investigated the interactions between simultaneous ENSO and IOD events. Some of the studies (Iizuka et al. 2000; Webster et al. 1999; Saji et al. 1999; Behera et al. 2006) argued that the phases in IOD are completely independent of external forces such as ENSO. However, a contradictory finding has emerged that the IOD is considerably interlinked with SO (Krishnamurthy and Kirtman 2003; Li et al. 2003; Huang and Shukla 2007; Zhang et al. 2015; Kajtar et al. 2016). El Niño conditions favor the development of a positive phase of IOD. Monsoon dynamics play an important role through air-sea interaction processes in the Indian Ocean and hence they are crucial for the ENSO-monsoon teleconnection (Bracco et al. 2007). Pokhrel et al (2012) investigated the dynamical linkages of ENSO and IOD in modulating ISMR in terms of the regional Hadley circulation and a planetary-scale Walker circulation. The IOD plays an important role as a modulator of the ISMR and influences the strength of the ISMR-ENSO relationship. It considerably affects the predictability of ISMR, as the ENSO determines about 54% of the variation in Indian rainfall (Surendran et al. 2015). The relative influences of ENSO and IOD events on ISMR were studied by Ashok et al. (2004a). The decadal modulation in the tropical Indo-Pacific variability associated with ENSO and IOD has the potential to modulate the ISMR and Asian Summer Monsoon Region (ASMR) on long timescales (Ashok et al. 2001, 2004b; Ashok and Saji 2007, Ummenhofer et al. 2011). The recent studies highlighted the potential role of anthropogenic climate change in modifying the characteristics of these climate drivers (Ashok et al. 2007, 2012).

The present investigation endeavored to understand trends in sub-divisional and regional changes in rainfall during the distant (1870–2017) and recent past (1970–2017). The study confirms the long-term and recent relationships of sub-divisional and regional rainfall over India with SO and IOD. The regional phases of weak and strong connections between SOI and AR are explored and discussed. An attempt has also been made to evaluate the influence of the SO-IOD relationship on the AR over the different parts of India.

2 Data and methodology

The India Meteorological Department (IMD) has divided entire India into 36 meteorological sub-divisions based on climatic conditions. Among them, 34 sub-divisions cover the mainland area (Fig. 1). For the present investigation, sub-division wise monthly rainfall data for the available period between 1871 and 2017 were obtained from IITM (Indian Institute of Tropical Meteorology). The study attempted to consider maximum available climatic data. On account of the unavailability of rain gauge stations before 1900, this mission had excluded the Arunachal Pradesh, Jammu and Kashmir, Uttarakhand, and Himachal Pradesh Sub-divisions. Therefore, the rainfall data of these sub-divisions (between 1901 and 2014) collected from IMD were considered. It is pertinent to mention that the rainfall regime over all the regions/meteorological sub-divisions is not uniform (Zubair and Ropelewski 2006), as the distribution of rainfall over India has a profound impact of physiography (Pai et al. 2014). For this reason, the annual, monsoon (JJAS) and post-monsoon (OND) rainfall were considered in this study. Among the selected sub-divisions, ~ 5% missing data of Arunachal Pradesh were estimated by the linear regression technique. Apart from this, the study has also considered regional rainfall data. By combining the sub-divisions in five homogeneous regions such as northwest India, North East India, Central North East India, Peninsular India, and West Central India (Fig. 1), IITM has derived regional area-weighted rainfall data series for the period between 1871 and 2016 (www.tropmet.res.in).

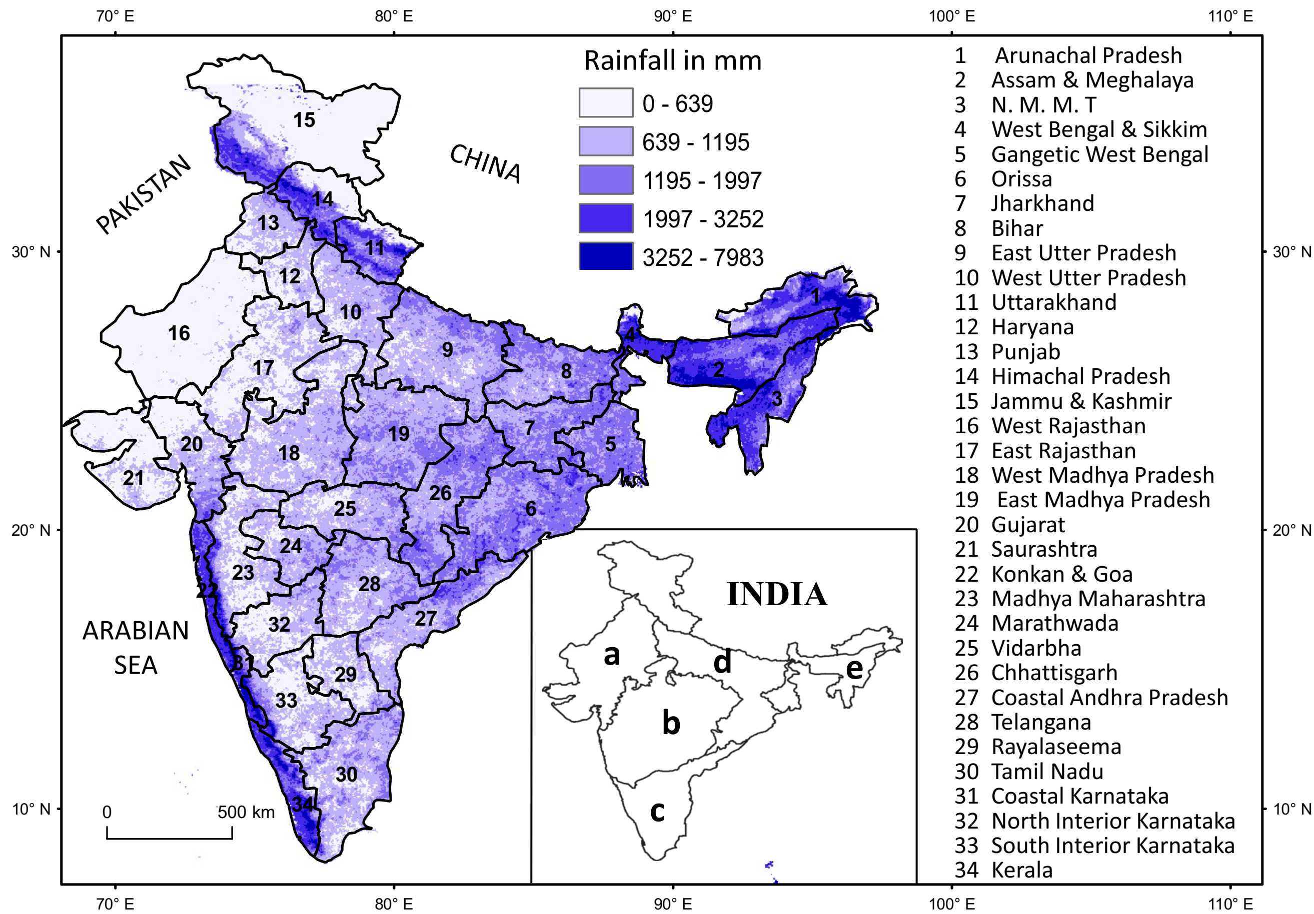

Fig. 1 Average annual rainfall over meteorological sub-divisions of India. Listed are the names of sub-divisions. Inset map shows meteorological homogeneous regions in India (a = northwest India, b = West Central India, c = Peninsular India, d = Central North East India and e = North East India). Rainfall classes are based on natural breaks. Source of TRMM Data: http://www.geog.ucsb.edu/~bodo/TRMM/

As the SO and IOD strongly influence the AR, month-wise data of SO and IOD Indices for the period between 1871 and 2017 were acquired from NOAA (National Oceanic and Atmospheric Administration) website (htpp://www.noaa.gov). SOI is one of the ENSO indicators, which considers the pressure anomalies over the eastern and western parts of the Pacific Ocean. The monthly index values in each year were averaged to obtain the annual mean SOI and the IOD data series. The year with ENSO Index < -0.5 or > 0.5 at least for consecutive five months is categorized as a La Niña or El Niño year, respectively (https://origin.cpc.ncep.noaa.gov). The annual cycles of the ENSO Index during observed El Niño and La Niña years between 1950 and 2016 are given in Fig. 2. It can be noticed that the threshold crossing anomalies in ENSO Index were observed between May and December. Similarly, considerable anomalies in IOD appear between June and November (Saji et al. 1999). Therefore, year-wise, SOI and IOD Index values were derived by averaging the values between May and December. The lower SOI values (negative values) indicate weak to strong

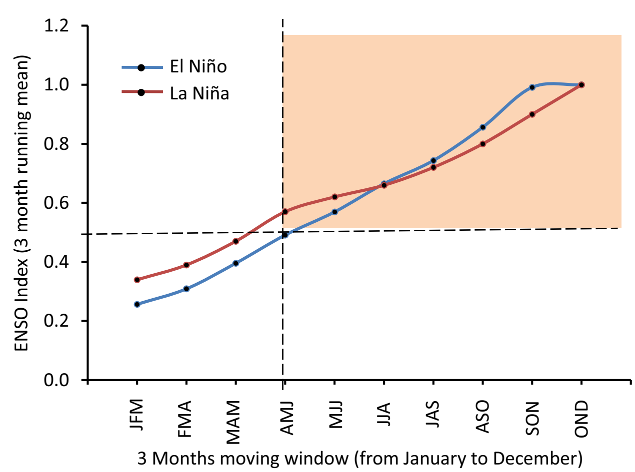

Fig. 2 Annual cycle of ENSO Index during observed El Niño and La Niña years between 1950 and 2016. Basic data source: NOAA (https://origin.cpc.ncep.noaa.gov), shaded is the threshold crossing period of ENSO Index. The absolute values of ENSO Index during La Niña years are considered for presentation purpose

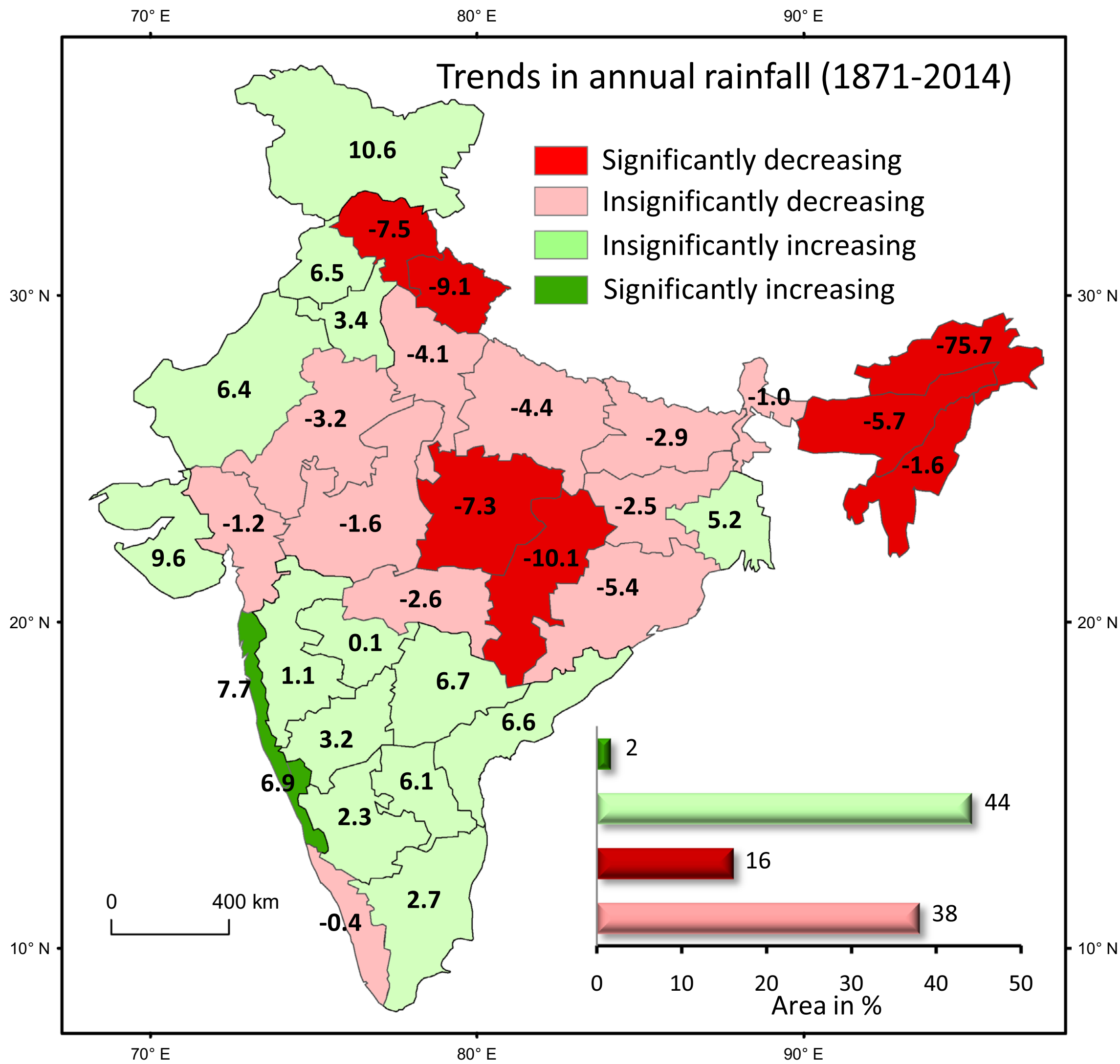

Fig. 3 Sub-division wise trends and magnitude of change (% of mean/100) in annual rainfall. 5% level of significance used

El Niño events (Ropelewski and Jones 1987). The positive phase of IOD denotes warming of SST in the western tropical Indian Ocean and cooling of SST in the eastern Indian Ocean (Zhang et al. 2015; Saha et al. 2021). To understand the connection between SO and IOD with rainfall (annual, monsoon and post-monsoon) over the selected sub-divisions and homogeneous regions, correlation and regression analyses were carried out. The annual mean temperatures over the Indian subcontinent (from 1901 to 2016) were collected from IITM. With the use of linear regression and Student's t test, the recent warming period over India was ascertained.

To identify the change in long-term rainfall (annual, monsoon and post-monsoon), annual and monsoon (average for May to December) data series of SOI and IOD Index, trend analysis was carried out by applying standard parametric and non-parametric statistical methods. Moreover, using the post-1971 data, recent trends in rainfall were ascertained. The Linear regression method was used to detect linear trends and the obtained results were verified by using non-parametric Spearman's *Rho* and Mann–Kendall Statistics. An attempt was also made to determine the point of initiation of step-change in the above-mentioned data series. For this, Cumulative sum (CUSUM), Cumulative Deviation, and Worsley Likelihood Ratio tests were applied. The obtained results of the year of step-change were verified by Student's t and Rank Sum Tests. The details of these methods are given in Kundzewicz and Robson (2000). To differentiate the effect of annual and monsoon (SOI and IOD Index) series on the regional/sub-divisional rainfall, Student's Paired t test was applied.

3 Results and discussion

3.1 Trends in sub-divisional rainfall

3.1.1 Trends in annual rainfall

Figure 3 exhibits regions with increasing and decreasing annual rainfall over India. Broadly, annual rainfall over about 54% and 46% of the areas show decreasing and increasing trends. All the sub-divisions in the Peninsular Region, excluding Kerala, reveal an increase in annual rainfall, although the trend is not significant. A significantly increasing trend is registered over the Coastal Karnataka and Konkan and Goa Sub-divisions. The study conducted by Guhathakurta and Rajeevan (2008) and Kumar et al. (2010) corroborates these findings. This increase is likely associated with vertically integrated moisture transport (VIMT) over the Arabian Sea, because VIMT is a result of low-level wind speed and moisture content together (Konwar et al. 2012). The rainfall over Kerala shows a declining trend, albeit it is not significant. These inconsistent trends in rainfall over the west coast (sub-division no 22, 31and 34) are very likely attributed to excessive use of biophysical resources (Krishnakumar et al., 2009) and the abnormal warming of SST of the Indian Ocean (Varikoden et al. 2019) mainly caused by ocean advection processes (Rao et al. 2012) and increased frequency of El Niño events during the recent decades (Abish et al. 2018; Roxy et al. 2014). Apart from this, the increased anthropogenic greenhouse gas (GHG) emissions into the atmosphere are observed to be another reason for the same (Dong and Zhou, 2014; Dong and McPhaden, 2016). Similarly, in northwest India, rainfall over Saurashtra, western Rajasthan, Punjab, Haryana, and Jammu and Kashmir exhibit an insignificant increase (Fig. 3), however, Kumar et al. (2010) have reported a significant increase in rainfall over the Punjab and Haryana. It may be due to consideration of longer data series with above and below-average epochs. On the other hand, all the sub-divisions in Central North India, North East India (except West Bengal), and the northern part of West Central India reveal a decrease in annual rainfall, which is significant over East Madhya Pradesh, Chhattisgarh, Uttarakhand, Himachal Pradesh and all the sub-divisions east to West Bengal and Sikkim (Fig. 3). The results that emerged from a study carried out by Kumar et al. (2010) are in good agreement. This may have resulted in increased frequency and intensity of drought events over the Jharkhand, Orissa, Kerala, East Madhya Pradesh and Chhattisgarh sub-divisions during the recent decades (Pai et al. 2011; Das et al. 2016). It should be noted that the northeast region of India (Assam, Meghalaya, Arunachal Pradesh, and N.M.M.T) receives a copious amount of rainfall (Fig. 1), where rainfall registered a significant decline. The decline in VIMT over the Bay of Bengal is causing a reduction in rainfall over Northeast India (Konwar et al. 2012). Particularly, the Meghalaya Sub-division, where Mawsynram is the wettest place on Earth, shows a notable decline in rainfall. A significant decreasing trend in rainfall is also observed in the Uttarakhand and Himachal Pradesh sub-divisions. The study carried out by Jain and Kumar (2012) observed a declining trend in annual rainfall over the Brahmaputra Basin (Arunachal Pradesh and Assam and Meghalaya Sub-divisions) which corroborates the findings that emerged from the present study. Similarly, the Mahanadi, Narmada, and Tapi Basins displayed a decline in rainfall (Mall et al. 2006; Jain and Kumar 2012; Singh et al. 2008), as they drain the East and West Madhya Pradesh, Chhattisgarh, Jharkhand, Vidarbha and Orissa Sub-divisions.

Apart from this, it is evident that the magnitude of change (% of mean/100 years) in annual precipitation over India (subdivision wise) during the past century varies between + 10% and -10% of a long-term annual mean (Fig. 1). Exceptionally, an unusually rapid and significant decline in rainfall (-76% of mean) is observed over Arunachal Pradesh, whereas the Uttarakhand, Himachal Pradesh, East Madhya Pradesh, and Chhattisgarh Sub-divisions registered a considerable decline by 5 to 10 percent. Although the decrease in annual rainfall is marginal (1.6%) over N.M.M.T Sub-division, it is statistically significant. It is pertinent to mention that perhaps due to decrease in rainfall, the intensity and frequency of meteorological droughts over the northern part of the West Central and North East Region are notably increased, particularly after 1941 (Kumar et al. 2013; Joshi et al. 2016), which can be a major concern from the agro-economic viewpoint (Kumar et al. 2013). On the other hand, Konkan and Goa, Coastal Karnataka, Jammu and Kashmir, West Rajasthan, Saurashtra, Punjab, Coastal Andhra Pradesh, and Telangana Sub-divisions show a tendency of increasing rainfall. Among all the sub-divisions, Konkan and Goa (7.7%) and Coastal Karnataka (6.9%) reveal a significant increase in rainfall.

3.2 Trends in monsoon (JJAS) and post-monsoon (OND) rainfall

The long-term trends in monsoon rainfall (JJAS) are in good agreement with annual rainfall trends. Majority of meteorological sub-divisions in India display decline in monsoon rainfall. The results obtained by Praveen et al. (2020) support this observation. This decrease is observed over about 58% and 52% of area in a country during 1871–2014 and 1971–2014, respectively (Table 1). Particularly, the Arunachal Pradesh, Assam, Meghalaya, Eastern Uttar Pradesh, Punjab and Haryana registered a significant

Table 1 Sub-division wise trends in monsoon (JJAS) and post-monsoon (OND) rainfall

Sr. No	Subdivision	MRF 1871-2014	PMRF 1871-2014	MRF 1971-2014	PMRF 1971-2014
1	ARNPR	-19.50*	-1.72	-6.00*	-3.98*
2	ASMEG	-1.07*	0.14	-5.81*	-1.81
3	NMAMT	-1.46*	0.04	-0.70	-1.62
4	SHWBL	-0.47	0.24	1.12	-1.67
5	GNWBL	0.50	0.21	-0.95	0.82
6	ORISS	-0.10	-0.06	4.44*	1.22
7	JHKND	-0.33	0.14	-1.75	0.17
8	BIHAR	-0.56	0.07	-2.04	-1.67*
9	EUPRA	-0.40	-0.08	-3.40*	-0.68
10	WUPPL	-0.40	0.02	-2.19	-0.60
11	UTTRKND	-1.44	-0.23	1.85	-0.91*
12	HARYA	0.14	-0.02	-3.45*	-0.33
13	PUNJB	0.41	0.01	-5.46*	-0.40
14	HIMCPR	-1.42*	0.06	-1.96	-0.83
15	J & K	0.42	0.29	2.08	-0.10
16	WRJST	0.12	0.02	-0.54	-0.10
17	ERJST	-0.24	0.03	-1.34	-0.61*
18	WMPRA	-0.22	0.04	-2.14	-0.81*
19	EMPRA	-0.92*	-0.02	-0.60	-0.53
20	GUJRT	-0.14	0.04	2.91	-0.81*
21	SAUKU	0.38	0.06	5.10*	-0.81*
22	KNGOA	1.65	0.27	0.96	1.40*
23	MADMH	0.13	0.01	2.06	0.04
24	MARAT	-0.20	0.15	0.72	-0.87
25	VDABH	-0.36	0.04	2.40	-0.77
26	CHHAT	-1.26*	-0.05	0.32	-0.06
27	COAPR	0.39	0.10	0.52	0.59
28	TELNG	0.23	0.21	-1.28	-1.16*
29	RLSMA	0.19	0.12	1.10	-0.25
30	TLNAD	-0.04	0.24	-0.84	0.78
31	COKNT	1.59	0.32	-5.00	1.85*
32	NIKNT	0.10	0.00	0.33	-0.28
33	SIKNT	0.21	-0.01	0.34	0.74
34	KERLA	-0.97	0.64*	-1.84	1.62
	All India	-1.82	0.42	-2.70	-4.18
	P India	1.36	1.05	-5.34	3.26
	WC India	-2.13	0.23	3.75	-5.86*
	CNE India	-4.9*	-0.23	-15.33*	-2.62
	NE India	-6.6*	1.48	-19.11*	-10.72*
	NW India	1.22	0.42	7.65	-3.42*

Table 1 (continued)

Red and green colors denote decreasing and increasing trends, respectively. Darks shades represent statistically significant trends at 0.05 level. The numbers in colored cells are slope (annual rate of change in mm) of regression line.

Serial numbers of sub-divisions correspond to Fig. 1. Sub-division names are given in abbreviated form.

MRF monsoon rainfall (JJAS), *PMR* post-monsoon rainfall (OND).

P Peninsular, *WC* West Central, *CNE* Central Northeast, *NE* Northeast, *NW* Northwest

Table 2 Trends in IOD Index and region-wise annual rainfall

Trends in IOD			Regional rainfall trends			
Months	r^2	Year of step-change	Regions	Slope (1871–2016)	Year of step-change	(% change[#])
January	0.27**	+ 1934*	All India	− 1.3	− 1964	(− 3.1)
February	0.15**	+ 1943*				
March	0.15**	+ 1960*	Peninsular India (PI)	3.5	+ 1914	(4.1)
April	0.15**	+ 1967*				
May	0.09*	+ 1966*	West Central India (WCI)	− 1.4	− 1964*	(− 4.0*)
June	0.06*	+ 1965*				
July	0.16**	+ 1960*	Central NE India (CNEI)	− 5.3*	− 1963*	(− 5.6*)
August	0.12*	+ 1960*				
September	0.13*	+ 1960*	North East India (NEI)	− 7.4*	− 1956*	(− 4.7*)
October	0.14*	+ 1960*				
November	0.16**	+ 1960*	Northwest India (NWI)	1.7	+ 1941	(6.0)
December	0.26**	+ 1960*				
Annual average	0.26**	+ 1960*				
Average for MD	0.20**	+ 1960*				

MD May to December, * and ** denote significant trend/step-change at 95% and 99% confidence levels, respectively, *Slope* rate of change in mm/decade, + and—signs with years denote step-increase and – decrease, respectively, after this year, [#] percentage change in rainfall after a year of step-change

decrease (by 30 to 60 mm/decade) in monsoon rainfall during the post-1970 period. It confirms the findings emerged from the previous studies (Naidu et al. 2009; Kumar et al. 2010; Praveen et al. 2020). On the contrary, Orissa and Saurashtra reveal considerable increase (by 50 mm/decade). Another observation can be made from Table 2 that most of the sub-divisions from Gujarat, Maharashtra, Karnataka, Andhra Pradesh and Tamil Nadu States (Sr. No 20 to 33 in Table 1) experienced increase in monsoon rainfall, albeit the trend is not significant. However, most of the CNE, NE India Regions and the states of Rajasthan, Madhya Pradesh, Punjab and Haryana observed with declining trend in monsoon rainfall during the last five decades.

Trends in post-monsoon (OND) rainfall during 1871–2014 and 1971–2014 reveal contradictory picture (Table 1). The long-term trends registered increasing rainfall over about 76% area of a country, although none of a subdivision exhibit significant rise. Almost a comparable observation emerged from the study undertaken by Guhathakurta and Rajeevan, (2008) which could not ascertained the recent trends in post-monsoon rainfall. This study highlighted that during the last five decades (1971–2014), majority of sub-divisions (75% of area) exhibit decline in post-monsoon rainfall. Some of them including Arunachal Pradesh, Bihar, Uttarakhand, Eastern Rajasthan, Western Rajasthan, Eastern Madhya Pradesh, Gujarat, Saurashtra and Telangana are observed with significant decline at the rate of 5 to 40 mm/decade (Table 1). The observed decline in post-monsoon rainfall is very likely associated with changes in Indian Ocean sea surface temperature during the last few decades (Kamil et al. 2017; Samanta et al. 2020). It should be noted that the sub-divisions in western and eastern coasts including Konkan and Goa, Madhya Maharashtra, Coastal Interior Karnataka, South Interior Karnataka, Kerala, Orissa, Coastal Andhra Pradesh and Tamil Nadu reveal increase in rainfall. Among them, Konkan and Goa, and Coastal Karnataka Sub-divisions registered considerable increase with 15 to 20 mm/decade.

3.3 Trends in regional rainfall

The regional trends in rainfall are given in Table 2. The All-India rainfall during the last 144 years reveals a decreasing trend, however, it is not statistically significant. It should be noted that about 54% of the land area in a country experienced a decline (4 to 6%) in rainfall after ~ 1960. Moreover, it is also observed that the monsoon and post-monsoon rainfall at All-India level show decline during the last 5 decades, which is not significant. The weakening of ENSO influence may have caused decline in Indian rainfall (Naidu et al. 2009). All the regions, except the PI and NWI, exhibit a decrease in long-term annual and monsoon precipitation (Table 1). Among them, the CNEI and NEI Regions registered a significant decline in annual rainfall, particularly after 1963 (by 6%) and 1956 (by 5%), respectively (Table 2), which is mainly caused by substantial decrease in monsoon rainfall. It should be noted that the rate of decline in monsoon rainfall over these regions is augmented (by 15 to 19 mm/year) in post-1971 period (Table 1). Although the annual rainfall over the CNEI Region is declined with maximum rate, the regional monsoon and post-monsoon rainfall show rapid decrease over NEI Region (particularly after 1971). This fact was previously highlighted by Guhathakurta et al. (2015). On the other hand, a notable change in regional trends in post-monsoon rainfall can be observed during 1871–2016 and 1971–2016 (Table 1). All the regions, except PI, exhibit decrease in post-monsoon rainfall in recent decades (after 1971). The WC, NE and NW Regions registered a significant reduction in post-monsoon rainfall (by 3 to 10 mm/year). Perhaps, due to declining rainfall, the coverage and frequency of droughts over CNEI, NEI, and partially WCI Regions were observed to be increased during recent decades (Guhathakurta et al. 2017). Particularly, CNEI and NEI meteorological regions need the special attention of hydrologists and water resources managers. The PI and NWI Regions (about 34% of the area) exhibit an insignificant increase in rainfall, as most sub-divisions in these two regions show an increasing trend (Fig. 3). These results are in good agreement with the findings of a study undertaken by Kumar et al. (2010). However, the monsoon rainfall over PI Region reveal insignificant decline in the last few decades (Table 1). Interestingly, the NW Region of India, characterized by the lowest annual mean precipitation (< 600 mm), shows an increase in rainfall, albeit it is not statistically significant.

3.4 Trends in Indian Ocean Dipole

Under the scenario of climate change, a notable variability in Indian Ocean Dipole is registered during the post-1960 period (Anteneh et al. 2019). The present investigation confirmed that the Indian Ocean Dipole Index (IODI) is significantly increasing (warming over Arabian Sea and cooling over the south-eastern Indian Ocean) from 1871 to 2017 (Table 2), as the annual average and month-wise IODI records exhibit a positive trend. It signifies that the SST of the western IO is increasing, particularly after 1960. The previous studies (Abish et al. 2018; Rao et al. 2012; Kripalani et al. 2004) support this observation. This warming is perhaps attributed to the extraordinary sinking of high-altitude wind and change in the atmospheric and oceanic fields during the El Niño and La Niña events (Abish et al. 2018) and increased upwelling in the eastern part of the Indian Ocean (Abram et al. 2008). It is also observed that the average IODI value for the period between 1871and 1960 is -0.09, whereas it is + 0.15 for the period between 1960 and 2017 (Fig. 4). The transported surplus heat from the Pacific Ocean to the IO is mainly responsible for the recent warming of the Indian Ocean (Dong et al. 2016). It is also argued that an increase in the absorption of solar energy (due to reduction in cloud cover) (Mayer et al. 2013) and an increase in greenhouse gases (Du and Xie 2008) are very likely attributed to the warming of IO. As the warming of the Arabian Sea is responsible for increased drought frequency over India (Kumar et al. 2013) and decline in the monsoon rainfall over Central India during the La Niño years (Samanta et al. 2020), it may aggravate the future water scarcity challenge in India. The occurrence of the positive phase of IOD in El Niño year reduces drought intensity over Western India (Ashok et al. 2004a; Todmal 2019). It suggests that the intensity of El Niño induced droughts in the future may get reduced due to the warming of the Arabian Sea.

The present investigation also confirmed that the annual mean temperature over India is significantly increasing. Particularly, after 1976, the rapid rise in temperature (0.18 °C/decade) is evident (Fig. 4). It should be noted that the annual precipitation (over CNEI and NEI regions) and IODI reveal a step-change after the 1960s. Moreover, the relationship between rainfall (region-wise and All India) and annual mean temperature over India is not statistically significant ($r^2 = 0.009$). On the other hand, the warming of western equatorial Indian Ocean explains about 4% variations in rainfall, which is statistically significant. It signifies that the declining trend in rainfall is very likely associated with the warming of western equatorial Indian Ocean rather than the temperature rise (Table 4).

3.5 Relationship between rainfall and SOI

Although it is well established that the SOI significantly affects the ISMR, the studies (including Kripalani and Kulkarni 1999; Ashrit et al. 2001; Ashok et al. 2004a; Sarkar et al. 2004; Krishnaswami et al. 2015) have highlighted variations in the strength of this connection. Therefore, an attempt has been made to confirm the influence of SOI on

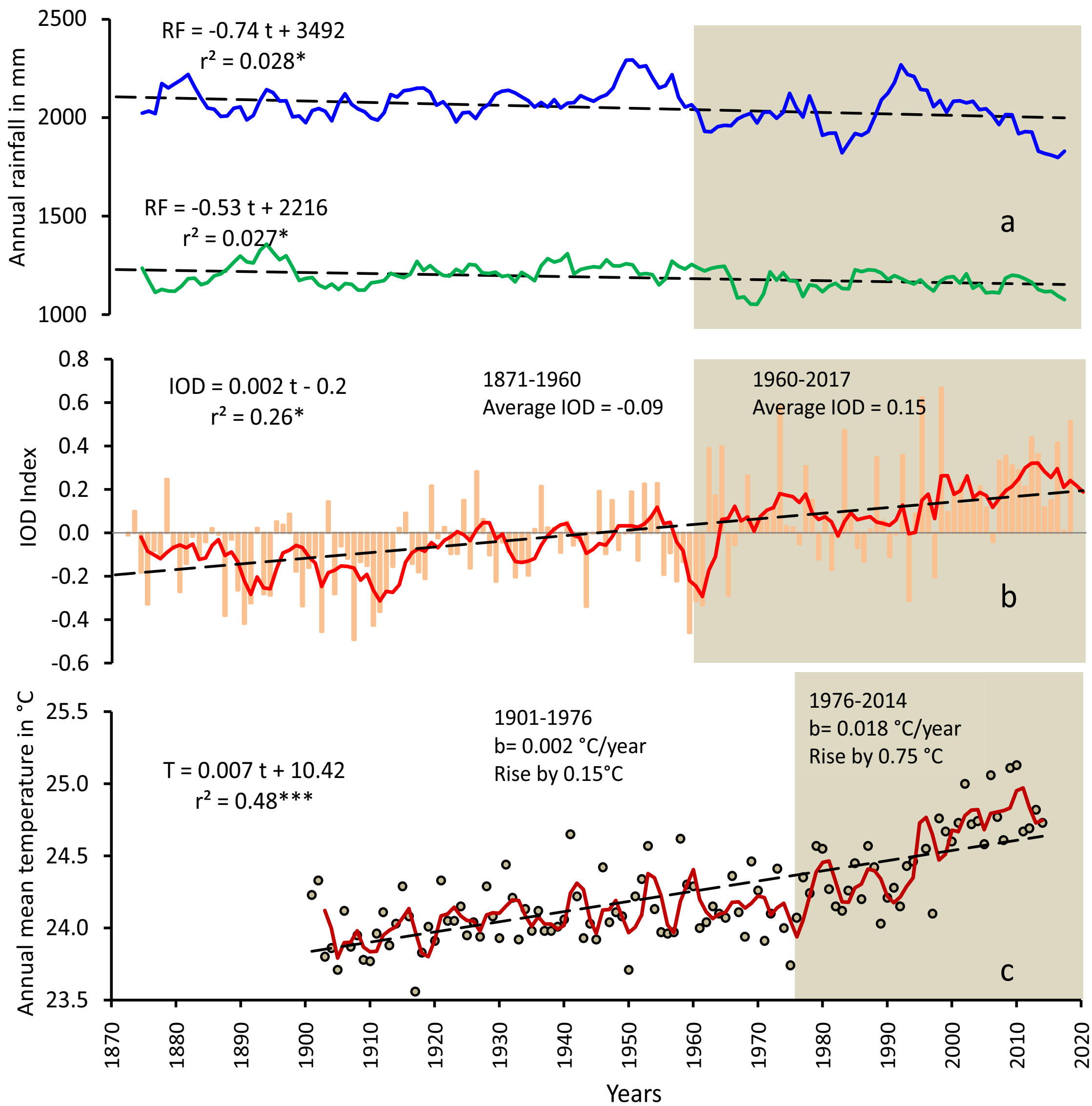

Fig. 4 Time series plot of a) annual rainfall over Central North East India (green line) and North East India (blue line) b) average annual IOD index c) all India average annual temperature. * and *** denote a significant trend at 95% and 99.9% confidence levels, respectively. Shaded is the period after step-change. Solid lines represent the 5-year moving average. T = temperature, t = time, RF = rainfall and b = rate of change. The trend in CNEI and NEI are significant, hence given here. Regression equations and r^2 values are for the entire period

the sub-divisional rainfall (annual, monsoon and post-monsoon) using the longest and recent data sets (1871–2015 and 1971–2017, respectively). It is clear from Fig. 5 and Table 3 that there is a considerable connection between SOI and rainfall over India. Broadly, the annual and monsoon (JJAS) rainfall over 84% and 80% of the area, respectively, has a positive link with the SOI. Almost the same picture can be observed in the case of monsoon rainfall. It suggests that the years with positive SOI (mild to strong La Niña events) registered a reasonably good amount of rainfall over India and vice-versa. During the El Niño phase (negative SOI), a shift in Walker circulation causes a notable reduction in ISMR (Ummenhofer et al. 2011). As a result, the severe droughts over the Indian Region are mostly observed during the El Niño phase (here negative SOI) (Kumar et al. 2006a; Varikoden et al. 2015). Another observation can be made is that the annual rainfall over about 67% and 47% of area exhibit a significant positive connection with average SOI for May to December (SOI^m) and annual average (SOI^a), respectively (Fig. 5). Particularly, the rainfall during the monsoon period (JJAS) has considerable connection with the SOI^m as compared to the SOI^a (Table 3). Among all

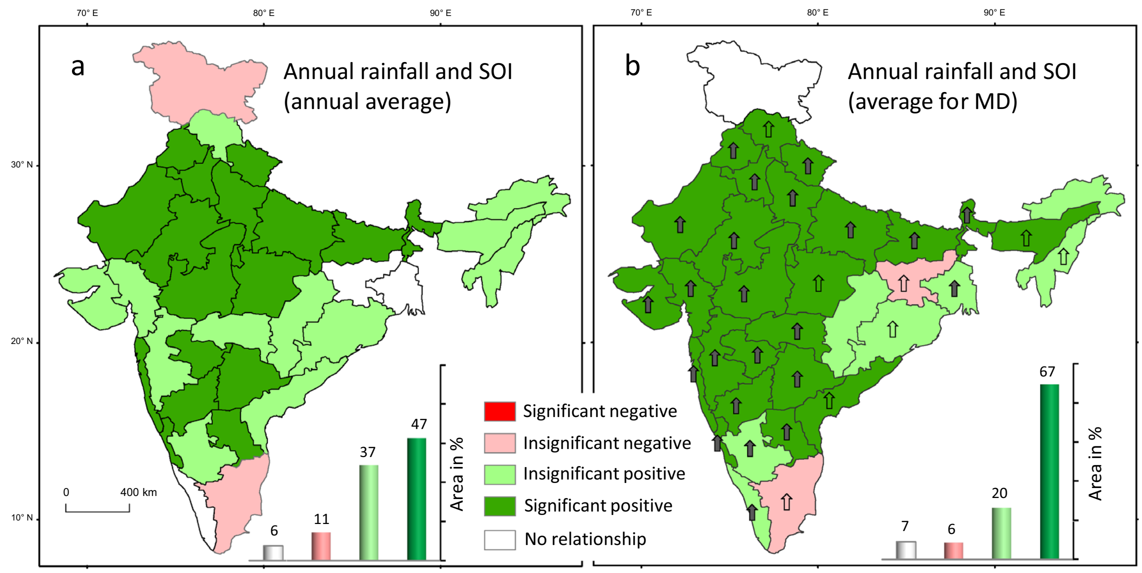

Fig. 5 Relationship of sub-divisional annual rainfall with a) annual average SOI and b) May to December average SOI. The upward arrows represent positive relationship during 1971–2016. The gray solid arrows denote significant relationship at 95% confidence level. The arrows are not shown for the sub-divisions with marginal/no correlation during post-1971 period. MD = May to December

the sub-divisions, Arunachal Pradesh, Assam and Meghalaya, N.M.M.T., Gangetic West Bengal, Orissa, Jharkhand and Eastern Madhya Pradesh registered negative correlation (insignificant), particularly after 1971 (Table 3). Due to this reason, the SOI^m has weaker relationship (insignificant positive) with monsoon rainfall over NEI and CNEI Regions Table 3. The AR-SOI^m relationships reveal almost consistent results (Fig. 5). It should also be noted that parts of these regions are mostly influenced by the enhanced cyclogenesis over the Bay of Bengal during the summer monsoon months, which produces more rainfall over the eastern region of India during El Niño years (Singh et al. 2002), which perhaps weakens the SOI-rainfall relationship. It can also be noticed from Table 3 that northeast monsoon over the majority of sub-divisions (> 60% of area) show negative relationship, as the SOI events/warmer conditions are associated with above-average rainfall, particularly after 1971. The results obtained by Kumar et al. (2006b) are in good agreement with this finding. As a result of this, the post-monsoon rainfall at All-India level exhibits inverse relationship with SOI, albeit it is not significant. Particularly, the PI Region registered a significant negative connection between SOI^m and post-monsoon rainfall (Table 3). Moreover, more than 50% of sub-divisions form the WCI Region registered negative connection of SOI-monsoon rainfall. This unusual characteristic of regional post-monsoon rainfall affected the strength of SOI-AR relationships (Fig. 5).

The almost comparable scenario can be observed at the regional scale. The SOI significantly determines the rainfall over all the regions and India as a whole (Table 4). The SOI^m has a notably strong connection with regional annual rainfall. The findings of a study conducted by Roy et al. (2017) are in good agreement with this observation. However, the relationship SOI^m- monsoon rainfall is observed to be weakening over the CNI and NEI Regions, particularly after 1971 (Table 3). As the observed relationship is positive, the years with positive SOI (mild to strong La Niña events) are associated with above-average rainfall and vice-versa. Moreover, the results of the Student's Paired t test indicate that the strength of correlation between rainfall (regional as well as sub-divisional) and SOI^m is significantly higher than the rainfall-SOI^a relationship. This finding highlights the applicability of SOI^m in forecasting monsoon over India. On the contrary, the All-India post-monsoon rainfall displays negative relationship with SOI, although it is not significant. Among all the regions, PI and WCI show inverse connection. The considerable relationship of SOI^m – post-monsoon rainfall over PI signifies that the positive SOI events (mild to strong La Niña events) caused below-average rainfall and vice-versa (Table 3). Apart from this, the NEI, CNEI and NWI Regions show positive relation with SOI^m, however, it is statistically significant over the NEI. It should be noted that the agricultural crop response has a noteworthy connection with Indian Rainfall and SOI (Krishna Kumar et al. 2004). Therefore, from the agro-economic viewpoint, it is imperative to incorporate SOI and IR variability to formulate annual agricultural planning.

Apart from the individual influence of SOI and IOD on rainfall, this investigation highlighted the effect of the SOI-IODI relationship on rainfall. The Indian rainfall is

Table 3 Sub-division and region wise relationships of rainfall (monsoon and post-monsoon) with SOI and IODI.

Sr. No	Subdivision	SOI[a] x MRF		SOI[m] x MRF		SOI[a] x PMRF		SOI[m] x PMRF		IODI[a] x MRF		IODI[m] x MRF		IODI[a] x PMRF		IODI[m] x PMRF	
		All	Po1971	All	Po1971	All	Po1971	All	Po1971	All	Po1971	All	Po1971	All	Po1971	All	Po1971
1	ARNPR	+	-	+	-	+	+	+	-	-*	-*	-*	-*	-*	-	-*	-
2	ASMEG	+	-	+*	-	+	+	+	+	-*	-	-*	-	-*	-*	-*	-*
3	NMAMT	+	-	+	-	+*	+	+*	+*	-*	-	-*	-	-*	-*	-*	-*
4	SHWBL	+*	+	+*	+*	+	+	+	+	-*	-	-*	-	-	-	-	-*
5	GNWBL	-	+	-	-	+*	+	+*	+	+	+	+	+	-	-	-*	-*
6	ORISS	-	-	-	-	+*	+	+*	+	+	+	-	+*	-*	-	-*	-
7	JHKND	+	+	-	-	+	-	+	+	+	+	+	+	-	+	-	+
8	BIHAR	+*	+	+*	+	+	+	+	+	-	+	-*	-	-	-	-	-
9	EUPRA	+*	+*	+*	+*	+	-	+	-	-*	-	-*	-*	-	-	-	-
10	WUPPL	+*	+*	+*	+*	+	-	+	-	-*	-	-*	-	-	-	-	-
11	UTTRKND	+*	+*	+*	+*	+*	+	+*	+	-*	-*	-*	-*	-*	-*	-*	-
12	HARYA	+*	+	+*	+*	+	-	+	-	-	-	-*	-	-	+	-	+
13	PUNJB	+*	+*	+*	+*	+	-	+	-	-	-	-	-	-	-	-	-
14	HIMCPR	+*	+*	+*	+*	+	-	+	-	-*	-*	-*	-*	+	+	-	+
15	J & K	+	+	+*	+	-	-*	-*	-*	-	-	-	+	+*	+	+*	+
16	WRJST	+*	+	+*	+*	+	+	+	+	-	-	-	-	+	+	-	+
17	ERJST	+*	+	+*	+*	+	-	+	-	+*	-	-*	-	-	-	-	-
18	WMPRA	+	+	+*	+	+	-	+	-	-	+	-	+	+	+	+	+
19	EMPRA	+*	-	+*	-	+	-	+	-	-	+	-	+	+	+	+	+
20	GUJRT	+	-	+*	+	+	+	+	+	-	+	-	+	-	-	-	-
21	SAUKU	+	+	+*	+*	+	+	+*	+	+	+	+	+	-	-	-	-*
22	KNGOA	+*	+	+*	+*	+	+	+	+	-	-	-	-	-	-	-	-
23	MADMH	+	+	+*	+*	+	-	+	-	-	-	-	-	+	+	+	+
24	MARAT	+*	+*	+*	+*	+	-	+	-	-*	+*	-*	-*	+	-	+	-
25	VDABH	+	+	+*	+*	+	+	+	+	-*	-	-*	-	+	-	+	-
26	CHHAT	+	+	+	+	+	-	+*	+	-	+	-	+	-	+	-	+
27	COAPR	+*	+*	+*	+*	+	-*	+	-*	-	-*	-*	-*	+	+*	+	+*
28	TELNG	+*	+*	+*	+*	+	-	+	-	-*	-*	-*	-*	+	-	+	-
29	RLSMA	+*	+	+*	+*	-	-	+	-	-*	-	-*	-	+	+	+	+
30	TLNAD	+*	+*	+*	+*	-*	-*	-*	-	-*	-*	-*	-*	-*	+	+*	+*
31	COKNT	+*	+*	+*	+*	-*	-	-	-	+	-	+	-	+	+	+	+
32	NIKNT	+*	+	+*	+*	+	-	+	-	-*	-	-*	-	+	-	-	-
33	SIKNT	+	+	+*	+*	-	-*	-	-	-*	-*	-*	-*	+	+	-	+
34	KERLA	+	+	+	+	-*	-*	-*	-	-	-	-	-	+	+	+	+
	All India	+*	+*	+*	+*	-	-	+	-	-*	-	-*	-	-	+	-	+
	P India	+*	+*	+*	+*	-*	-*	-*	-*	-	-	-*	-	+	+*	+*	+*
	WC India	+*	+	+*	+*	+*	-	+*	-	-*	-	-*	+	+	+	+	+
	CNE India	+*	+*	+*	+	+*	+	+*	+	-	-	-	-	-	-	-*	-
	NE India	+*	+	+*	+	+*	+	+*	+*	-*	+	-*	-	-*	-*	-*	-*
	NW India	+*	+	+*	+*	+*	+	+*	+	-	-	-	-	-	-	-	-

[a] and [m] represent average for May to December and for the entire year, respectively

+ and – (with green and red colors, respectively) denote positive and negative relationships, respectively

[*] (dark color shades) represent statistically significant relationship at 0.05 level

All = period between 1871 and 2016, Po1971 = period between 1971 and 2016. Serial numbers of sub-divisions are corresponding to Fig. 1. Sub-division names are given in abbreviated form

MRF Monsoon rainfall (JJAS), *PMRF* Post-monsoon rainfall (OND), *SOI* Southern Oscillation Index, *IODI* Indian Ocean Dipole Index

Table 4 Relationship of regional annual rainfall with SOI and IOD

Regions	Coefficient of correlation (r)							
	SOI^a – RF 1871–2016	SOI^m – RF 1871–2016	SOI^m – RF 1971–2016	IOD^a – RF 1871–2016	IOD^m – RF 1871–2016	IOD^m – RF 1971–2016	RF–($IOEN^m$) 1871–2016	RF–($IOEN^m$) 1971–2016
All India	**0.34**	**0.45**	**0.39**	**– 0.17**	**– 0.20**	0.13	**0.50**	**0.62**
Peninsular India	0.12	**0.22**	**0.21**	0.01	0.01	0.03	**0.58**	**0.41**
West Central India	**0.25**	**0.35**	**0.33**	– 0.14	– 0.15	0.12	**0.51**	**0.24**
Central NE India	**0.33**	**0.33**	**0.22**	**-0.20**	**– 0.21**	0.10	0.01	0.11
North East India	**0.17**	**0.24**	**0.19**	**– 0.19**	**– 0.24**	**0.18**	0.13	– 0.16
Northwest India	**0.28**	**0.39**	**0.35**	– 0.08	– 0.11	0.03	**0.55**	**0.62**

RF annual total rainfall, *a* annual mean; *m* average for May to December, Bold values indicate a statistically significant correlation (relationship) at 95% confidence level. + and – denote positive and negative relationships, respectively.

IOEN correlation (r) between IODI and SOI

positively associated with the SOI-IOD relationship, as all the regions show a significant inter-linkage, except CNEI and NEI Region (Table 4). Particularly, during the post-1971 period, about 38% of the variation in rainfall over India is explained by the SOI-IOD relationship. It signifies that the Indian Sub-continent receives a good amount of rainfall in the year with interlinked SO and IOD and vice-versa. Almost a comparable significant connection of rainfall over PI, WCI and NWI Regions with the SOI-IODI relationship is exhibited. However, the CNEI and NEI Regions were observed to be not associated with the strength of SOI-IODI bonding. It can also be noticed that the influence of this relationship is slightly reduced over PI and WCI Region during the last 50 years.

3.6 Relationship between rainfall and IOD

Figure 6 shows the sub-division wise correlation between annual rainfall and IOD. Most of the sub-divisions (about 75% of the area) exhibit a negative relationship between the two during 1871–2016. Almost comparable results can be observed with the monsoon rainfall (Table 3). Therefore, the IOD has a significant negative relationship with the annual and monsoon (JJAS) rainfall at All-India level (Tables 3 and 4). The monsoon rainfall over all the sub-divisions reveal a negative connection with IOD, except the Orissa and Gangetic West Bengal sub-divisions with the entire states of Madhya Pradesh, Bihar and Gujarat. It suggests that the IOD-positive phase (warmer SST of the western part of IO) is likely associated with below-average monsoon and annual rainfall over the Indian Sub-continent and vice-versa. The study undertaken by Wang et al. (2006) corroborates this finding. Moreover, this relationship plays a crucial role in extreme rainfall events over India during recent decades (Krishnaswami et al. 2015). The Orissa subdivision is solitary exception where the monsoon rainfall-IOD^m relationship is positive and significant (Table 3). Another observation can be made from Table 3 that this relationship is observed to be weakened after 1971, as about ~ 35% and 25% of area display significant connection before and after 1971, respectively. Particularly, the monsoon rainfall in Arunachal Pradesh, Eastern Uttar Pradesh, Uttarakhand, Himachal Pradesh, Marathwada, Coastal Andhra Pradesh, Telangana, Tamil Nadu and South Interior Karnataka Sub-divisions has a significant inverse connection with IOD^m during the last five decades (Table 3). The study conducted by Saha et al. (2021) observed comparable results over the NEI. This study signifies that the above-mentioned sub-divisions/regions experience mild to severe drought conditions during the positive phase (warmer SST of the Arabian Sea) of IOD and vice-versa. The study conducted by Kumar et al. (2013) concluded an almost comparable relationship. In the case of annual rainfall, the post-1971 period exhibits almost no relationship between IOD and AR over Gujarat, Eastern and Western Madhya Pradesh, Coastal Karnataka, Coastal Andhra Pradesh, Jammu and Kashmir, Jharkhand, Gangetic West Bengal, Konkan, Tamil Nadu and Kerala sub-divisions (Fig. 6). The results obtained from the study undertaken by Ashok and Saji (2007) and Hrudya et al. (2020) are in good agreement with this finding. Very likely due to this reason, the rainfall over PI, WCI, and NWI Regions do not show a significant connection with IOD (Table 4).

Although, the IOD has a significant negative relationship with the annual and monsoon rainfall (Table 4), it shows positive connection with post-monsoon rainfall (Table 3), particularly after-1971 (Table 3). As the majority of sub-divisions in PI Region are observed with positive relationship with IOD, it indicates that the region receives excess post-monsoon (OND) rainfall during the positive phase of IOD (warmer SST of Arabian Sea). The study carried out by Kripalani and Kumar (2004) corroborates this fact. The results suggest that the contradictory influence of IOD on

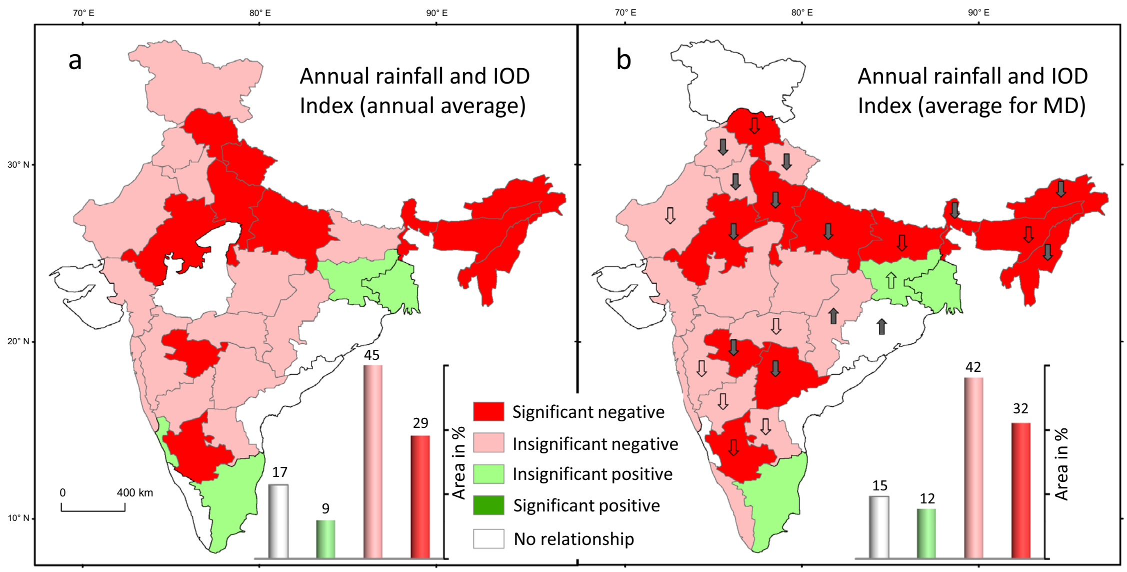

Fig. 6 Relationship of sub-divisional annual rainfall with a) annual average IOD and b) May to December average IOD. The upward and downward arrows represent positive and negative relationships, respectively, during 1971–2016. The gray solid arrows denote significant relationship at 95% confidence level. The arrows are not shown for the sub-divisions with marginal/no correlation during post-1971 period. MD = May to December

monsoon and post-monsoon rainfall has weaken the IOD-AR relationship at sub-divisional (Tamil Nadu, Kerala, Rayalaseema and Coastal Andhra Pradesh) (Fig. 6b) and regional (PI and WCI) levels as well (Table 4). The study undertaken by Nageswararao et al. (2019) observed that the NEM rainfall has a weakened connection with IOD, Particularly after 1988. The regional inconsistency in influence of IOD observed in the present investigation may have caused this. Among all the regions, CNEI, NEI and NWI exhibit negative relationship. Among them, this relationship is significant over the NEI. It signifies that these regions receive considerably below-average post-monsoon rainfall in the positive phase of IOD (Table 3). Another observation that can be made from Fig. 6 and Table 3 is that there is no substantial difference in the strength and coverage of rainfall relationship (sub-divisional and regional) with IOD^a and average IOD^m. The result of the Student's t test supports this finding (see Table 4).

3.7 All-India annual rainfall, IOD and SOI inter-connections

The SST anomalies over the Indo-Pacific Sector and the Indian rainfall have intricate relationships. The scientific studies have divergent findings in this regard. It is argued that the ocean–atmosphere interactions in the Indian Ocean are influenced by ocean dynamics (Iizuka et al., 2000) and the phenomenon of IOD is completely independent of external forces (Webster et al. 1999; Saji et al. 1999) such as ENSO. The phases in dipole mode are chiefly determined by the inherent processes within a basin (Behera et al., 2006). On the contrary, the group of investigations (Krishnamurthy and Kirtman 2003; Li et al. 2003; Huang and Shukla 2007; Zhang et al. 2015; Kajtar et al. 2016) reported a considerable influence of SO on the IOD. The present study observed that the SOI and IODI have a significant negative correlation during 1871–2016, albeit the strength of the relationship fluctuates notably (Fig. 7a). It denotes that the positive phase of IOD (warmer SST of the Arabian Sea) is associated with negative SOI (mild to severe El Niño) events and vice-versa. The variations in this relationship reveal episodic behavior, which is perhaps caused due to amplified Walker circulation after 1970 (Yuan and Li 2008). The phases of notably strong connections are registered during 1897–1940 and 1988–2005, whereas it is weakened between 1943 and 1985. The recent weakening phase is started after 2007, which is associated with the development of different spatial patterns in SOI (Ham et al. 2017). Apart from this, the link between the IOD and tropical Pacific climate was associated with the modulation of Walker circulation connecting the tropical Indian Ocean and tropical Pacific, where heat is transferred between these regions. These impacts enhance the responses of winter tropical Pacific SST and surface zonal winds to IOD. In addition, the IOD impacts were also tied to the SST anomalies in large parts of the tropical Pacific during the boreal summer and fall, demonstrating the significant impact of the IOD on the development phase of ENSO (Le et al., 2020). The ENSO inter-annual variability has likely been forced by changes in the IOD since 1950, indicating the necessity of considering Indian Ocean forcing to improve

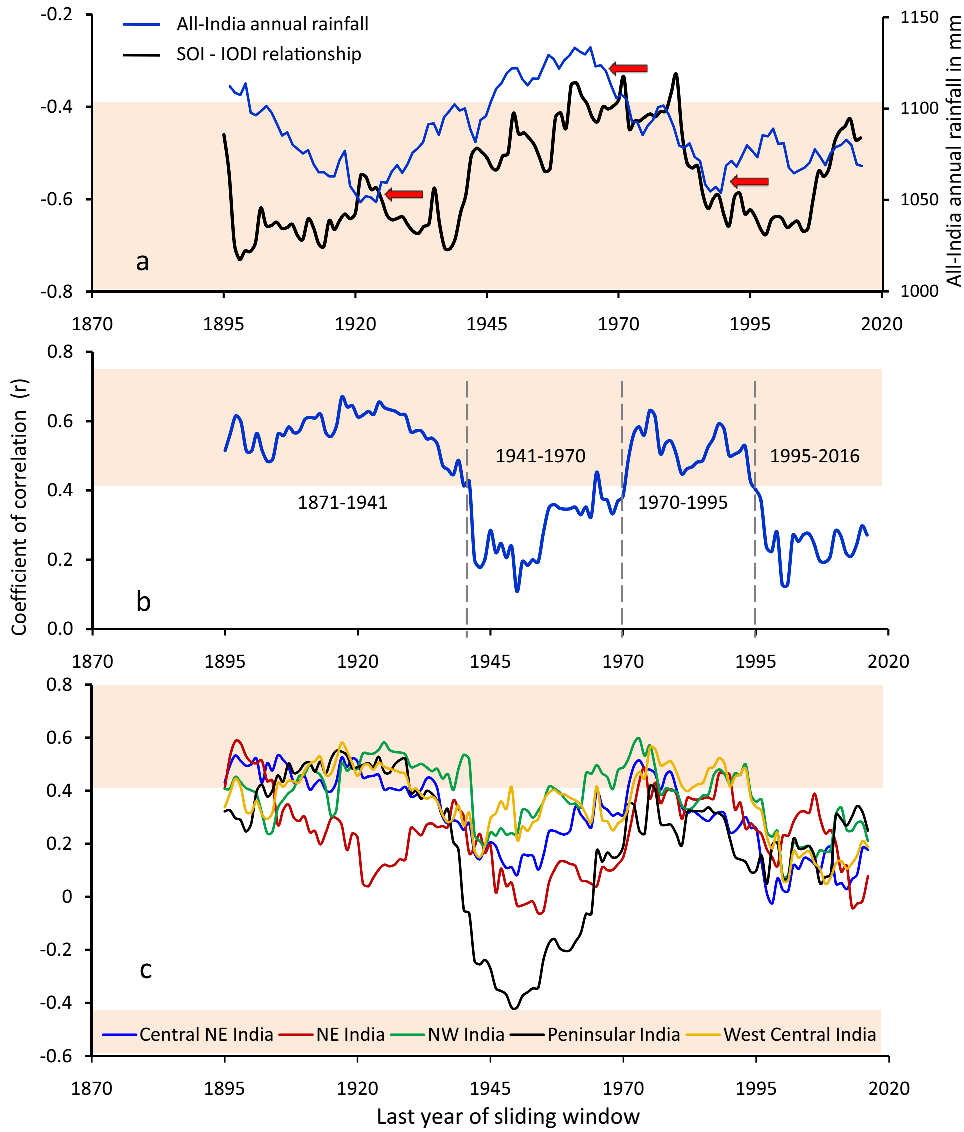

Fig. 7 Temporal variations in a 25-years moving correlation coefficient between a) SOI and IOD Index b) SOI and All-India annual rainfall c) region wise temporal variations is SOI-AR relationships. Pink bands highlight a statistically significant correlation coefficient at 95% confidence level (n = 25). Red arrows show a lag in rainfall series. All-India annual rainfall is the 25-years moving average data series. SOI and IOD data series are annual averages from May to December

ENSO predictability. Thus, the effects of the IOD on ENSO and the tropical Pacific might be more significant in the recent periods with an increase in variability of the eastern Pacific El Niño (Cai et al., 2018) due to greenhouse warming, it may stronger impacts of eastern Pacific El Niño on the IOD in the future. Hence, further studies related to the causal interactions between eastern Pacific ENSO and the IOD are necessary. Figure 7a shows that the annual rainfall over India (lag by 10 years) directly follows the SO-IOD relationship. This connection ($r^2 = 0.74$) is observed to be significant at 99% confidence level during 1930–2010. In addition to this, Table 4 also confirms that the regional (except NEI and CNEI) and All-India Level rainfall has a considerable influence of the SO-IOD relationship. It signifies that the stronger linkage in SO and IOD resulted in good rainfall over India and vice-versa.

A temporal fluctuation in the ENSO/SOI–rainfall relationship is an indispensable factor in the monsoon forecast (Webster et al. 1998; Shi and Wang 2019). The SOI and AR relationship is observed to be positive during the last 145 years (Fig. 7b). It implies that the negative SOI years (warmer SST of central/western Pacific Ocean) are associated with below-average rainfall over India and vice-versa. Therefore, the Indian Sub-continent is considerably vulnerable to drought conditions during moderate to extreme El Niño events (Kumar et al. 2006a). Apart from this, the present investigation confirmed that the strength of the SOI-AR over India relationship is not uniform during the last 146 years (Fig. 7b). Non-stationarity in this relationship may attribute to greenhouse gases and aerosols (Wittenberg et al. 2014). The cyclic variations in the SOI-AR relationship (Fig. 7b) denote that these changes are not due to global warming (Ashrit et al. 2001). Apart from this, Kumar et al.

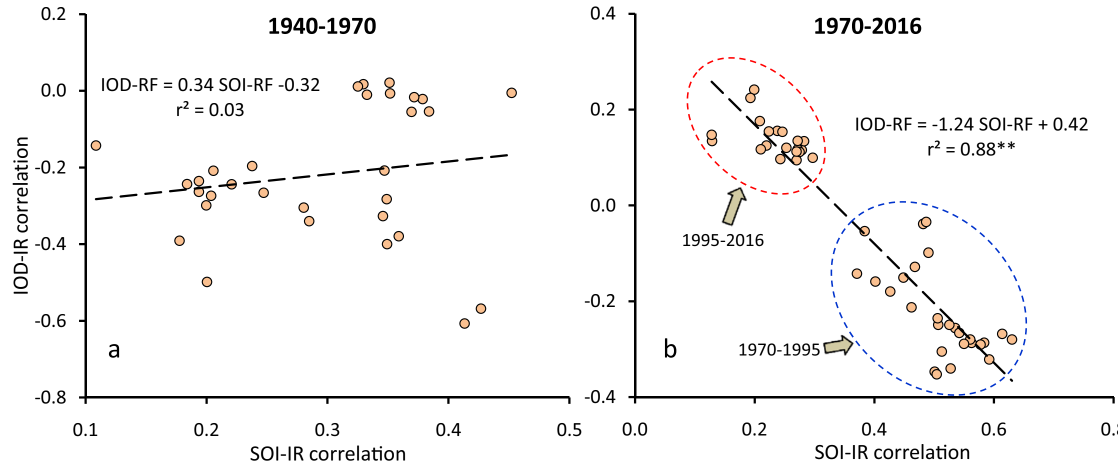

Fig. 8 Linear relationship between IOD-IR (correlation) and SOI-IR (correlation) during a) 1940–1970 and b) 1970–2016 (refer Fig. 7b). SOI and IOD data series are annual average from May to December. IR = Indian annual rainfall, ** denotes statistically significant relationships at 99% confidence level. Observations in blue and red ovals represent strong and weak SOI-IR connections, respectively

(1999) mentioned that the anomalous Walker circulation in the upper troposphere is a decisive bridge through which the tropical central-eastern Pacific SST anomalies are associated with ENSO and influence ISMR remotely. However, the almost unchanged Walker circulation anomalies in the upper troposphere and the apparent shift in 850-hPa wind anomalies imply that the SSTAs in other tropical oceans associated with ENSO might contribute to the inter-decadal shift of the ENSO–ISMR relationship through lower troposphere systems. It can be observed that there are two episodes (1871–1941 and 1970–1995) with a statistically significant SOI-AR relationship. During these periods, ENSO/SOI was one of the important drivers of the Indian monsoon. However, this connection was weakened between 1941 and 1970 and between 1995 and 2016 (Fig. 7b). During these epochs, the coefficient of correlation declined notably, which is not significant. The recent (1995–2016) weakening of the SOI-AR relationship is very likely attributed to human-induced warming (Ashrit et al. 2001) and inter-decadal inflections (Feba et al. 2019; Krishnamurthy and Krishnamurthy 2014). Consideration of such a weak connection in monsoon forecast is irrational and affects the predictability of the model. The temporal variations in the relationship between regional rainfall and SOI can be noticed in Fig. 7c. Broadly, all the regions, except PI, mimic the temporal pattern in the strength of the SOI–rainfall relationship at the All India level. The rainfall over PI Region was observed to be weakly associated with SOI, particularly after 1925 (Fig. 7c). It should be noted that this region witnessed switching of positive relationship into negative during 1940–1965, although it is not statistically significant.

The SOI-AR over India relationship is not consistent between 1940 and 2016. Each of the periods mentioned in Fig. 8 (1940–1970 and 1970–2016) has two epochs of the SOI-AR relationship (phases of weak and strong connection) (Fig. 7b). The previous studies (Yun and Timmermann 2018; Yuan and Li 2008) support these results. However, the inter-decadal variations in SOI-ISMR may be caused due to the zonal shift in the center of ENSO (Fan et al. 2017) and the effect of global warming (Azad and Rajeevan 2016). This investigation emphasizes that the SOI and IOD are the major tropical phenomena in the Indo-Pacific sector, which play a modulator of Indian rainfall, particularly during the post-1970 period. Interestingly, this connection has not existed during 1940–1970 (Fig. 8a). The SOI-AR relationship has a significant inverse connection with the IOD-AR relation after 1970 (Fig. 7b). It signifies that the weakening of the SOI-AR relationship is associated with strengthening the IOD-AR relationship and vice-versa. Therefore, this study confirms the observed effects of IOD-AR relationships on SOI-AR connection highlighted by Ashok et al. (2001), Sarkar et al. (2004), Gadgil et al. (2004) Anil et al. (2016) and Behera and Ratnam (2018). The Indian Rainfall is mainly affected by the low-level circulation and moisture transport over the equatorial Indian Ocean and sea surface changes during the recent positive and negative phases of IOD (Hrudya et al. 2020). Moreover, region-wise asymmetric effects on rainfall are observed during these phases of IOD (Behera and Ratnam 2018). Apart from this, under the current climate change scenario, IOD-induced variability in Indian Rainfall may increase (Abram et al. 2008). Therefore, the finding that emerged from the present investigation has notable implications in the monsoon forecast. Particularly, during weak SOI-AR relations, the IOD-AR relationship would be the practical substitute for precise monsoon predictions. It should be noted that this study has not conducted a numerical experiment to understand the separate or joint impact of ENSO and IOD. However, Shen et al., (2021) conducted numerical experiments to verify the effects of IOD and ENSO. Based on these simulation experiments, we may able to further verify the individual or joint roles of IOD and ENSO.

4 Limitations of the study

Although this study highlights various dimensions in rainfall over India and its connections with SO and IOD, it has some limitations as follows:

- The study has not carried out an analysis to explain the physical mechanism behind the trends and temporal variations in relationships of rainfall with SO and IOD.
- As the investigation intended to provide a generalized picture of seasonal and annual variability in Indian rainfall and its drives, monthly trends and relationships are not considered.
- To separate the impact of ENSO and IOD or other forcing, the investigation has not conducted a numerical experiment.

5 Summary and Conclusion

The present investigation highlights decline in annual rainfall over majority of sub-divisions in the Indian subcontinent, which intensified during the last 5 decades. Particularly, the NEI and CNEI regions have experienced a significant reduction in annual rainfall. This decline is mainly attributed to the decrease in monsoon rainfall after 1971. The NEI region registered significant and rapid reduction in precipitation, as the monsoon and post-monsoon rainfall as well observed to be declined considerably. Therefore, to cope with upcoming water scarcity, these regions seek special attention of hydrologists, water resources managers and agronomists. The study also highlights an interesting feature in seasonal rainfall that the post-monsoon rainfall is decreased over all the regions of India. PI Region is the solitary exception where the post-monsoon rainfall registered increase. Apart from this, the IOD influences the SOI-AR relationship and the positive phase of IOD is associated with below-average rainfall over India. The present study detected a considerable increase in IODI during the post-1960 period. Therefore, it can be state that the continuous warming of the Indian Ocean Sea Surface (western part) along with temperature rise may augment the rainfall variability and eventually aggravate the water scarcity challenge in India. In this context, the semi-arid regions (about 38% area) in India which are characterized by low annual precipitation will be more vulnerable.

This investigation emphasized that the SO is the prime influencing factor, as the SOI has a remarkable linkage with rainfall (annual, monsoon and post-monsoon) over India as compared IOD. The study underlined a significant positive relationship between rainfall and SOI. As about 80% of sub-divisions show positive connection between SOI and monsoon rainfall, almost a comparable picture is observed in the case of annual rainfall. The observed weakening of SOI-AR relationship over the NEI and CNEI Regions may have resulted in weakening of SOI-AR connection at All-India level, especially during the last few decades. However, it is interesting to note that majority of the sub-divisions from the PI Region has negative connection between post-monsoon rainfall and SOI. It points out the need to separately investigate the most relevant and influential factor for precise rainfall predictions over Northeast Monsoon rainfall region. Moreover, it is also validated that the SOI^m can provide comparatively precise estimations of rainfall (particularly, monsoon rainfall) over the Indian subcontinent.

Nevertheless, perhaps due to orbital variations, greenhouse gases and aerosols, the SOI-AR relationship has epochs of a weak and strong relationship. The study provides important observation that very likely due to the exactly opposite relationships (positive and negative) of monsoon and post-monsoon rainfall, respectively, with SOI, the annual rainfall over PI Region shows comparatively weaker connection with SOI. The study deciphered that the IOD-AR relationship is another factor that inversely affects the SOI-AR relationship. The strengthening of the IOD-AR relationship is mainly responsible for the weakening of the SOI-AR connection. This influential connection came into existence after 1970. Apart from this, the strength of the relationship between SOI and IOD fluctuates notably. Strengthening of this relationship is positively associated with the annual rainfall, which is another facet of SOI-IODI-AR inter-linkage. Although, this relationship has marginal influence on the AR over CNEI and NEI Regions, the variations in strength of SO-IOD connection modulate the AR over PI, WCI, NWI and All-India regions to the considerable extent. Therefore, it is advisable to confirm the strength of these relationships before assigning weightage to SO, IOD and the SO-IOD inter-connection in the monsoon forecast. Particularly, during the phase of weak SOI-AR relation, the IOD-AR and SO-IOD relationships could be good substitute for a precise rainfall forecast.

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Declaration

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References

Abish B, Cherchi A, Ratna SB (2018) ENSO and the recent warming of the Indian Ocean. Int J Climatol 38:203–214. https://doi.org/10.1002/joc.5170

Abram NJ, Gagan MK, Cole JE, Hantoro WS, Mudelsee M (2008) Recent intensification of tropical climate variability in the Indian Ocean. Nat Geosci 1:849–853. https://doi.org/10.1038/ngeo357

Anil N, Ramesh Kumar MR, Sajeev R, Saji PK (2016) Role of distinct flavours of IOD events on Indian summer monsoon. Nat Hazards 82:1317–1326. https://doi.org/10.1007/s11069-016-2245-9

Annamalai H, Hafner J, Sooraj KP, Pillai P (2013) Global warming shifts the monsoon circulation, drying South Asia. J Clim 26:2701–2718. https://doi.org/10.1175/JCLI-D-12-00208.1

Anteneh ZA, MelesseAM, Seyoum WM, Abtew W (2019) Drought and climate teleconnection and drought monitoring. In: Melesse AM, Abtew W (ed). Gabriel Senay, Extreme Hydrology and Climate Variability, Elsevier, 2019, pp 275–295. doi:https://doi.org/10.1016/B978-0-12-815998-9.00022-1

Ashok K, Saji NH (2007) On the impacts of ENSO and Indian Ocean dipole events on sub-regional Indian summer monsoon rainfall. Nat Hazards 42:273–285. https://doi.org/10.1007/s11069-006-9091-0

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. https://doi.org/10.1029/2001GL013294

Ashok K, Wing-Le C, Tatsuo M, Yamagata T (2004a) Decadal variability of the Indian Ocean dipole. Geophys Res Lett. https://doi.org/10.1029/2004GL021345

Ashok K, Guan Z, Saji NH, Yamagata T (2004b) Individual and combined influences of ENSO and the Indian Ocean dipole on the Indian summer monsoon. J Clim 17:3141–3155. https://doi.org/10.1175/1520-0442(2004)017%3c3141:IACIOE%3e2.0.CO;2

Ashok K, Behera SK, Rao SA, Weng H, Yamagata T (2007) El Nin˜o Modoki and its possible teleconnection. J Geophys Res. https://doi.org/10.1029/2006JC003798

Ashok K, Sabin TP, Swapna P, Murtugudde RG (2012) Is a global warming signature emerging in the tropical Pacific? Geophys Res Lett. https://doi.org/10.1029/2011GL050232

Ashrit RG, Kumar R, Krishna Kumar K (2001) ENSO-monsoon relationship in a greenhouse warming scenario. Geophys Res Lett 28:1727–1730. https://doi.org/10.1029/2000GL012489

Azad S, Rajeevan M (2016) Possible shift in the ENSO-Indian monsoon rainfall relationship under future global warming. Sci Rep 6:1–6. https://doi.org/10.1038/srep20145

Behera SK, Ratnam JV (2018) Quasi-asymmetric response of the Indian summer monsoon rainfall to opposite phases of the IOD. Sci Rep 8:1–8. https://doi.org/10.1038/s41598-017-18396-6

Behera SK, Luo JJ, Masson S et al (2006) A CGCM study on the interaction between IOD and ENSO. J Clim 19:1688–1705. https://doi.org/10.1175/JCLI3797.1

Bollasina MA, Ming Y, Ramaswamy V (2011) Anthropogenic aerosols and the weakening of the South Asian summer monsoon. Science 334:502–505. https://doi.org/10.1126/science.1204994

Bracco A, Kucharski F, Molteni F, Hazeleger W, Severijns C (2007) A recipe for simulating the interannual variability of the Asian summer monsoon and its relation with ENSO. Clim Dyn 28:441–460

Cai W, Wang G, Dewitte B et al (2018) Increased variability of eastern Pacific El Niño under greenhouse warming. Nature 564(7735):201–206. https://doi.org/10.1038/s41586-018-0776-9

CDKN (2014) What's in it for South Asia?, Climate and Development Knowledge Network, The IPCC's Fifth Assessment Report (2014): Available at http://cdkn.org/wp-content/uploads/2014/04/CDKN-IPCC-Whats-in-it-forSouth-Asia-AR5.pdf (Accessed on 19 December 2016).

Das PK, Dutta D, Sharma JR, Dadhwal VK (2016) Trends and behaviour of meteorological drought (1901–2008) over Indian region using standardized precipitation–evapotranspiration index. Int J Climatol 36:909–916. https://doi.org/10.1002/joc.4392

Dong L, McPhaden MJ (2016) Interhemispheric SST gradient trends in the Indian ocean prior to and during the recent global warming hiatus. J Clim 29:9077–9095. https://doi.org/10.1175/JCLI-D-16-0130.1

Dong L, Zhou T (2014) The indian ocean sea surface temperature warming simulated by CMIP5 models during the twentieth century: Competing forcing roles of GHGs and anthropogenic aerosols. J Clim 27:3348–3362. https://doi.org/10.1175/JCLI-D-13-00396.1

Dong G, Zhang H, Moise A, Hanson L, Liang P, Ye H (2016) CMIP5 model-simulated onset, duration and intensity of the Asian summer monsoon in current and future climate. Clim Dyn 46:355–382. https://doi.org/10.1007/s00382-015-2588-z

Du Y, Xie SP (2008) Role of atmospheric adjustments in the tropical Indian Ocean warming during the 20th century in climate models. Geophys Res Lett 35:L08712. https://doi.org/10.1029/2008GL033631

Fan F, Dong X, Fang X et al (2017) Revisiting the relationship between the South Asian summer monsoon drought and El Niño warming pattern. Atmos Sci Lett 18:175–182. https://doi.org/10.1002/asl.740

Feba F, Ashok K, Ravichandran M (2019) Role of changed Indo-Pacific atmospheric circulation in the recent disconnect between the Indian summer monsoon and ENSO. Clim Dyn 52:1461–1470. https://doi.org/10.1007/s00382-018-4207-2

Gadgil S, Vinayachandran PN, Francis PA, Gadgil S (2004) Extremes of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean Oscillation. Geophys Res Lett. https://doi.org/10.1029/2004GL019733

GoI (2020) (Government of India) Chapter VII: Agriculture and food management, In: Economic Survey of India 2019–20, https://www.indiabudget.gov.in/economicsurvey/doc/vol2chapter/echap07_vol2.pdf
Guhathakurta P, Rajeevan M (2008) Trends in the rainfall pattern over India. Int J Climatol 28:1453–1469. https://doi.org/10.1002/joc.1640
Guhathakurta P, Rajeevan M, Sikka DR, Tyagi A (2015) Observed changes in southwest monsoon rainfall over India during 1901–2011. Int J Climato 135:1881–1898. https://doi.org/10.1002/joc.4095
Guhathakurta P, Menon P, Inkane PM, Krishnan U, Sable ST (2017) Trends and variability of meteorological drought over the districts of India using standardized precipitation index. J Earth Syst Sci 126:120. https://doi.org/10.1007/s12040-017-0896-x
Ham Y, Choi J, Kug J (2017) The weakening of the ENSO–Indian Ocean Dipole (IOD) coupling strength in recent decades. Clim Dyn 49:49–261. https://doi.org/10.1007/s00382-016-3339-5
Hrudya PPVH, Varikoden H, Vishnu RN (2020) Changes in the relationship between Indian Ocean dipole and Indian summer monsoon rainfall in early and recent multidecadal epochs during different phases of monsoon. Int J Climatol 41:E305–E318. https://doi.org/10.1002/joc.6685
Hrudya PH, Varikoden H, Vishnu R (2021) A review on the Indian summer monsoon rainfall, variability and its association with ENSO and IOD. Meteorol Atmos Phys 133:1–14. https://doi.org/10.1007/s00703-020-00734-5
Huang B, Shukla J (2007) Mechanisms for the interannual variability in the tropical Indian Ocean. Part I: The role of remote forcing from the tropical pacific. J Clim 20:2917–2936
Iizuka S, Matsuura T, Yamagata T et al (2000) The Indian Ocean SST dipole simulated in a coupled general circulation model. Geophys Res Lett 27:3369–3372. https://doi.org/10.1029/2000GL011484
Jain SK, Kumar V (2012) Trend analysis of rainfall and temperature data for India. Curr. Sci. Jan: 37–49. https://www.jstor.org/stable/24080385
Joshi N, Gupta D, Suryavanshi S, Adamowski J, Madramootoo CA (2016) Analysis of trends and dominant periodicities in drought variables in India: a wavelet transform based approach. Atmos Res 182:200–220. https://doi.org/10.1016/j.atmosres.2016.07.030
Kajtar JB, Santoso A, England MH, Cai W (2016) Tropical climate variability: interactions across the Pacific, Indian, and Atlantic Oceans. Clim Dyn 48:2173–2190. https://doi.org/10.1007/s00382-016-3199-z
Kamil S, Almazroui M, Kucharski F, Kang IS (2017) Multidecadal changes in the relationship of storm frequency over Euro-Mediterranean region and ENSO during boreal winter. Earth Syst Environ 1:1–10. https://doi.org/10.1007/s41748-017-0011-0
Konwar M, Parekh A, Goswami BN (2012) Dynamics of east-west asymmetry of Indian summer rainfall trends in recent decades. Geophys Res Lett. https://doi.org/10.1029/2012GL052018
Kripalani RH, Kulkarni A (1997) Rainfall variability over South-east Asia—connections with Indian monsoon and ENSO extremes: new perspectives. Int J Climatol 17:1155–1168. https://doi.org/10.1002/(SICI)1097-0088(199709)17:11%3c1155::AID-JOC188%3e3.0.CO;2-B
Kripalani RH, Kulkarni A (1999) Climatological impact of El Nino on the Indian monsoon: a new perspective. Weather 52:39–46. https://doi.org/10.1002/j.1477-8696.1997.tb06267.x
Kripalani RH, Kumar P (2004) Northeast monsoon rainfall variability over south peninsular India vis-à-vis the Indian Ocean dipole mode. Int J Climatol 24:1267–1282. https://doi.org/10.1002/joc.1071
Krishna Kumar K, Rupa Kumar K, Ashrit RG, Deshpande NR, Hansen JW (2004) Climate impacts on Indian agriculture. Int J Climatol 24:1375–1393. https://doi.org/10.1002/joc.1081
Krishnakumar KN, Prasada Rao GSLHV, Gopakumar CS (2009) Rainfall trends in twentieth century over Kerala, India. Atmos Environ 43:1940–1944. https://doi.org/10.1016/j.atmosenv.2008.12.053
Krishnamurthy V, Kirtman BP (2003) Variability of the Indian Ocean: Relation to monsoon and ENSO. Q J R Meteorol Soc 129:1623–1646. https://doi.org/10.1256/qj.01.166
Krishnamurthy L, Krishnamurthy V (2014) Influence of PDO on South Asian summer monsoon and monsoon-ENSO relation. Clim Dyn 42:2397–2410. https://doi.org/10.1007/s00382-013-1856-z
Krishnaswami J, Vaidyanathan S, Rajagopalan B, Bonnel M, Sankaran M, Bhalla RS, Badiger S (2015) Non-stationary and non-linear influence of ENSO and Indian Ocean Dipole on Indian summer monsoon rainfall and extreme rain events. Clim Dyn 45:174–185. https://doi.org/10.1007/s00382-014-2288-0
Kulkarni A (2012) Weakening of Indian summer monsoon rainfall in warming environment. Theor Appl Climatol 109:447–459. https://doi.org/10.1007/s00704-012-0591-4
Kumar V, Jain SK (2011) Trends in rainfall amount and number of rainy days in river basins of India (1951–2004). Hydrol Res 42:290–306. https://doi.org/10.2166/nh.2011.067
Kumar KK, Rajagopalan B, Cane MA (1999) On the weakening relationship between the indian monsoon and ENSO. Science 284:2156–2159. https://doi.org/10.1126/science.284.5423.2156
Kumar KK, Rajagopalan B, Hoerling M, Bates G, Cane M (2006a) Unraveling the mystery of Indian monsoon failure during El Niño. Science 314:115–119. https://doi.org/10.1126/science.1131152
Kumar P, Rupa Kumar K, Rajeevan M, Sahai AK (2006b) On the recent strengthening of the relationship between ENSO and northeast monsoon rainfall over South Asia. Clim Dyn 28:649–660. https://doi.org/10.1007/s00382-006-0210-0
Kumar V, Jain SK, Singh Y (2010) Analysis of long-term rainfall trends in India. Hydrol Sci J 55:484–496. https://doi.org/10.1080/02626667.2010.481373
Kumar KN, Rajeevan M, Pai DS, Srivastava AK, Preethi B (2013) On the observed variability of monsoon droughts over India. Weather Clim Extremes 1:42–50. https://doi.org/10.1016/j.wace.2013.07.006
Kundzewicz ZW, Robson A (2000) Setting the scene, In: Kundzewicz ZW, Robson A (eds), Detecting Trend and Other Changes in Hydrological Data. World Climate Program – Water, WMO/UNESCO, WCDMP-45, WMO/TD 1013, Geneva, pp. 1–5.
Lacombe G, McCartney M (2014) Uncovering consistencies in Indian rainfall trends observed over the last half century. Clim Chang 123:287–299. https://doi.org/10.1007/s10584-013-1036-5
Le T, Ha KJ, Bae DH, Kim SH (2020) Causal effects of Indian Ocean Dipole on El Niño-Southern Oscillation during 1950–2014 based on high-resolution models and reanalysis data. Environ Res Lett 15:1040b6. https://doi.org/10.1088/1748-9326/abb96d
Li T, Wang B, Chang CP, Zhang Y (2003) A theory for the Indian Ocean dipole-zonal mode. J Atmos Sci 60:2119–2135. https://doi.org/10.1175/1520-0469(2003)060%3c2119:ATFTIO%3e2.0.CO;2
Mall RK, Gupta A, Singh R, Singh RS, Rathore LS (2006) Water resources and climate change: An Indian perspective. Curr Sci June: 1610–1626. https://www.jstor.org/stable/24091910
Mayer M, Trenberth KE, Haimberger L, Fasullo JT (2013) The response of tropical atmospheric energy budgets to ENSO. J Clim 26:4710–4724. https://doi.org/10.1175/JCLI-D-12-00681.1
Nageswararao MM, Sannan MC, Mohanty UC (2019) Characteristics of various rainfall events over South Peninsular India during northeast monsoon using high-resolution gridded dataset (1901–2016). Theor Appl Climatol 137:2573–2593. https://doi.org/10.1007/s00704-018-02755-y
Naidu CV, Durgalakshmi K, Krishna KM et al (2009) Is summer monsoon rainfall decreasing over India in the global warming era? J Geophys Res Atmos. https://doi.org/10.1029/2008JD011288

Pai DS, Sridhar L, Guhathakurta P, Hatwar HR (2011) District-wide drought climatology of the southwest monsoon season over India based on standardized precipitation index (SPI). Nat Hazards 59:1797–1813. https://doi.org/10.1007/s11069-011-9867-8

Pai DS, Sridhar L, Rajeevan M et al (2014) Development of a new high spatial resolution (0.25° × 0.25°) long period (1901–2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region. Mausam 65:1–18

Pal I, Al-Tabbaa A (2011) Assessing seasonal precipitation trends in India using parametric and non-parametric statistical techniques. Theor Appl Climatol 103:1–11. https://doi.org/10.1007/s00704-010-0277-8

Pokhrel S, Chaudhari HS, Saha SK, Dhakata A, Yadav RK, Salenke K, Mahaptra S, Rao SA (2012) ENSO, IOD and Indian summer monsoon in the NCEP climate forecast system. Clim Dyn. https://doi.org/10.1007/s00382-012-1349-5

Praveen B, Talukdar S, Shahfahad et al (2020) Analyzing trend and forecasting of rainfall changes in India using non-parametrical and machine learning approaches. Sci Rep 10:1–21. https://doi.org/10.1038/s41598-020-67228-7

Rao SA, Dhakate AR, Saha SK et al (2012) Why is Indian Ocean warming consistently? Clim Change 110:709–719. https://doi.org/10.1007/s10584-011-0121-x

Ropelewski CF, Jones PD (1987) An extension of the tahiti-darwin Southern scillation index. Mon Weather Rev 115:2161–2165. https://doi.org/10.1175/1520-0493(1987)115%3C2161%3AAEOTTS%3E2.0.CO%3B2

Roxy MK, Ritika K, Terray P, Masson S (2014) The curious case of Indian Ocean warming. J Clim 27:8501–8509. https://doi.org/10.1175/JCLI-D-14-00471.1

Roxy MK, Ritika K, Terray P, Murtugudde R, Ashok K, Goswami BN (2015) Drying of Indian subcontinent by rapid IndianOcean warming and a weakening land-sea thermal gradient. Nat Commun 6:7423. https://doi.org/10.1038/ncomms8423

Roy I, Tedeschi RG, Collins M (2017) ENSO teleconnections to the Indian summer monsoon in observations and models. Int J Climato l37:1794–1813. https://doi.org/10.1002/joc.4811

Saha K, Guha A, Banik T (2021) Indian summer monsoon variability over North-East India: Impact of ENSO and IOD. J Atmos Solar-Terrestrial Phys 221:105705. https://doi.org/10.1016/j.jastp.2021.105705

Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian Ocean. Nature 401:360–363. https://doi.org/10.1038/43854

Samanta D, Rajagopalan B, Karnauskas KB, Zhang L, Goodkin NF (2020) La Niña's diminishing fingerprint on the central Indian summer monsoon. Geophys Res Lett 47:e2019GL086237. https://doi.org/10.1029/2019GL086237

Sarkar S, Singh RP, Kafatos M (2004) Further evidences for the weakening relationship of Indian rainfall and ENSO over India. Geophys Res Lett. https://doi.org/10.1029/2004GL020259

Shen H, Gong Z, Liu B et al (2021) Remote Effects of IOD and ENSO on motivating the atmospheric pattern favorable for snowfall over the tibetan plateau in early winter. Front Clim 3:694384. https://doi.org/10.3389/fclim.2021.694384

Shi H, Wang B (2019) How does the Asian summer precipitation-ENSO relationship change over the past 544 years? Clim Dyn 52:4583–4598. https://doi.org/10.1007/s00382-018-4392-z

Singh OP, Ali Khan TM, Rahman S (2002) Impact of Southern Oscillation on the frequency of monsoon depressions in the Bay of Bengal. Nat Hazards 25:101–115. https://doi.org/10.1023/A:1013736923929

Singh P, Kumar V, Thomas T, Arora M (2008) Changes in rainfall and relative humidity in river basins in northwest and central India. Hydrol Process 22:2982–2992. https://doi.org/10.1002/hyp.6871

Singh N, Sontakke NA, Singh HN, Pandey AK (2005) Recent trend in spatiotemporal variation of rainfall over India an investigation into basin-scale rainfall fluctuations. In: Franks S, Wagener T, Bogh E, Gupta HV, Bastidas L, Nobre C, Galvao C (eds). Regional hydrological impacts of climatic change-hydroclimatic variability. Brazil, LAHS Publication 296, pp 273–282.

Surendran S, Gadgil S, Francis PA, Rajeevan M (2015) Prediction of Indian rainfall during the summer monsoon season on the basis of links with equatorial Pacific and Indian Ocean climate indices. Environ Res Lett 10:094004. https://doi.org/10.1088/1748-9326/10/9/094004

Todmal RS (2019) Droughts and Agriculture in the Semi-Arid Region of Maharashtra, Western India. Weather Clim Soc 11:741–754. https://doi.org/10.1175/WCAS-D-18-0131.1

Todmal RS (2022) Link between monsoon rainfall variability and agricultural drought in the semi-arid region of Maharashtra. India Curr Sci 122:934–944. https://doi.org/10.18520/cs/v122/i8/934-944

Ummenhofer CC, Sen Gupta A, Lil Y, Taschetto AS, England MH (2011) Multi-decadal modulation of the El Niño-Indian monsoon Relationship by Indian Ocean variability. Environ Res Lett. https://doi.org/10.1088/1748-9326/6/3/03400l6

Varikoden H, Revadekar JV, Choudhary Y, Preethi B (2015) Droughts of Indian summer monsoon associated with El Niño and Non-El Niño years. Int J Climato 135:1916–1925. https://doi.org/10.1002/joc.4097

Varikoden H, Revadekar JV, Kuttippurath J et al (2019) Contrasting trends in southwest monsoon rainfall over the Western Ghats region of India. Clim Dyn 52:4557–4566. https://doi.org/10.1007/s00382-018-4397-7

Wang X, Li C, Zhou W (2006) Interdecadal variation of the relationship between Indian rainfall and SSTA modes in the Indian Ocean. Int J Climatol 26:595–606. https://doi.org/10.1002/joc.1283

Webster PJ, Magana VO, Palmer TN, Shukla J, Tomas RA, Yanai MU, Yasunari T (1998) Monsoons: Processes, predictability, and the prospects for prediction. J Geophys Res 3:14451–14510. https://doi.org/10.1029/97JC02719

Webster PJ, Moore AM, Loschnigg JP, Leben RR (1999) Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997–98. Nature 401:356–360. https://doi.org/10.1038/43848

Wittenberg AT, Rosati A, Delworth TL, Vecchi GA, Zeng F (2014) ENSO modulation: is it decadally predictable? J Clim 27:2667–2681. https://doi.org/10.1175/JCLI-D-13-00577.1

Yuan Y, Li C (2008) Decadal variability of the IOD-ENSO relationship. Sci Bull 53:1745–1752. https://doi.org/10.1007/s11434-008-0196-6

Yun KS, Timmermann A (2018) Decadal Monsoon-ENSO Relationships Reexamined. Geophys Res Lett 45:2014–2021. https://doi.org/10.1002/2017GL076912

Zhang W, Wang Y, Jin FF et al (2015) Impact of different El Niño types on the El Niño/IOD relationship. Geophys Res Lett 42:8570–8576. https://doi.org/10.1002/2015GL065703

Zubair L, Ropelewski CF (2006) The strengthening relationship between ENSO and northeast monsoon rainfall over Sri Lanka and southern India. J Clim 19:1567–1575. https://doi.org/10.1175/JCLI3670.1

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