



Characteristics of southwest summer monsoon rainfall events over East India

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Abstract

The variability in Indian summer monsoon rainfall (ISMR) has an immense socioeconomic impact on India, especially over the monsoon core region. In this study, a thorough analysis of the ISMR (June to September—JJAS) has been performed for East India (EI), a part of the monsoon core zone, and for its four subdivisions (Odisha, Chhattisgarh, Jharkhand, and Bihar). The long-term climatology, variability, and trends of various categorical rainfall events as defined by India Meteorological Department (IMD) have been analyzed by using IMD high-resolution ($0.25^\circ \times 0.25^\circ$) gridded dataset for 116 years (1901–2016). Also, the percentage contribution of various rainfall events to the total seasonal rainfall and wet days is estimated. To get the changes in the frequency of various dry spells, rainfall events, and associated seasonal rainfall, study period is divided into two halves, earlier period (P1: 1901–1958) and recent period (P2: 1959–2016). The results suggest that the percentage contribution of medium-intensity rainfall events (7.6–64.4 mm/day) to the total ISMR is higher (~72%) followed by high-intensity rainfall events (~15%) and low-intensity rainfall events (12%), while most percentage contribution to the total number of wet days is from low-intensity rainfall events (~54%) followed by medium-intensity rainfall events (~43%) and high-intensity rainfall events (~3%). In the recent period (P2), the ISMR significantly decreased over the central part of EI because of the significant decrease in the frequency of low and medium-intensity rainfall events and wet days. The remarkable decrease of wet days leads to an increase in the short (1 week) and long-duration (> 2 week) dry spells in P2. And at the same time, high-intensity rainfall events significantly increased over EI in the recent period (P2) and led to an increase in the flood situation over this region. The profound relation of deficit rainfall of EI with ENSO is getting weak in the P2. This study is certainly useful in determining the effects on various sectors because of the variability and changes in various categorical extreme rainfall events, short and long-duration dry spells during summer monsoon time over EI. Also, this study may assist the risk management sectors in acclimating advanced technologies for a sustainable future in the changing climate of the present global warming era.

1 Introduction

The earth's surface air temperature during the last few decades has been rising sharply due to global warming (IPCC 2013) and its impact is evident at various parts of the globe, in

particular, on the hydrological cycle and precipitation patterns. The increasing surface air temperature leads to increase the atmosphere's water holding capacity; in addition, evaporation from ocean's surface is also increased (Nageswararao et al. 2016). This leads to the increase of water vapor content in the atmosphere over the globe. Increasing water vapor content in the atmosphere leads to an increase in the intensity and frequency of extreme precipitation events at the regional level, even in the regions where the total precipitation has not changed or decreased (Nageswararao et al. 2016). Many studies (Mason et al. 1999; Easterling et al. 2000; Zhang et al. 2001; Hong 2004; Groisman et al. 2005; King et al. 2013; Fischer and Knutti 2016; Nageswararao et al. 2016, 2019a, b; Deng and Ritchie 2019; Li and Hu 2019; Swain et al. 2020) have evident remarkable changes in the intensity, duration, and frequency of heavy rainfall events at the regional level. Since the recent few years, different parts of India are

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experiencing high-intensity rainfall events, and at the same time, some other parts of India are experiencing drought-like conditions (Goswami et al. 2006; Kishtawal et al. 2010; Guhathakurta et al. 2011; Pai et al. 2015; Swain et al. 2018; Nageswararao et al. 2016, 2019a, b).

The southwest summer monsoon season, i.e., June to September (JJAS), is the main rainy season of India by contributing around 80% of annual rainfall except Tamil Nadu and Jammu Kashmir (Saha et al. 2014; Mishra et al. 2016; Nageswararao et al. 2019a). Agricultural products and gross domestic products (GDP) of India get impacted by year to year fluctuations in Indian summer monsoon rainfall (ISMR) (Ghosh et al. 2016). So, the understanding of changing patterns of ISMR at the regional level is important. The variation in ISMR from its climatological mean remains steady with a variation coefficient which is about 10% (Mishra et al. 2012), whereas the mean rainfall over India has decreased in recent decades (Dash et al. 2009). The southwest monsoon is associated with land-sea thermal contrast, and semi-permanent features of monsoon such as low-pressure systems (LPS), monsoon trough, Somalian jet, westerlies, and easterlies. The reduction of ISMR over the monsoon core region (part of Central and East India) is the main reason for the weakening of seasonal mean rainfall for India as a whole (Kulkarni 2012).

Moreover, west, south, and east boundaries of India are surrounded by large water bodies, and the sea surface temperature (SST) of these water bodies plays an important role in distributing the ISMR. Recently, Mishra et al. (2012) identified a north-south dipole in ISMR which has associated with SST over the Arabian Sea (AS) and Bay of Bengal (BoB). Gangetic plains along with East India have experienced below normal rainfall when SST over AS and BoB is above normal while peninsular India has experienced above normal rainfall and vice versa (Mishra et al. 2012). It is well known that the western Indian Ocean shows continuous warming in the recent few decades (Rao et al. 2012; Roxy et al. 2014) and the Gangetic plains and East India are recently expecting below normal rainfall conditions due to combining the effect of warming of SST, reduction of land-sea thermal contrast, weakening of low-level monsoon circulation, and decrease in mid-tropospheric geopotential gradient (Kulkarni 2012; Mishra et al. 2012; Roxy et al. 2015; Das et al. 2016; Nath et al. 2017).

Formerly, the El-Niño Southern Oscillations (ENSO) had a good correlation with below normal rainfall over India; nowadays, Indian Ocean Dipole (IOD) is considered an indicator for above/below normal rainfall conditions for India, especially positive IOD condition is favorable to form a good amount of rainfall and negative IOD condition is associated to form deficit rainfall conditions over the Indian landmass (Ashok et al. 2001; Saji and Yamagata 2003; Gadgil et al. 2019).

The reduction in ISMR over the monsoon core region triggers to form drought-like conditions for all India bases as this region receives more rainfall than other regions. So, analysis of drought frequency, severity over this region, is an important issue. Some recent studies have shown that the droughts are shifting over Indo-Gangetic plains and signifying the socioeconomic vulnerability (Mallya et al. 2016; Nath et al. 2017). This shift occurred because of various climatic and non-climatic factors. One of them is the potential evapotranspiration (PET), and it has increased over the eastern part of India and decreased over the western part of India, which is an arid region and which emphasize sin increased in drought condition over East India and good rainfall over the western region (Das et al. 2016). On the other hand, different attempts are made to understand the impact of climate change on the frequency and intensity of extreme rainfall events over India and results show a significant increasing trend in the frequency of heavy rainfall events over the monsoon core region (Goswami et al. 2006; Guhathakurta et al. 2011; Ghosh et al. 2016; Nageswararao et al. 2019b; Swain et al. 2018). It is not clear whether these increases in heavy rainfall events are the consequence of intense surface heating/urbanization or not. Because heavy rainfall events are occurring mostly over a small region, however, drought conditions have large spread. Additionally, nowadays, mega-cities, like Mumbai, Bengaluru, and Chennai, have experienced frequent occurrences of heavy rainfall events which highlight the importance of urbanization effects (Kumar et al. 2008; Sahany et al. 2010; Seenirajan et al. 2017).

So, to check whether ISMR is decreasing or increasing over the monsoon region, long-term analysis of rainfall distribution as well as different rainfall events is necessary. Previously, the study regions for the spatial analysis of different rainfall events were selected either based on homogeneity in mean and standard deviation of seasonal rainfall i.e., monsoon core region (Goswami et al. 2006) or based on homogeneous regions of India (Parthasarathy 1995; Guhathakurta et al. 2015) or some time subdivisions of homogeneous region (Pai et al. 2015). The region which has experienced below normal rainfall in recent decades as discussed by Kulkarni (2012) and Mishra et al. (2012) was taken as the study area for this study and named it as East India (EI), which includes Odisha, Jharkhand, Chhattisgarh, and Bihar that are states of India (which is a large part of Gangetic plain). The vulnerability index of forest to the projected impacts of climate change has shown that forests over Central India come under the vulnerable to most vulnerable category (Chaturvedi et al. 2011). Most of the area of this region come under rainfed agriculture and it is one of the major rice production areas of India (Dey and Sarkar 2011; Tesfaye et al. 2017). But, the detailed analysis of various categorical extreme rainfall events for this region is hardly available. The India Meteorological Department (IMD) has developed a high-resolution ($0.25^\circ \times 0.25^\circ$) daily gridded rainfall dataset. Pai et al. (2014a) and Nageswararao et al. (2018a) tested this dataset

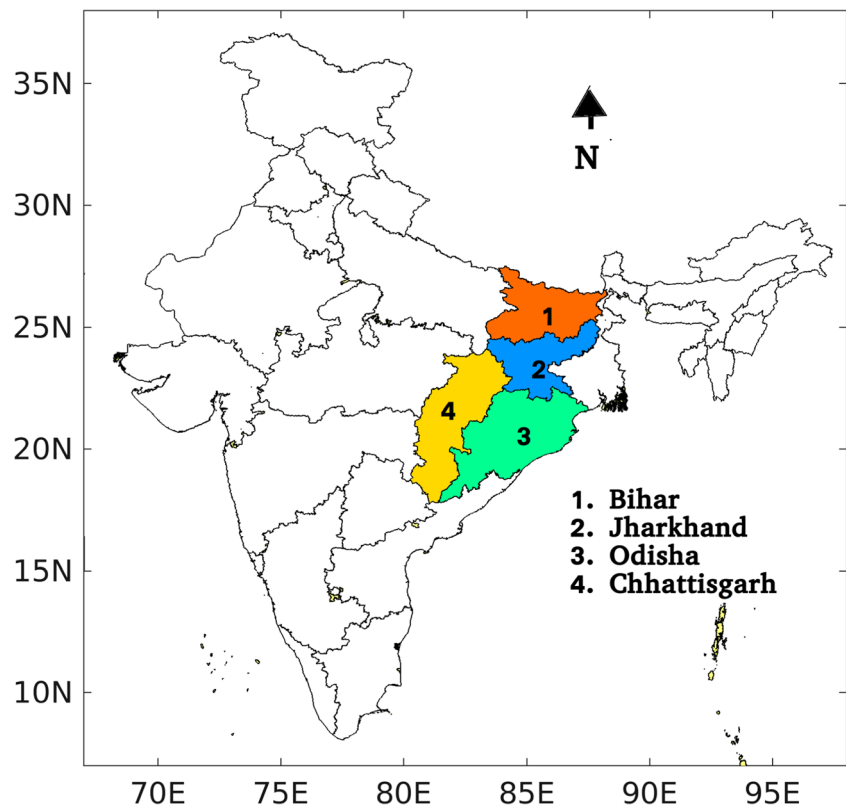
against in situ observations and the other existing datasets and found the superiority of this dataset. Yet, no study exists that involves the use of IMD new high-resolution gridded rainfall dataset for spatiotemporal analysis of various rainfall events over EI which is vital for the water resource management sector in India as Mahanadi Basin and part of Gangetic plains lie within this region. Thus, it is very important to investigate the characteristics of various JJAS rainfall events over EI using the IMD new high-resolution rainfall gridded dataset to explore the variability of ISMR and check teleconnections with El Niño. The abbreviations used in this study are given in Table 1.

2 Data and methodology

The high-resolution gridded rainfall dataset ($0.25^\circ \times 0.25^\circ$) from 1901 to 2016 provided by IMD is used in this study and it is available in the archive of National Data Centre IMD, Pune. This dataset is prepared by using 6955 rain gauge station records in India (Pai et al. 2014b) and the distribution of these stations is available in Nageswararao et al. (2019b). This dataset presents more realistic rainfall over west of Western Ghats and Northeast India and low rainfall over the leeward side of Western Ghats during the southwest monsoon season, i.e., JJAS, and it shows realistic winter (December to February—DJF) precipitation over the Himalayan region and post-monsoon (October to December—OND) rainfall over

the southern peninsular region of India (Pai et al. 2014b; Nageswararao et al. 2016, 2018a). Many studies (Nageswararao et al. 2016, 2018a, b, c, 2019a, b; Samantaray et al. 2019; Swain et al. 2018, 2019; Mohanty et al. 2019a, b; Swain et al. 2019) have used the IMD high-resolution gridded rainfall analysis dataset for evaluating the performance of atmospheric-ocean general circulation models over India and also study the characteristics of various categorical rainfall events over India during different seasons and its global teleconnections. Over EI, 654 grid points are available and the different rainfall events are analyzed based on these grid points. The geological location of EI lies between 80° E to 88° E and 18° N to 28° N, and it has 4 states of India—Odisha (OD), Jharkhand (JH), Chhattisgarh (CH), and Bihar (BH); the state-wise division map of EI is illustrated in Fig. 1. The EI region comes under the monsoon core zone. Recently, it is found that the moderate rainfall events are decreased and extreme rainfall events have increased over India; in particular, Central India has experienced a widespread increase in heavy rainfall events (Goswami et al. 2006; Roxy et al. 2017). To check the rainfall climatology and for analyzing the various categorical JJAS extreme rainfall events defined by IMD such as very light rainfall (VLR), light rainfall (LR), moderate rainfall (MR), rather heavy rainfall (RHR), heavy rainfall (HR), very heavy rainfall (VHR), and extremely heavy rainfall (EHR) over EI and for its four subdivisions/states (OD, JH, CH, and BH), the IMD high-resolution dataset

Fig. 1 Map depicting East India (EI) consisting 4 Indian states



for the period of 116 years (1901–2016) is considered. The rainfall intensity ranges of various rainfall events which are categorized by IMD are illustrated in Table 2. To check the variability in the frequency of various rainfall events and associated ISMR, the entire study period (1901–2016) is divided into two equal periods, earlier (1901–1958, P1) and recent periods (1959–2016, P2).

Central India has experienced a severe drought condition in the last few years (Das et al. 2016; Nath et al. 2017). So, the 1-week and > 2-week dry spell spatial extent over EI has been checked for P1 and P2. To understand the increasing/decreasing trends of various rainfall events, total number of wet days (rainfall > 2.5 mm/day), and total number of dry days (rainfall < 2.5 mm/day), simple linear regression method is used for EI and its subdivisions for the entire study period (1901–2016) and further for its two halves (P1 and P2). The percentage (%) contribution of various rainfall events to the total seasonal rainfall and wet days is also analyzed for both periods (P1 and P2). The large-scale circulation, such as ENSO, has the potential to alter the regional scale climate, and ENSO is associated with deficit rainfall particularly in India (Sikka 1980; Kumar et al. 1999). In this study, the teleconnection of ENSO with ISMR of EI has been analyzed. The Student's *t* test has been applied to determine the statistical significance of the trends and differences in the frequency of dry spells, various rainfall events, and the associated seasonal rainfall between the two periods.

3 Results

In this study, the characteristics of various categorical rainfall events and associated JJAS rainfall over East India are

Table 1 List of abbreviations used in the study along with their full forms

Abbreviations	Full form
JJAS	June, July, August, September
ISMR	Indian summer monsoon rainfall
SST	Sea surface temperature
AS	Arabian Sea
BoB	Bay of Bengal
PET	Potential evapotranspiration
EI	East India
OD	Odisha
CH	Chhattisgarh
JH	Jharkhand
BH	Bihar
IAV	Inter-annual variability
CV	Coefficient of variance

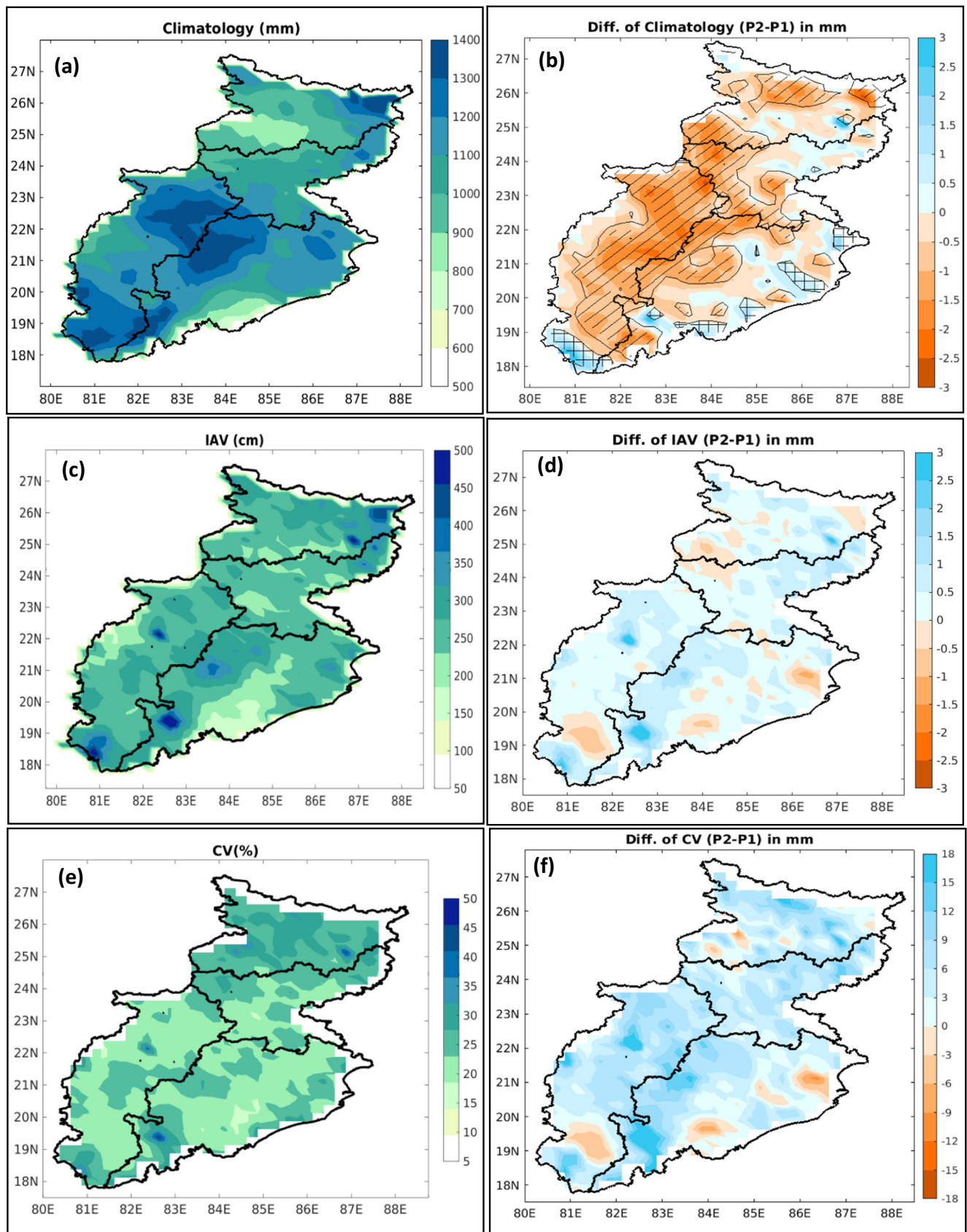
analyzed using the IMD new high-resolution rainfall gridded analysis dataset, and the results are discussed in the following subsections.

3.1 Spatial distribution of various JJAS rainfall events and associated seasonal rainfall

The climatological mean, inter-annual variability (IAV), and coefficient of variation (CV) of ISMR at grid point level over EI for 116 years (1901–2016) are computed. The change in the seasonal rainfall, IAV, and CV in the recent period (P2) as compared with the earlier period (P1) is also calculated, and the significance of these changes is tested and depicted in Fig. 2. From Fig. 2a, it can be observed that the central part of EI, i.e., northeast of CH and northwest of OD, is a maximum rainfall zone and a secondary maximum rainfall zone is noticed over the southwest in CH and northeast in Bihar (BH). It is interesting to notice that there is a significant reduction (at 90% confidence level) in the ISMR in most parts of the EI except the coastal and southern tip of EI where the significant increase has been found (Fig. 2b). The IAV and CV analyses indicate that the patterns of IAV and CV are similar to the climatological mean pattern (Fig. 2c, e). In most parts of EI, the IAV and CV of ISMR remarkably increased in the recent periods; however, the seasonal rainfall amount has been significantly decreased for same period (Fig. 2b, d, f). The decreasing seasonal rainfall and the increasing in inter-annual variability have adverse effects on various sectors over this region.

The percentage (%) contribution of various categorical rainfall events to the total number of wet days for the entire study period and the recent changes in the frequency of various rainfall events are computed and presented in Fig. 3. The distribution of various rainfall events to the total number of wet days indicates that the percentage contribution of low-intensity rainfall events (VLR and LR) is relatively more over the coastal and northern parts of EI than the other parts, while the medium-intensity rainfall event (MR and RHR) contribution is high over the central and western parts of EI. However, the high-intensity rainfall events' (HR, VHR, and EHR) contribution is large over the south-central part of EI where the seasonal mean rainfall is relatively higher than the other parts (Fig. 3a, c, e, g, i, k, and m). It is interesting to notice that the contribution of low-intensity rainfall events (VLR and LR) to the total number of wet days is greater than 70% in most parts

Fig. 2 **a** The spatial distribution of summer monsoon (JJAS) seasonal rainfall at grid point level over East India for the study period (1901–2016). **b** Climatological mean difference between the recent (P2) and earlier (P1) half periods. **c–d** and **e–f** Same as **a–b** but for inter-annual variability (IAV) and coefficient of variation (CV) respectively. The area enclosed with hatches (cross/parallel lines) indicates that the changes (positive/negative) are significant at 90% confidence level



of EI except the central part of EI, whereas the medium-intensity rainfall events' contribution is more than 70%. The climatological mean difference (P2–P1) of various rainfall events indicates the profound decrease in the frequency of low (VLR and LR) and medium-intensity rainfall events (MR and RHR) in most parts of EI in the recent period, while the remarkable increase in the frequency of high-intensity rainfall events in most parts of EI has been observed (Fig. 3b, d, f, h, j, l, and n). The remarkable decrease in the frequency of low and medium-intensity rainfall events in most parts of EI leads to a significant decrease in the ISMR in most parts of the EI except the coastal and southern tip of EI, whereas a significant increase in the ISMR is due to the significant increase in the frequency of high-intensity rainfall events over this region. The number of EHR events is observed over western parts of OD and its frequency has significantly increased over this region in the recent period and leads to more flood situations over this region in recent years. The frequency of dry spells during the JJAS season with 1 week and > 2 weeks at grid point level over EI for the entire study period and its changes in the recent period have been calculated and depicted in Fig. 4. The dry spell analysis reveals that 1-week dry spells have occurred in most parts of EI, while > 2-week dry spells have been noticed only over western parts of EI (Fig. 4a, c). In the recent period, the occurrence of 1-week and > 2-week dry spells is more in most parts of EI when compared with the earlier period, and the increase in the frequency of these dry spells is significant at 90% confidence level (Fig. 4b, d) and affects adversely on various sectors such agriculture, hydro-power, and water resource management sectors over this region.

The above analysis shows that the significant decrease in the ISMR in the recent period is because of decrease in low and medium-intensity rainfall events, which provides continuous rainfall during the JJAS season and the increased in 1-week and > 2-week dry spells and leads to more drought years in this region in the recent years. The reduction in the ISMR is mainly due to the increase of the SST over the western Indian Ocean (Mishra et al. 2012), and tends to form anti-cyclonic

circulation patterns over the northwest of the AS and BoB in the lower troposphere (Zhao and Zhang 2016). In addition to this, the decrease in the frequency of monsoon depressions which are coming from the BoB leads to a reduction in mid-tropospheric relative humidity that causes a weakening of monsoon circulation which is producing the maximum rainfall over this region (Vishnu et al. 2016). The spatial analysis of various rainfall events and dry spells suggests that the total number of wet days and the frequency of low and medium-intensity rainfall events remarkably decrease in the recent period while the frequency of high-intensity rainfall events is increased over EI; this leads to form flood-like situations over this region. The heavy rainfall events are located over small areas; however, the dry spells have large spread. So, EI is facing heavy rainfall condition over the small area and drought-like condition over a large area.

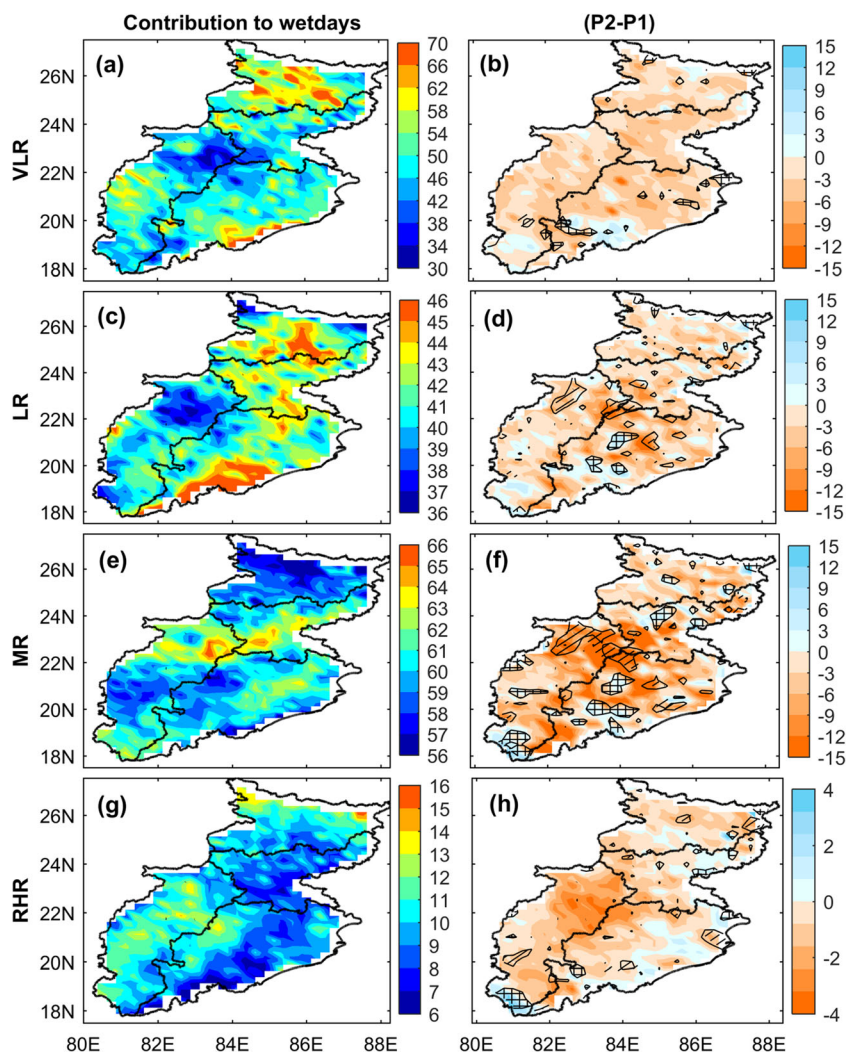
3.2 Analysis of daily rainfall over EI and its four subdivisions

The daily climatological mean, IAV of daily scale rainfall, and its changes (P2–P1) in the recent period at subdivision level as well as EI as a whole for the study period (1901–2016) have been computed and portrayed in Fig. 5. The daily rainfall has increased continuously from the 1st of June to around the 1st week of August and after that, gradually decrease for all the subdivisions as well as EI as a whole (Fig. 5a). It has been noticed that Chhattisgarh has experienced a high amount of rainfall followed by OD, JH, and BH. It is interesting to notice that the daily analysis of mean climatology reveals that BH shows inverse behavior than others for August. In case of IAV of daily rainfall analysis, it has seen that IAV is notably increased up to the end of the 2nd week of June and after that, it has maintained almost steady IAV (slight decrease) for EI and its subdivisions (Fig. 5b). It is also noticed that after mid-August, the rainfall value decreased but IAV does not show rapid decrease (Fig. 5a, b). The difference in the daily climatological mean rainfall between recent and earlier periods reveals that the daily rainfall over EI and all of its subdivisions show a significant decrease (90% confidence level) in many days of JJAS in the recent period and a decrease of daily rainfall due to the decrease of low and medium-intensity rainfall events (Fig. 5c, d). It is interesting to notice that the decreasing in the daily rainfall in the recent period is more

Table 2 Various categories of rainfall events and respective rainfall intensity ranges as defined by India Meteorological Department (IMD)

Description term used	Rainfall amount (mm/day)
Very light rain (VLR)	0.1–2.4
Light rain (LR)	2.5–7.5
Moderate rain (MR)	7.6–35.5
Rather heavy rain (RHR)	35.6–64.4
Heavy rain (HR)	64.5–124.4
Very heavy rain (VHR)	124.5–244.4
Extremely heavy rain (EHR)	> 244.5

Fig. 3 **a** The percentage contribution of VLR events to the total number of wet days during the summer monsoon (JJAS) at grid point level over East India for the study period (1901–2016). **b** Climatological mean difference of VLR events between the recent and earlier half periods. **c–d, e–f, g–h, i–j, k–l** and **m–n** Same as **a–b** but for LR, MR, RHR, HR, VHR, and EHR events respectively. The area enclosed with hatches (cross/parallel lines) indicates that the changes (positive/negative) are significant at 90% confidence level



significant in the peak monsoon months (July and August) for all the subdivisions as well as the EI as a whole, while it has increased from the 3rd week of September onwards.

3.3 Normalized time series of seasonal (JJAS) rainfall over EI

To get the clear picture of change in seasonal rainfall, the normalized time series have been prepared as an area weighted average of mean seasonal—JJAS—rainfall of EI for the period of 1901–2016 and the normalized values are calculated from the long-period climatological mean of 116 years (1901–2016) and 31 years; moving average of ISMR of EI is also calculated and depicted in Fig. 6. To categorize the years, the normal rainfall year is considered when the standardized anomaly lies between ± 1 , for excess and deficit years when the standardized anomaly is > 1 and < -1 have been considered respectively. By using this criterion, it has found 20 excess and 17 deficit rainfall years out of 116 years in the ISMR of EI. Among them, 12 excess (1917, 1919, 1922, 1925, 1933,

1934, 1936, 1942, 1943, 1946, 1953, and 1956) and 4 deficits (1901, 1903, 1915, and 1951) have occurred in the earlier period, while 8 excess (1961, 1980, 1984, 1994, 2001, 2006, 2007, and 2008) and 13 deficit (1962, 1965, 1966, 1972, 1974, 1979, 1982, 2000, 2002, 2004, 2009, 2010, and 2015) rainfall years have occurred in the recent period. If the analysis of the number of excess and deficit rainfall years during P1 and P2 take into consideration, the drastic change in extreme rainfall years (excess and deficit) is observed, in P1, and the excess rainfall years are dominant, while the deficit rainfall years are leading in P2 (Fig. 6a). It is interesting to notice that the below normal (a year having standardized anomaly between -1 and 0) rainfall years (22 years) notably increased in the recent half period when compared with the earlier half period (15 years) of the study period. In addition to this, it has also revealed that the number of above normal years (a year having standardized anomaly which lies between 0 and 1) decreased drastically (15 above normal years) in the recent period as compared with the earlier period (27 above normal years). It is interesting to notice that the mean seasonal rainfall

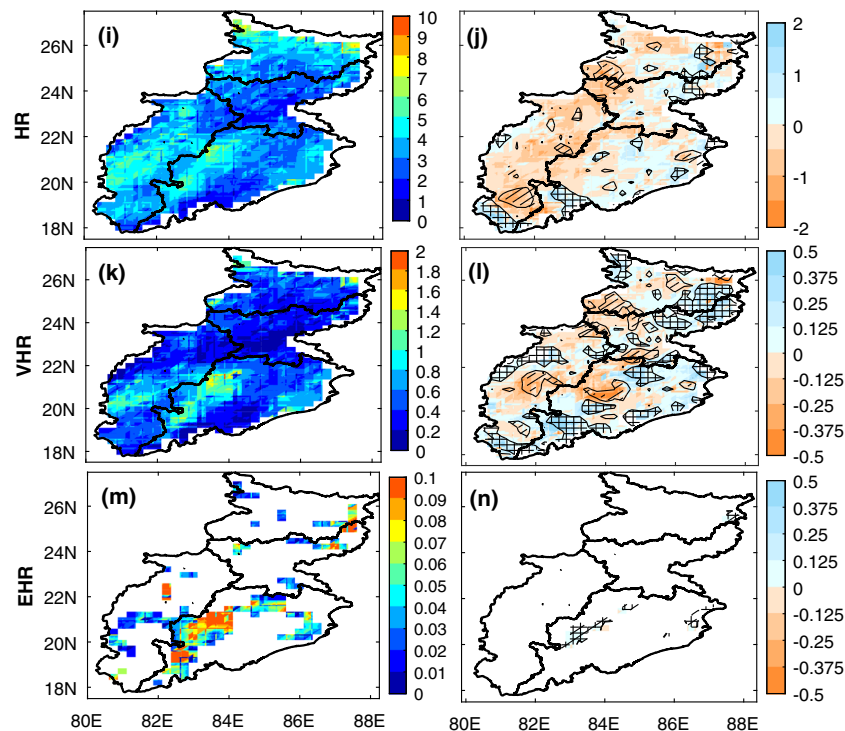


Fig. 3 continued.

of EI is showing the wave-like pattern; for the first 30-year groups, i.e., up to groups 1931–1961 (the mean year 1946), it is almost steady. From groups 1962–1992 (mean year 1977), seasonal rainfall has been gradually decreased. During phase I, the peak rainfall is about 1175 mm, wherein during phase II, seasonal rainfall mean is getting reduced to 1075 mm (Fig. 6a, b). Consequences of good correlation between El Niño and Indian summer monsoonal rainfall is observed only in P1, and the all 4 deficit rainfall years co-occurred with El Niño years (Sikka 1980; Kumar et al. 1999, 2016; Roxy et al. 2017). Besides, in P2, among 13 deficit years, only 6 deficit rainfall years co-occurred with El Niño years, because El Niño and Indian summer monsoon correlation get weaker in recent decades (Kumar et al. 1999; Ashok et al. 2001; Pai 2004; Feba et al. 2019). It is essential to check the percentage (%) contribution of various rainfall events based on various rainfall intensities provided by IMD to seasonal rainfall and the wet days.

3.4 Percentage (%) contribution of various rainfall events to the seasonal rainfall and wet days

The percentage contribution of various categorical rainfall events to the total number of wet days and associated seasonal rainfall over EI has been computed and depicted in Fig. 7. In both periods (P1 and P2), it has observed that the MR (50 and 49%) event contribution to the ISMR is high followed by RHR (22.2 and 21.6%), HR (12.5 and 12.8%), LR (9.5 and

9.6%), VLR (2.3 and 2.3%), VHR (2.3 and 2.2%), and HER events (0.2 and 0.5%) (Fig. 7a, b). It has also been observed that the majority contribution to the total number of wet days is from MR (37.34 and 36.77%) in both the periods (P1 and P2) followed VLR (28.67 and 29%), LR (25.77 and 26%), RHR (6 and 5.66%), HR (1.88 and 1.92%), VHR (0.26 and 0.31%), and EHR (0.01 and 0.02%) (Fig. 7c, d). It is interesting to notice that the percentage contribution of low-intensity rainfall events (VLR and LR) to the total number of wet days is high in both the periods (54.4 and 55%) while its contribution to the ISMR is only 11.8 and 11.9% for the P1 and P2 respectively. In the recent period, the percentage contribution of medium-intensity rainfall events (MR and RHR) to the total number of wet days as well as to the seasonal rainfall is remarkably decreased, while the percentage contribution of low and high-intensity rainfall events to the total number of wet days as well as the seasonal rainfall is increased. The huge decrease in the frequency of medium-intensity rainfall events leads to a decrease in the seasonal mean rainfall and increase of dry spells in the recent period as compared with the earlier period. The high-intensity rainfall events' contribution to the total number of wet days and associated seasonal rainfall is less but still has a great impact on a local scale. The percentage contribution of various categorical rainfall events to change in the ISMR and the total number of wet days between P2 and P1 are evaluated and illustrated in Fig. 7e. The negative sign in the y-axis indicates the decrease in the percentage of contribution and a positive sign for the increase in the percentage of

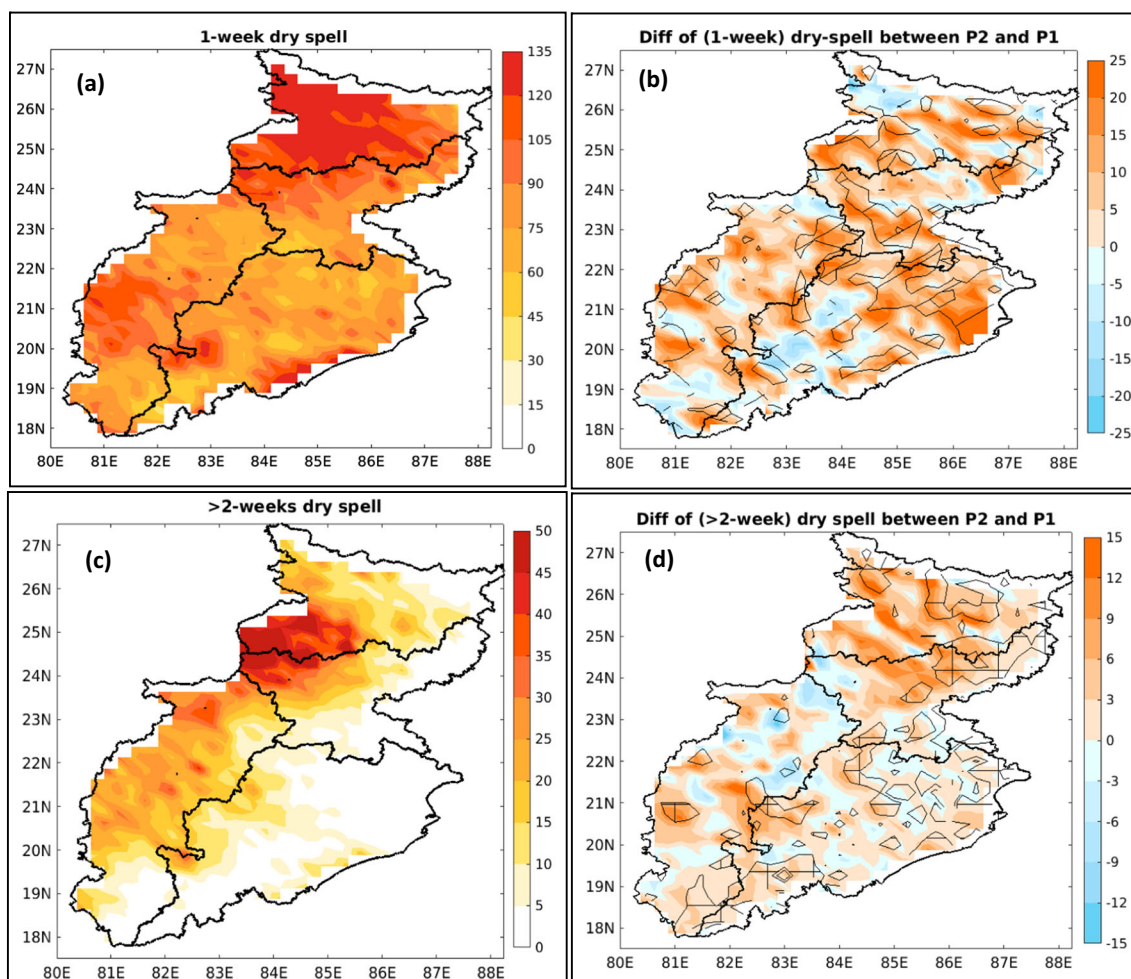


Fig. 4 **a** Spatial distribution of 1-week dry spells during summer monsoon (JJAS) over East India for the study period (1901–2016). **b** Difference of 1-week dry spells between the recent and earlier half

periods. **c** and **d** Same as **a** and **b** but for >2-week dry spells. The area enclosed with hatches (cross/parallel lines) indicates the changes (positive/negative) are significant at 90% confidence level

contribution. The major contribution to the reduction in the ISMR as well as wet days in the recent period is from MR events (−67 and −48%) followed by RHR (−32 and −9%), LR (−8 and −20%), HR (−6 and −1%), and VLR (−2 and −22%) events, while the VHR (10 and 0.5%) and EHR (5 and 0.3%) events support to increase the seasonal rainfall as well as wet days. However, the low and medium-intensity rainfall event domination is higher than the high-intensity rainfall events on the total seasonal rainfall as well as wet days and it leads to decrease the seasonal rainfall as well as wet days in the recent period.

3.5 Trends in the frequency of various rainfall events over EI and its subdivisions

Figure 8 shows the inter-annual variations in the frequency of various summer monsoon (JJAS) rainfall events (VLR, LR, MR, RHR, HR, VHR, EHR, wet, and dry) over EI for the study period and its two halves with trend lines fitted for the total and two halves of the study period. It has found

remarkable year-to-year variation in the frequency of various rainfall events and dry days over EI in the entire period (Fig. 8). The VLR event trend analysis reveals that there is a notable decreasing trend in the frequency of VLR events for the whole period and its two halves (Fig. 8a). In the case of LR events, it has observed increasing trend for the earlier period while it has increased trend for recent and whole study period (Fig. 8b). For the entire study period, the VLR, LR, MR, RHR, and wet days show a decreasing trend, while it has shown an increasing trend in HR and VHR for the whole period. Moreover, there is a significant increasing trend in the RHR, HR, VHR, and EHR events in the period. It is interesting to notice that there is a remarkable decreasing (increasing) trend in the total number of wet days (dry days) for the whole period and the recent half period, while there is a significant increasing (decreasing) trend in the wet days (dry days) for the earlier half period. The Mann Kendall test is also used to check the monotonous trend for various rainfall events and it shows similar results which is discussed in Fig. 8 (Table 3). The non-parametric Mann Kendall test checks null hypothesis of

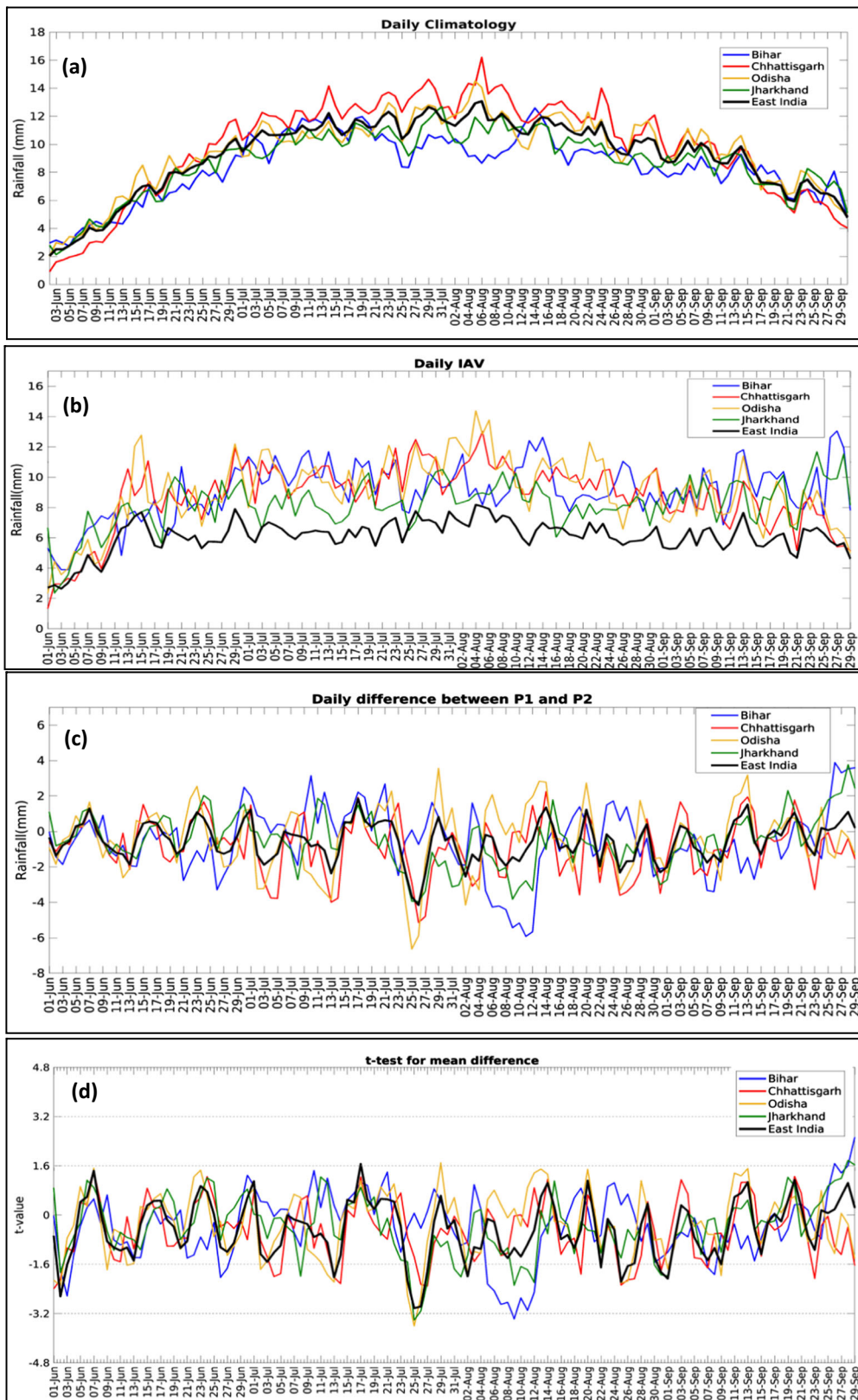


Fig. 5 Statistical analysis of daily rainfall (mm) during summer monsoon (JJAS) over East India for the study period (1901–2016). **a** Climatological mean. **b** IAV. **c** Climatological mean difference between recent (P2) and earlier (P1) halves of the study period. **d** t value of **c**. The significant t value at 90% for the difference of daily rainfall between the two periods is ± 1.67

no trend versus alternate hypothesis of trend which are observed for the variable is under consideration (Kumar et al. 2010). The positive/negative values of Z indicate the increasing/decreasing trend. Here, it is observed that the HR, VHR, and EHR events have increased in P2 while VLR, LR, and MR events are decreased for same time period (Table 3).

The year-to-year variation in the frequency of various rainfall events (VLR, LR, MR, RHR, HR, VHR, and EHR) for the study period (1901–2016) with trend line fitting the whole study period and its two halves (P1 and P2) has been analyzed at subdivision level, and the slope, R^2 (R is the correlation coefficient), mean of the whole study period, and its two halves, difference (P2–P1) of mean of the frequency of various rainfall events between the two half periods, are illustrated in Table 4 and it gives detailed information about the contribution of various rainfall events to wet days for the P1, P2, and entire study period. The mean difference (P2–P1) of the frequency of different rainfall events between two periods reveals that in the recent period (P2), VLR, LR, MR, and RHR events' contribution is a decrease in seasonal rainfall over all subdivisions (Table 4). The trend analysis at each four subdivisions for the entire study period as well for the recent period indicates that all the subdivisions of EI show significant (at 95% confidence level) decreasing trend in the low and medium-intensity rainfall events (VLR, LR, MR, and RHR), while a notable increasing trend (at 95% confident level) in the high-intensity (HR, VHR, and EHR) rainfall events has been observed.

4 Discussion

From this study, it is observed that the mean rainfall over EI gets reduced by ~ 100 mm in the recent period (P2) which is a very huge amount. One of the semi-permanent features of the summer monsoon season, LPS, that were formed over BoB and crossed the East Indian coastline and provide moisture supply for Indian subcontinent has got reduced in P2 (Krishnamurthy and Ajayamohan 2010; Vishnu et al. 2016). On the other hand, the surface temperature over South India increased compared with Central India which cause a change in profound Indian land-sea temperature gradient during summer months and set a new circulation, and due to which, moisture converges over the southern peninsular India and very less amount of moisture is available for the EI (Roxy et al. 2015). Previously, El Niño has a

good correlation with deficit rainfall over India; the relation is getting weaker and IOD-ISMR relation is setting for the last few years (Ashok et al. 2001; Feba et al. 2019). We also found the same results for EI. In P1, all deficit rainfall years co-occurred with EL Niño years and it is not consistent in P2.

During positive IOD phase, SST over AS gets warmer compared with a normal condition and near the Indonesian coastline, it has experienced low SST compare with a normal condition; this condition is favorable to form convection over AS and have good rainfall over Indian land (Ashok et al. 2001; Behera and Ratnam 2018). Because of the warming of the western Indian Ocean, the positive phase of IOD events has frequently occurred. A study on IOD and ISMR has shown that during positive IOD, North and South India have a good amount of rainfall; however, Central India receives below normal rainfall (Behera and Ratnam 2018). Further, Chung and Ramanathan (2006) have shown that monsoon circulation gets weakened due to weakening in the summer time SST gradient, resulting in below normal seasonal rainfall over India. In addition, Walker circulation also has shifted eastward and moisture convergence over East India gets reduced (Behera and Ratnam 2018). The combined effect of all these phenomena confirmed that the rainfall over EI gets reduced in P2. Further, over the north and west part of EI, low and medium-intensity rainfall events are reduced and high-intensity rainfall events are increasing (CH, JH, and BH); this is having a good agreement with various studies on these regions (Das et al. 2016; Meshram et al. 2017; Chandniha et al. 2017; Warwade et al. 2018).

5 Summary and conclusions

In the present study, the long-term climatology, variability, trends of various categorical rainfall events as defined by India Meteorological Department (IMD), and associated ISMR over East India (EI) using IMD high-resolution ($0.25^\circ \times 0.25^\circ$) gridded analysis dataset of 116 years (1901–2016) have been analyzed. The percentage contribution of various rainfall events to the total seasonal rainfall as well as wet days during the JJAS over EI has also been estimated. The climate change impact on various categorical extreme rainfall events and its associated seasonal rainfall, 1-week and >2 -week dry spells in the recent period (1959–2016, P2) have been analyzed. The trends in the frequency of various rainfall events (VLR, LR, MR, RHR, HR, VHR, and EHR) over EI and its four subdivisions (Odisha, Chhattisgarh, Jharkhand, and Bihar) for the study period (1901–2016) and its two halves (P1 and P2) have been analyzed. The Student's t test has been used in this study, to know the significance of the recent change in the various dry spells, rainfall events and

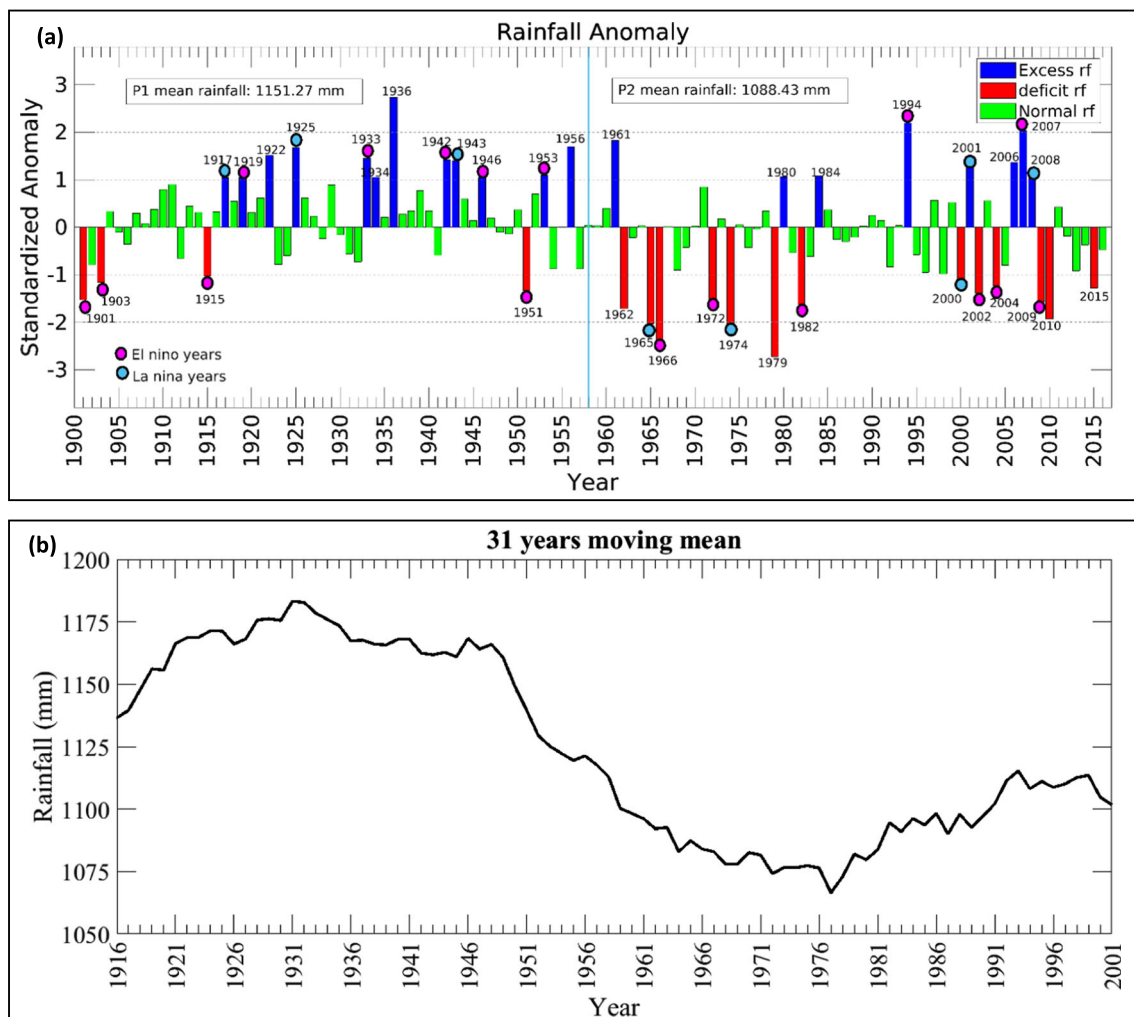


Fig. 6 **a** The normalized time series of summer monsoon (JJAS) season rainfall of East India (EI) from 1901 to 2016, and years which co-occurred with El Niño and La Niña are shown by pink and blue circles respectively. **b** Thirty-one years running mean of summer monsoon seasonal rainfall of EI

associated seasonal rainfall, and trends in the various rainfall events. The major outcomes of the study are summarized below:

- It has been observed that the climatological mean and IAV are relatively higher over the central part of EI, i.e., north-east of Chhattisgarh (CH) and northwest of Odisha (OD), and a secondary maximum rainfall zone is noticed over the southwest in CH and northeast in Bihar (BH).
- In the recent period P2 (1901–1958), there is a significant (at 90% of confident level) reduction in the seasonal rainfall in most parts of EI and it is mainly due to a significant decrease in the frequency of low (VLR and LR) and medium-intensity rainfall (MR and RHR) events over this region in the recent period.
- It is interesting to notice that there is a huge decrease in the number of wet days in most parts of EI in the recent period, while the remarkable increase is observed in the high-intensity rainfall events as well as 1-week and >2-week dry spells in most parts of EI in the recent period. Hence, EI is prone to experiencing climate extremes, heavy rainfall events, and long-duration dry spells in the recent years. The high-intensity rainfall events are concentrated over a small area, while deficit rainfall condition is widespread.
- The normalized time series analysis of ISMR over EI for 116 years indicates that there is a noteworthy year-to-year variation in the ISMR of EI and it has found 17 deficit and 20 excess rainfall years out of 116 years. In P1 (1901–1958), 4 deficit and 12 excess rainfall years have been observed, whereas, in P2 (1959–2016), 13 deficit and 8 excess rainfall years have been noticed.
- It has observed that all 4 deficit rainfall years in the P1 have co-occurred with El Niño, while only 7 out of 13 deficit years co-occurred with El Niño years in the recent period P2. Therefore, there is a strong linkage in the

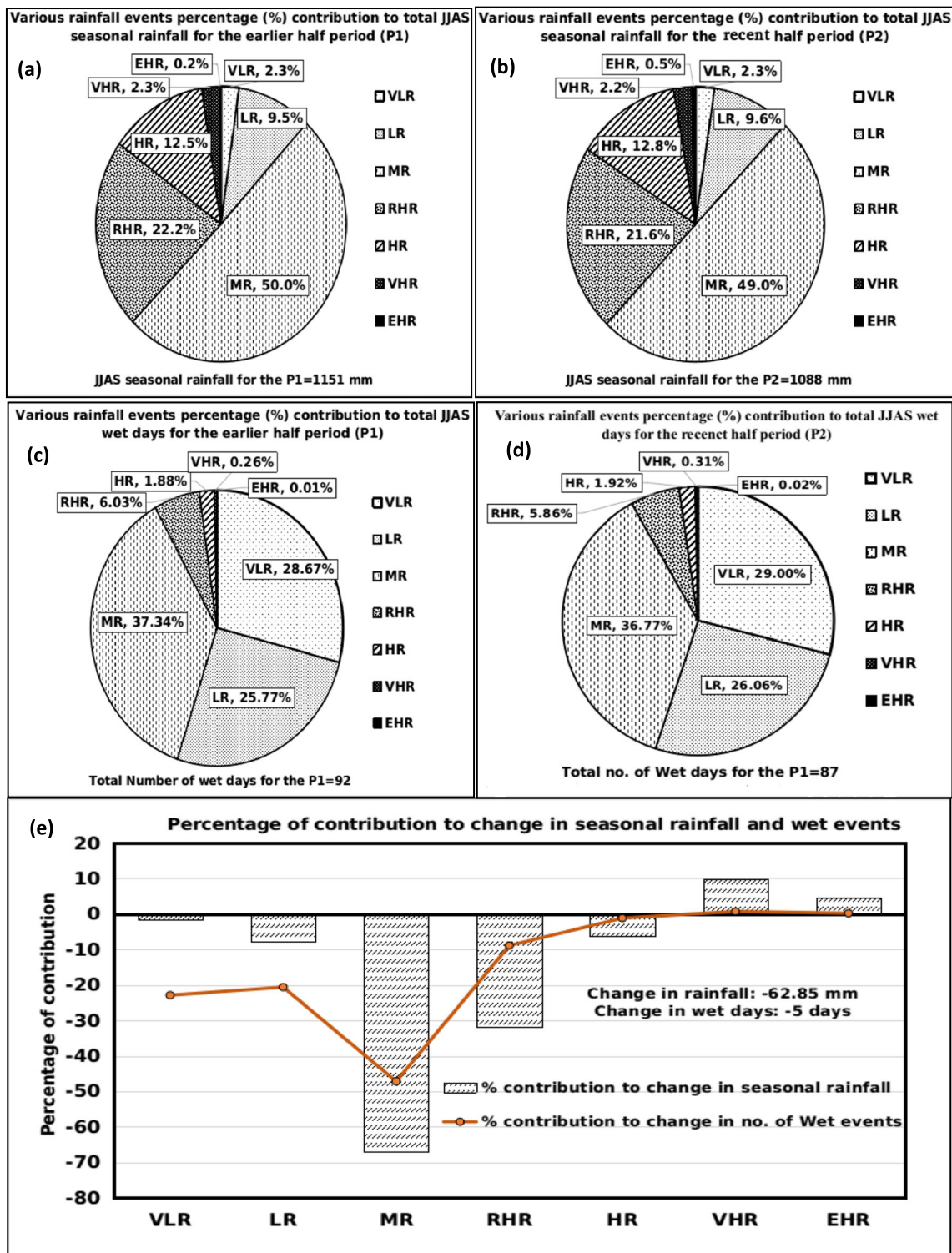


Fig. 7 The percentage (%) contribution of various rainfall events. **a** and **b** The total summer monsoon seasonal (JJAS) rainfall. **c** and **d** The total number of wet days over EI for the recent (1959–2016, P2) and earlier

(1901–1958, P1) periods respectively. **e** The percentage (%) contribution of various rainfall events to change in seasonal rainfall as well as wet days between period 1 and period 2

earlier period between the El Niño and deficit ISMR of EI, and the relationship is getting weaker in the recent period.

- It is interesting to notice that the amount of JJAS seasonal mean rainfall of EI is 1175.27 mm in the earlier period (P1), and in the recent period (P2), it is 1075.43 mm. So, in

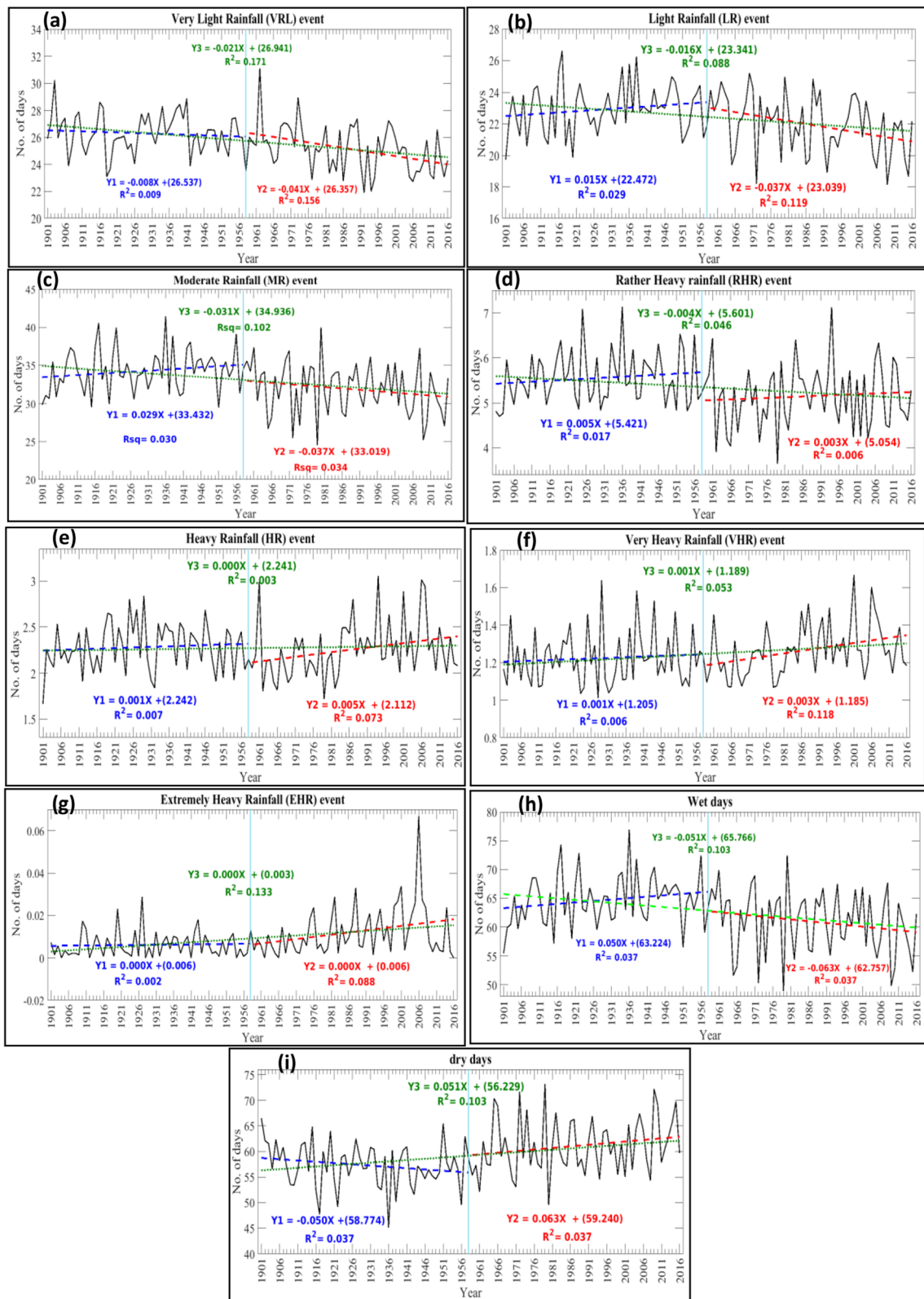


Fig. 8 The trends in the frequency of various rainfall events over EI for period of 116 years (1901–2016) and its two halves. **a** VLR. **b** LR. **c** MR. **d** RHR. **e** HR. **f** VHR. **g** EHR. **h** Total number of wet days. **i** Total

number of dry days. The significant R^2 values at 90% confidence level are 0.02 and 0.04 for 58 and 116 years respectively

Table 3 Trend analysis of various rainfall events over East India by using the Mann Kendall test during 1901–2016

Name	Whole study time		P1 (1901–1958)		P2 (1959–2016)	
	Z	p value	Z	p value	Z	p value
VLR	- 4.4095	1.0363e-05*	- 0.2482	0.8040	- 2.8308	0.0046*
LR	- 2.7130	0.0067*	1.5026	0.1329*	- 2.7100	0.0067*
MR	- 3.1639	0.0016*	1.5160	0.1295*	- 1.7307	0.0835*
RHR	- 2.2191	0.0265*	0.8117	0.4170*	0.5635	0.5731
HR	- 0.3913	0.6956	0.3824	0.7022	1.5764	0.1149*
VHR	2.3193	0.0204*	0.2147	0.8300	2.4350	0.0149*
EHR	4.1542	3.2649e-05*	0.6507	0.5153	1.6837	0.0922*
Wet days	- 2.9516	0.0032*	1.5697	0.1165*	- 1.4489	0.1474*
Dry days	2.9516	0.0032*	- 1.5697	0.1165*	1.4489	0.1474*

Table 4 The 116-year (1901–2016) trend analysis of frequency of various Indian summer monsoon rainfall events at state level over EI. *, **, and *** indicate the trends in the frequency of various rainfall events significant at 90%, 95%, and 99% confidence levels respectively

State	Categorical rainfall event	Earlier half period (1901–1958, P1)			Recent period half (1959–2016, P2)			Entire study period (1901–2016)			Frequency difference between two periods (P2–P1)
		Mean frequency	Slope	R ²	Mean frequency	Slope	R ²	Mean frequency	Slope	R ²	
Jharkhand	VLR	28.30	0.00	6.75e-06	28.20	- 0.04	0.084***	28.25	- 0.03	0.129***	- 0.10
	LR	25.77	0.01	0.012***	26.17	- 0.04	0.068***	25.97	- 0.02	0.061***	0.40
	MR	37.78	0.02	0.0124***	37.43	- 0.05	0.0302***	37.61	- 0.04	0.075***	- 0.35
	RHR	5.36	0.01	0.006**	5.31	0.00	0.0004	5.34	0.00	0.013***	- 0.04
	HR	1.46	0.00	0.0007	1.49	0.00	0.0112***	1.48	0.00	0.00113	0.02
	VHR	0.16	0.00	0.0004	0.20	0.00	0.054***	0.18	0.00	0.0214***	0.04
	EHR	0.00	0.00	0.003**	0.02	0.00	0.04***	0.01	0.00	0.072***	0.01
Bihar	VLR	31.13	- 0.02	0.0214***	30.88	- 0.04	0.034***	31.01	- 0.04	0.149***	- 0.25
	LR	24.31	0.02	0.014***	24.40	- 0.03	0.031***	24.36	- 0.02	0.076***	0.09
	MR	34.36	0.00	0.0001	34.61	- 0.04	0.016***	34.48	- 0.03	0.048***	0.25
	RHR	6.45	- 0.01	0.005**	6.28	0.01	0.009***	6.37	- 0.01	0.027***	- 0.16
	HR	2.32	0.00	0.001	2.31	0.01	0.023***	2.31	0.00	0.0030***	- 0.01***
	VHR	0.29	0.00	0.016***	0.34	0.00	0.001*	0.31	0.00	0.0021***	0.05
	EHR	0.01	0.00	0.0009	0.02	0.00	0.006**	0.01	0.00	0.030***	0.01
Chhattisgarh	VLR	27.50	- 0.03	0.0326***	28.07	0.01	0.008**	27.78	- 0.01	0.027***	0.56
	LR	24.14	0.03	0.0537***	24.98	- 0.02	0.025***	24.55	0.00	0.003***	0.84
	MR	38.08	0.06	0.0480***	37.29	- 0.08	0.061***	37.70	- 0.04	0.0645***	- 0.79
	RHR	6.73	0.01	0.0387***	6.23	- 0.01	0.018***	6.49	- 0.01	0.071***	- 0.50
	HR	2.11	0.00	0.0120***	1.97	0.00	0.001*	2.04	0.00	0.019***	- 0.14
	VHR	0.27	0.00	0.0001	0.28	0.00	0.075***	0.27	0.00	0.005***	0.01
	EHR	0.01	0.00	0.004**	0.02	0.00	0.0040**	0.01	0.00	0.032***	0.01
Odisha	VLR	28.36	0.01	0.002*	29.09	- 0.10	0.287***	28.71	- 0.02	0.097***	0.73
	LR	25.63	0.01	0.002*	25.59	- 0.07	0.22***	25.61	- 0.03	0.16***	- 0.04
	MR	37.24	0.02	0.0107***	36.34	- 0.02	0.004**	36.80	- 0.04	0.103***	- 0.90
	RHR	5.56	0.00	0.0018*	5.52	0.01	0.049***	5.54	0.00	0.006***	- 0.03
	HR	1.75	0.00	0.009***	1.88	0.01	0.099***	1.81	0.00	0.010***	0.14
	VHR	0.29	0.00	0.0037**	0.38	0.01	0.009***	0.33	0.00	0.040***	0.08
EHR	0.01	0.00	0.0312***	0.02	0.00	0.050***	0.02	0.00	0.062***	0.01	

P2, the huge amount, i.e., ~100 mm of JJAS mean seasonal rainfall of EI, is reduced.

- Further, the analysis of daily rainfall over EI and its four subdivisions reveals that there is a significant reduction (90% confidence level) in a daily rainfall amount in the recent period which is observed in the 2nd of June and 25th of July to the second week of August (which is the prime time of ISMR).
- The trend analysis also reveals that there is a significant decreasing trend in the low and medium-intensity rainfall events as well as wet days. However, a remarkable increasing trend has been observed for the high-intensity rainfall events and long-duration dry spells for EI and its four subdivisions. Hence, over EI, heavy rainfall and drought conditions both are increased, but heavy rainfall events occurred over small area; however, drought events have large spread over EI.

Therefore, the outcomes of this study are very useful in determining the effects on various sectors due to the variability in the various extreme rainfall events and associated seasonal rainfall and the increasing trend of long-duration dry spells during the southwest summer season over East India and assist the risk management sectors in adopting advanced technologies for a sustainable future in the present global warming era.

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References

- 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(23):4499–4445. <https://doi.org/10.1029/2001GL013294>
- Behera SK, Ratnam JV (2018) Quasi-asymmetric response of the Indian summer monsoon rainfall to opposite phases of the IOD. *Sci Rep* 8(1):123. <https://doi.org/10.1038/s41598-017-18396-6>
- Chandniha SK, Meshram SG, Adamowski JF, Meshram C (2017) Trend analysis of precipitation in Jharkhand State, India. *Theoretical and Applied Climatology*, 130(1-2): 261-274. <https://doi.org/10.1007/s00704-016-1875-x>
- Chaturvedi RK, Gopalakrishnan R, Jayaraman M, Bala G, Joshi NV, Sukumar R, Ravindranath NH (2011) Impact of climate change on Indian forests: a dynamic vegetation modeling approach. *Mitig Adapt Strateg Glob Chang* 16(2):119–142
- Chung CE, Ramanathan V (2006) Weakening of North Indian SST gradients and the monsoon rainfall in India and the Sahel. *J Clim* 19(10):2036–2045
- Das PK, Dutta D, Sharma JR, Dadhwal VK (2016) Trends and behavior of meteorological drought (1901–2008) over Indian region using standardized precipitation–evapotranspiration index. *Int J Climatol* 36(2):909–916. <https://doi.org/10.1002/joc.4392>
- Dash SK, Kulkarni MA, Mohanty UC, Prasad K (2009) Changes in the characteristics of rain events in India. *J Geophys Res Atmos* 114(D10). <https://doi.org/10.1029/2008JD010572>
- Deng D, Ritchie EA (2019) An unusual extreme rainfall event in Canberra Australia on February 2018. *J Geophys Res Atmos* 124(8):4429–4445. <https://doi.org/10.1029/2019JD030420>
- Dey P, Sarkar AK (2011) Revisiting indigenous farming knowledge of Jharkhand (India) for conservation of natural resources and combating climate change. *Indian J Tradit Knowl* 10(1):71–79
- Easterling DR, Evans JL, Groisman PY, Karl TR, Kunkel KE, Ambejje P (2000) Observed variability and trends in extreme climate events: a brief review. *Bull Am Meteorol Soc* 81(3):417–426. [https://doi.org/10.1175/1520-0477\(2000\)081<0417:OVATIE>2.3.CO;2](https://doi.org/10.1175/1520-0477(2000)081<0417:OVATIE>2.3.CO;2)
- 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(3-4):1461–1470. <https://doi.org/10.1007/s00382-018-4207-2>
- Fischer EM, Knutti R (2016) Observed heavy precipitation increase confirms theory and early models. *Nat Clim Chang* 6(11):986–991. <https://doi.org/10.1038/nclimate3110>
- Gadgil S, Francis PA, Vinayachandran PN (2019) Summer monsoon of 2019: understanding the performance so far and speculating about the rest of the season. *Curr Sci* 117(5):783–793
- Ghosh S, Vittal H, Sharma T, Karmakar S, Kasiviswanathan KS, Dhanesh Y, Sudheer KP, Gunthe SS (2016) Indian summer monsoon rainfall: implications of contrasting trends in the spatial variability of means and extremes. *PLoS One* 11(7):e0158670. <https://doi.org/10.1371/journal.pone.0158670>
- Goswami BN, Venugopal V, Sengupta D, Madhusoodanan MS, Xavier PK (2006) Increasing trend of extreme rain events over India in a warming environment. *Science* 314(5804):1442–1445. <https://doi.org/10.1126/science.1132027>
- Groisman PY, Knight RW, Easterling DR, Karl TR, Hegerl GC, Razuvaev VN (2005) Trends in intense precipitation in the climate record. *J Clim* 18(9):1326–1350. <https://doi.org/10.1175/JCLI3339.1>
- Guhathakurta P, Sreejith OP, Menon PA (2011) Impact of climate change on extreme rainfall events and flood risk in India. *J Earth Syst Sci* 120(3):359–373. <https://doi.org/10.1007/s12040-011-0082-5>
- Guhathakurta P, Rajeevan M, Sikka DR, Tyagi A (2015) Observed changes in southwest monsoon rainfall over India during 1901–2011. *Int J Climatol* 35(8):1881–1898. <https://doi.org/10.1002/joc.4095>
- Hong SY (2004) Comparison of heavy rainfall mechanisms in Korea and the central US. *Journal of the Meteorological Society of Japan*. Ser II 82(5):1469–1479. <https://doi.org/10.2151/jmsj.2004.1469>
- IPCC 2013 Climate Change (2013) *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* T F Stocker et al (Cambridge: Cambridge University Press) at press
- King AD, Alexander LV, Donat MG (2013) The efficacy of using gridded data to examine extreme rainfall characteristics: a case study for Australia. *Int J Climatol* 33(10):2376–2387. <https://doi.org/10.1002/joc.3588>
- Kishtawal CM, Niyogi D, Tewari M, Pielke RA Sr, Shepherd JM (2010) Urbanization signature in the observed heavy rainfall climatology over India. *Int J Climatol* 30(13):1908–1916. <https://doi.org/10.1002/joc.2044>

- Krishnamurthy V, Ajayamohan RS (2010) Composite structure of monsoon low pressure systems and its relation to Indian rainfall. *J Clim* 23(16):4285–4305. <https://doi.org/10.1175/2010JCL12953.1>
- Kulkarni A (2012) Weakening of Indian summer monsoon rainfall in warming environment. *Theor Appl Climatol* 109(3–4):447–459. <https://doi.org/10.1007/s00704-012-0591-4>
- Kumar KK, Rajagopalan B, Cane MA (1999) On the weakening relationship between the Indian monsoon and ENSO. *Science* 284(5423):2156–2159. <https://doi.org/10.1126/science.284.5423.2156>
- Kumar A, Dudhia J, Rotunno R, Niyogi D, Mohanty UC (2008) Analysis of the 26 July 2005 heavy rain event over Mumbai, India using the Weather Research and Forecasting (WRF) model. *Q J R Meteorol Soc* 134(636):1897–1910. <https://doi.org/10.1002/qj.325>
- Kumar V, Jain SK, Singh Y (2010) Analysis of long-term rainfall trends in India. *Hydrological Sciences Journal—Journal des Sciences Hydrologiques* 28;55(4):484–496
- Kumar S, Sheoran S, Kumar SK, Kumar P, Meena RS (2016) Drought: a challenge for Indian farmers in context to climate change and variability. *Progressive Research – An International Journal* 11:6243–6246
- Li X, Hu Q (2019) Spatiotemporal changes in extreme precipitation and its dependence on topography over the Poyang Lake Basin, China. *Adv Meteorol* 2019:1–15. <https://doi.org/10.1155/2019/1253932>
- Mallya G, Mishra V, Niyogi D, Tripathi S, Govindaraju RS (2016) Trends and variability of droughts over the Indian monsoon region. *Weather Clim Extremes* 12:43–68. <https://doi.org/10.1016/j.wace.2016.01.002>
- Mason SJ, Waylen PR, Mimmack GM, Rajaratnam B, Harrison JM (1999) Changes in extreme rainfall events in South Africa. *Clim Chang* 41(2):249–257. <https://doi.org/10.1023/A:1005450924499>
- Meshram SG, Singh VP, Meshram C (2017) Long-term trend and variability of precipitation in Chhattisgarh State, India. *Theor Appl Climatol* 129(3–4):729–744. <https://doi.org/10.1007/s00704-016-1804-z>
- Mishra V, Smoliak BV, Lettenmaier DP, Wallace JM (2012) A prominent pattern of year to-year variability in Indian Summer Monsoon Rainfall. *Proc Natl Acad Sci* 109(19):7213–7217. <https://doi.org/10.1073/pnas.1119150109>
- Mishra V, Aadhar S, Asoka A, Pai S, Kumar R (2016) On the frequency of the 2015 monsoon season drought in the Indo-Gangetic Plain. *Geophys Res Lett* 43(23):12102–12112. <https://doi.org/10.1002/2016GL071407>
- Mohanty UC, Nageswararao MM, Sinha M, Nair A, Singh A, Rai RK, Kar SC, Ramesh KJ, Singh KK, Ghosh K, Rathore LS, Sharma R, Kumar A, Dhekale BS, Maurya RKS, Sahoo RK, Dash GP (2019a) Evaluation of performance of seasonal precipitation prediction at regional scale over India. *Theor Appl Climatol* 135(3–4):1123–1142. <https://doi.org/10.1007/s00704-018-2421-9>
- Mohanty UC, Sinha P, Mohanty MR, Maurya RKS, Nageswararao MM, Pattanaik DR (2019b) A review on the monthly and seasonal forecast of the Indian summer monsoon. *Mausam* 70(3):425–442
- Nageswararao MM, Mohanty UC, Ramakrishna SSVS, Nair A, Prasad SK (2016) Characteristics of winter precipitation over Northwest India using high-resolution gridded dataset (1901–2013). *Glob Planet Chang* 147:67–85. <https://doi.org/10.1016/j.gloplacha.2016.10.017>
- Nageswararao MM, Mohanty UC, Ramakrishna SSVS, Dimri AP (2018a) An intercomparison of observational precipitation data sets over Northwest India during winter. *Theor Appl Climatol* 132(1–2):181–207. <https://doi.org/10.1007/s00704-017-2083-z> ISSN: 0177-798X
- Nageswararao MM, Mohanty UC, Dimri AP, Osuri KK (2018b) Probability of occurrence of monthly and seasonal winter precipitation over Northwest India based on antecedent monthly precipitation. *Theor Appl Climatol* 132(3–4):1247–1259. <https://doi.org/10.1007/s00704-017-2171-0> ISSN: 0177-798X
- Nageswararao MM, Dhekale BS, Mohanty UC (2018c) Impact of climate variability on various Rabi crops over Northwest India. *Theor Appl Climatol* 131(1–2):503–521. <https://doi.org/10.1007/s00704-016-1991-7> ISSN: 0177-798X
- Nageswararao MM, Sannan MC, Mohanty UC (2019a) Characteristics of various rainfall events over South Peninsular India during northeast monsoon using high-resolution gridded dataset (1901–2016). *Theor Appl Climatol* 137(3–4):2573–2593. <https://doi.org/10.1007/s00704-018-02755-y>
- Nageswararao MM, Sinha P, Mohanty UC, Panda RK, Dash GP (2019b) Evaluation of district level rainfall characteristics over Odisha using high-resolution gridded dataset (1901–2013). *SN Appl Sci* 1(10):1211. <https://doi.org/10.1007/s42452-019-1234-5>
- Nath R, Nath D, Li Q, Chen W, Cui X (2017) Impact of drought on agriculture in the Indo-Gangetic Plain, India. *Adv Atmos Sci* 34(3):335–346. <https://doi.org/10.1007/s00376-016-6102-2>
- Pai DS (2004) A possible mechanism for the weakening of El Niño–monsoon relationship during the recent decade. *Meteorol Atmos Phys* 86(3–4):143–157. <https://doi.org/10.1007/s00703-003-0608-8>
- Pai DS, Sridhar L, Rajeevan M, Sreejith OP, Satbhai NS, Mukhopadhyay B (2014a) 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):1–18
- Pai DS, Sridhar L, Badwaik MR, Rajeevan M (2014b) Analysis of the daily rainfall events over India using a new long period (1901–2010) high-resolution (0.25° × 0.25°) gridded rainfall data set. *Clim Dyn*. <https://doi.org/10.1007/s00382-014-2307-1>
- Pai DS, Sridhar L, Badwaik MR, Rajeevan M (2015) Analysis of the daily rainfall events over India using a new long period (1901–2010) high resolution (0.25 × 0.25) gridded rainfall data set. *Clim Dyn* 45(3–4):755–776. <https://doi.org/10.1007/s00382-014-2307-1>
- Parthasarathy B (1995) Monthly and seasonal rainfall series for all India, homogeneous regions and meteorological subdivisions: 1871–1994. Indian Institute of Tropical Meteorology Research Report.
- Rao SA, Dhakate AR, Saha SK, Mahapatra S, Chaudhari HS, Pokhrel S, Sahu SK (2012) Why is Indian Ocean warming consistently? *Clim Chang* 110(3–4):709–719. <https://doi.org/10.1007/s10584-011-0121-x>
- Roxy MK, Ritika K, Terray P, Masson S (2014) The curious case of Indian Ocean warming. *J Clim* 27(22):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 Indian Ocean warming and a weakening land-sea thermal gradient. *Nat Commun* 6:7423. <https://doi.org/10.1038/ncomms8423>
- Roxy MK, Ghosh S, Pathak A, Athulya R, Mujumdar M, Murtugudde R, Terray P, Rajeevan M (2017) A threefold rise in widespread extreme rain events over central India. *Nat Commun* 8(1):708. <https://doi.org/10.1038/s41467-017-00744-9>
- Saha A, Ghosh S, Sahana AS, Rao EP (2014) Failure of CMIP5 climate models in simulating post-1950 decreasing trend of Indian monsoon. *Geophys Res Lett* 41(20):7323–7330. <https://doi.org/10.1002/2014GL061573>
- Sahany S, Venugopal V, Nanjundiah RS (2010) The 26 July 2005 heavy rainfall event over Mumbai: numerical modeling aspects. *Meteorol Atmos Phys* 109(3–4):115–128. <https://doi.org/10.1007/s00703-010-0099-3>
- Saji NH, Yamagata T (2003) Possible impacts of Indian Ocean dipole mode events on global climate. *Clim Res* 25(2):151–169. <https://doi.org/10.3354/cr025151>
- Samantaray AK, Singh G, Ramadas M, Panda RK (2019) Drought hotspot analysis and risk assessment using probabilistic drought monitoring and severity–duration–frequency analysis. *Hydrol Process* 33(3):432–449. <https://doi.org/10.1002/hyp.13337>

- Seenirajan M, Natarajan M, Thangaraj R, Bagyaraj M (2017) Study and analysis of Chennai flood 2015 using GIS and multicriteria technique. *J Geogr Inf Syst* 9(02):126–140. <https://doi.org/10.4236/jgis.2017.92009>
- Sikka DR (1980) Some aspects of the large scale fluctuations of summer monsoon rainfall over India in relation to fluctuations in the planetary and regional scale circulation parameters. *Proc Indian Acad Sci Earth Planet Sci* 89(2):179–195. <https://doi.org/10.1007/BF02913749>
- Swain M, Pattanayak S, Mohanty UC (2018) Characteristics of occurrence of heavy rainfall events over Odisha during summer monsoon season. *Dyn Atmos Oceans* 82:107–118. <https://doi.org/10.1016/j.dynatmoce.2018.05.004>
- Swain M, Sinha P, Pattanayak S, Guhathakurta P, Mohanty UC (2020) Characteristics of observed rainfall over Odisha: an extreme vulnerable zone in the east coast of India. *Theor Appl Climatol* 139:517–531. <https://doi.org/10.1007/s00704-019-02983-w>
- Tesfaye K, Aggarwal P, Mequanint F, Shirsath P, Stirling C, Khatri-Chhetri A, Rahut D (2017) Climate variability and change in Bihar, India: challenges and opportunities for sustainable crop production. *Sustainability* 9(11):1998. <https://doi.org/10.3390/su9111998>
- Vishnu S, Francis PA, Shenoi SSC, Ramakrishna SSVS (2016) On the decreasing trend of the number of monsoon depressions in the Bay of Bengal. *Environ Res Lett* 11(1):014011. <https://doi.org/10.1088/1748-9326/11/1/014011>
- Warwade P, Tiwari S, Ranjan S, Chandniha SK, Adamowski J (2018) Spatio-temporal variation of rainfall over Bihar State, India. *J Water Land Dev* 36(1):183–197. <https://doi.org/10.2478/jwld-2018-0018>
- Zhang X, Hogg WD, Mekis É (2001) Spatial and temporal characteristics of heavy precipitation events over Canada. *J Clim* 14(9):1923–1936. [https://doi.org/10.1175/1520-0442\(2001\)014<1923:SATCOH>2.0.CO;2](https://doi.org/10.1175/1520-0442(2001)014<1923:SATCOH>2.0.CO;2)
- Zhao Y, Zhang H (2016) Impacts of SST Warming in tropical Indian Ocean on CMIP5 model-projected summer rainfall changes over Central Asia. *Clim Dyn* 46(9-10):3223–3238. <https://doi.org/10.1007/s00382-015-2765-0>

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