



## Observed Changes in Indian Summer Monsoon Rainfall at Different Intensity Bins during the Past 118 Years over Five Homogeneous Regions

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**Abstract**—In the present paper, the variabilities and long-term trends of summer monsoon rainfall for different intensity bins (dry, low, moderate, high, very high, and extreme) are studied for five homogeneous regions, namely Northeast India (NEI), Northcentral India (NCI), Northwest India (NWI), Westcentral India (WCI), and Peninsular India (PI) for 118 years (1901–2018). The study was carried out based on gridded rainfall data from the India Meteorological Department (IMD). The rainfall characteristics such as number of rainy days, percentage contribution, and periodicity of rainfall intensity classes are analysed and found to be different in different homogeneous regions. The long-term trend (1901–2018) of total rainfall showed a significant increasing trend (19.9 mm decade<sup>-1</sup>) in NEI and significant decreasing trends in NCI (9.6 mm decade<sup>-1</sup>) and PI (4.9 mm decade<sup>-1</sup>). Analysis on rainfall intensity indicates a significant increasing trend for high, very high, and extreme classes in NEI, a significant increasing trend for dry, and a decreasing trend for moderate and very high classes over NCI and PI. From correlation analysis among the homogeneous regions, it is found that the rain events in different intensity classes show different relationships, which indicate the regional heterogeneity in rainfall characteristics. It is also important to note that an increase in rainfall contribution from very high and extreme classes was found over NEI, NWI, and WCI in the multidecadal period of 1991–2018, while NCI showed a decrease during this period; however, in NCI, a drastic increase for these intensity bins is distinct during the 1961–1990 multidecadal period. In addition to the trends and variabilities, we also explored spatial heterogeneity of different rainfall intensity categories, and found remarkable differences from one homogeneous region to another.

**Keywords:** Indian summer monsoon rainfall, rainfall trend, regional rainfall variability, rainfall intensities, homogeneous region, multidecadal variabilities.

### 1. Introduction

The Indian summer monsoon rainfall (ISMR) is a significant rainy season from June to September, which is a part of the Asian monsoon system that accounts for about 75–80% of the annual rainfall over major parts of India. It is fundamentally driven by land–sea thermal contrast (Meehl & Washington, 1993) between the Asian landmass and neighbouring water bodies in the Northern Hemisphere summer, which leads to meridional temperature and pressure gradients that results in cross-equatorial flow (Turner & Annamalai, 2012). Thus, ISMR is a highly complex system that differs both in space and time, exhibiting significant variabilities from diurnal to multidecadal time scales (Sahany et al., 2010; Varikoden et al., 2012; Guhathakurta et al., 2014; Seetha et al., 2020; Rajesh & Goswami, 2020). All the major sectors in India, including agriculture and industry, depend directly or indirectly on the ISMR, and the latter plays a key role in altering the economy of India (Gadgil & Gadgil, 2006).

Awareness of spatial and temporal variability of rainfall is important for meteorology, freshwater resources, agricultural production, telecommunication, and climate science. The rainfall and its variability cause severe droughts and floods and form an important component of the hydrological cycle and affect the growth of all living organisms as well. In the past, attempts have been made in India to establish patterns in rainfall; such patterns suggest that monsoon variability has significantly modulated in recent decades (Dash et al., 2011; Singh et al., 2014; Ghosh et al., 2016; Mohan & Rajeevan, 2017; Preethi et al., 2017; Varikoden et al., 2019). Therefore, studies on the spatio-temporal patterns and the

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variability of ISMR are of great relevance. Trends in southwesterly low-level monsoon circulation and rainfall have been reported in several studies (Joseph & Simon, 2005; Naidu et al., 2009; Kumar et al., 2010; Mishra et al., 2012; Kulkarni, 2012; Varikoden et al., 2013; Roxy et al., 2015; Karmakar et al., 2017; Chou et al., 2018). However, Huang et al. (2020) have indicated that it is showing a decline from 1950 to 1999 with a recovery from 1999 to 2013. From the 1980s, ISMR shows a decreasing trend over North India and Northwest India. It was hypothesized that the large-scale irrigation (40% of total land cover in India) development that started in the 1950s has resulted in land surface cooling, which slowed large-scale atmospheric circulation, exerting significant influences on ISMR with the high spatial and temporal heterogeneity (Chou et al., 2018; Douglas et al., 2009; Feddema et al., 2005; Ghosh et al., 2009; Kuttippurath et al., 2021; Varikoden & Revadekar, 2020). The south-east, north-west, and north-east regions of India showed a significant increasing trend in summer monsoon rainfall, and a decreasing trend ( $0.04 \text{ mm year}^{-1}$ ) in and around central India (Fukushima et al., 2019; Varikoden et al., 2013).

Looking at the categorized rainfall analysis, precipitation indices show a tendency towards increase in extreme precipitation events throughout the twentieth and twenty-first century over several homogeneous regions in India (Alexander et al., 2006; Goswami et al., 2006; Dash et al., 2007; Rajeevan, 2008; Pattanaik & Rajeevan, 2010; Krishnan et al., 2015; Singh et al., 2014; Guhathakurta et al., 2011; Roxy et al., 2017; Varikoden & Revadekar, 2020; Luwangleima & Shrivastava, 2021). The increase in extreme rainfall events has been attributed to the increase in convective available potential energy, low-level moisture convergence and water-holding capacity of the atmosphere (Singh et al., 2014), higher precipitable water content associated with warming of the Indian Ocean and Indian subcontinent (Goswami et al., 2006; Rajeevan et al., 2008; Krishnan et al., 2015; Guhathakurta et al., 2011), as well as the upper-tropospheric heating that destabilizes the atmosphere and enhances precipitation (Lau et al., 2006). Summer monsoon rainfall studies over central India during 1951–2000 do not show a significant trend in mean rainfall; however, a

significant decreasing trend is observed in the moderate and low intensity events (Goswami et al., 2006; Rajeevan et al., 2010; Dash et al., 2011). More concentrated studies are reported in Northeast India, which conclude that a significant increasing (decreasing) trend is observed in consecutive dry days, very high rainfall events, and extreme rainfall events (low rainfall events) (Luwangleima & Shrivastava, 2021; Sheikh et al., 2015; Varikoden & Revadekar, 2020). Nair et al. (2018) found a negative trend in rainfall in Peninsular India, Northcentral India, and Northeast India, and positive trends in Westcentral India and Northwest India with high significance in Northwest India in recent multidecades (1979–2017). Contrasting trends are also reported in rainfall in the northern and southern regions of the Western Ghats, and these contrasting trends were attributed to the northward shifting of low-level winds (Sudeepkumar et al., 2018; Varikoden et al., 2019).

Several studies have reported that the temporal and spatial distributions of ISMR have changed in the recent past and that these changes are likely to amplify in the near future (Rajendran et al., 2012; Krishnan et al., 2013; Menon et al., 2013; Li et al., 2017; Sabeerali and Ajaymohan, 2018). Variability in monsoon rainfall can lead to far-reaching impacts on the general population for a developing country like India. Thus, the study of variabilities in ISMR has a significant socio-economic relevance. Studies on trend analysis conducted so far are either for total rainfall or for different rainfall intensity in a particular area. Classification of seasonal rainfall patterns over India into different intensity bins to identify dominant modes of spatio-temporal variability is essential. Understanding of these patterns will lead to identification of its mechanisms and thus improving sustainable water management, agricultural production, electricity generation, etc.

In this study, we analysed the long-term trend of total summer monsoon rainfall and rainfall patterns in six intensity bins for the five homogeneous regions (Northeast India, Northcentral India, Northwest India, Westcentral India, and Peninsular India). We also explored the long-term and multidecadal spatial coherence of rainfall intensity classes among the homogeneous regions. We also compared the variations in number of days and percentage of

contribution by each rainfall intensity class in the regions over the multidecadal periods. We also examined the periodicity of the intensity classes over the regions. The paper is organised as three main sections. Section 2 introduces the new observational data set, period of study, different homogeneous regions, intensity bins, and methods of analysis used in the study. Section 3 describes the long-term trend and variability of different rainfall intensities during the summer monsoon period over the five homogeneous regions. The main results are summarised in Sect. 4.

## 2. Data and Methods

We analysed long-term daily gridded rainfall data for 118 years from 1901 to 2018 provided by the India Meteorological Department (IMD) at a spatial resolution of  $0.25^\circ \times 0.25^\circ$  latitude–longitude grid (<https://www.imdpune.gov.in>). We made seasonal rainfall in each year for the southwest monsoon (JJAS) to explore interannual variability in the seasonal rainfall in addition to its long-term trends. The data sets were prepared from 6955 rain-gauge stations all over India in which missing data were filled with rainfall data from a nearby rain-gauge station using interpolation [inverse distance weighted interpolation scheme proposed by Shepard (1968)]. The station density is relatively high in the south Peninsular India and relatively low in Northwest India, Northeast India, and the eastern parts of central India. On average, data from about 2600 stations were available on a yearly basis for the preparation of daily grid point data. The data density varied from year to year, ranging from about 1450 in 1901 to about 3950 in 1991–1994. From 1951 onwards, the data density was relatively higher, greater than 3100 stations per day, with the exception for the period 2008–2010, when it dropped to around 1900 stations per day. The gridded data set was created after performing quality control on basic rain-gauge stations. When the quality of the gridded rainfall analysis was compared to similar global gridded rainfall data sets, it was discovered that the IMD gridded rainfall analysis is better in terms of realistic representation of spatial rainfall distribution (Pai et al., 2014; Rajeevan et al., 2005).

As known from several studies in India, as a whole, ISMR is not showing a unique pattern. Hence, in this study, the Indian region was subdivided into five homogeneous regions as per the classification of Indian Institute of Tropical Meteorology ([www.tropmet.res.in](http://www.tropmet.res.in)). They are Northeast India (NEI), Northcentral India (NCI), Northwest India (NWI), Westcentral India (WCI), and Peninsular India (PI) as shown in Fig. 1. In order to study the multidecadal variabilities in ISMR, the study period is further subdivided into four multidecades of 30 years each, except the last multidecade that contains only 28 years (1901–1930, 1931–1960, 1961–1990, 1991–2018). The different rainfall intensity classes on the basis of the percentile values were obtained over these multidecadal periods in each homogeneous region. The calculation of percentile values was based on the entire period and categorized in different intensity classes in percentile values as shown in Table 1. After the percentile calculation and classification, the data set was redistributed over the four multidecadal periods. The average range of rainfall attained during four multidecadal periods for different intensity classes are given in Table 2. It is observed that the homogeneous regions have variable range in each rainfall intensity class.

Statistical analyses such as Sen's slope estimation (Sen, 1968), Mann–Kendall's test (Kendall, 1975; Mann, 1945), and Student's *t* test were carried out in order to check the long-term trend and its significance for total rainfall and each rainfall intensity class over the sub-regions. To study the periodicity of rainfall in each intensity class for the different regions, spectral analysis was carried out. In order to study the spatial coherence of rainfall patterns throughout the Indian region, linear correlation coefficient analysis was carried out among the different homogeneous regions for each intensity class during 1901–2018 and for the four multidecadal periods. Multidecadal variabilities in each intensity class were also examined by studying the rainfall characteristics in each intensity class such as average rainfall, total number of rainy days in each intensity bin, percentage contribution to the total rainfall, standard deviation from the mean, and sum of rainfall.

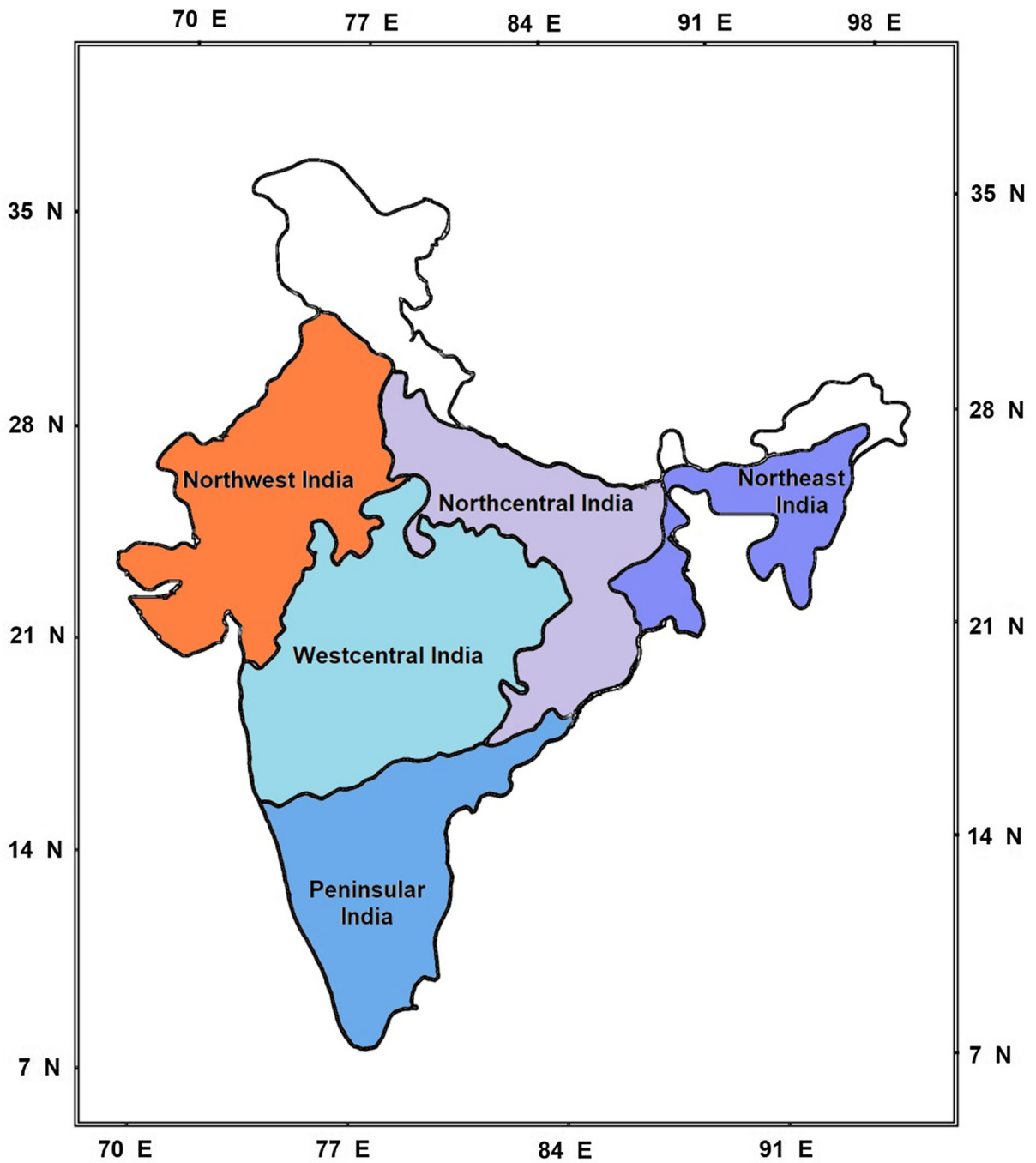


Figure 1

Schematic diagram of monsoon rainfall homogeneous regions over India considered for the present study. Prepared as per the homogeneous regions of India classified by the Indian Institute of Tropical Meteorology ([www.tropmet.res.in](http://www.tropmet.res.in))

Table 1  
Percentile value for each intensity class

Percentile value (%)	Rainfall intensity class
Below 10	Dry
10–50	Low
51–90	Moderate
91–95	High
96–99	Very high
Above 99	Extreme

### 3. Results and Discussion

#### 3.1. Long-Term Trends and Variability of Seasonal Rainfall

The long-term trend and variabilities of summer monsoon rainfall of five homogeneous regions over 118 years are shown in Fig. 2. It is found that different homogeneous regions show different trends in both direction and magnitudes. It is found there is a significant increasing trend in NEI (Fig. 2a), and the value of the linear trend is  $19.9 \text{ mm decade}^{-1}$ . A significant decreasing trend is found in NCI (Fig. 2b) and PI (Fig. 2e) with rates of  $9.6 \text{ mm decade}^{-1}$  and  $4.9 \text{ mm decade}^{-1}$ , respectively. All these trends are significant at a 0.05 level. These decreasing trends were also reported by Nair et al. (2018), but with different magnitudes, and it may be due to their chosen time period from 1979 to 2017. Insignificant increasing and decreasing trends are noticed in NWI

and WCI, respectively. The total rainfall received during the summer monsoon period is highest in NEI and lowest in NWI.

It is found from the 11-year running mean and the long-term mean of rainfall in each region that summer monsoon rainfall is below normal from 1901 to about 1965 in NEI (Fig. 2a). During this period, the rainfall showed low-amplitude multi-decadal variability and a very low interannual variability. A similar finding was also reported by Kuttippurath et al. (2021) in the northeast regions of India based on the long-term station rainfall data set. But the rainfall trend shows a dramatic increase from 1970 to the mid-1980s and thereafter a declining trend, even though the rainfall is above normal till 2000. After 2000, the rainfall is below normal, and it starts to revive to normal from 2010 onwards, which almost resembles the pattern of variability in pre-1960 condition.

Contrasting rainfall patterns with above and below-normal rainfall are observed in NCI before and after 1960, respectively (Fig. 2b). Multidecadal and interannual variabilities are seen but with less variability after 1960 with below normal rainfall condition, and it persists till 2018. However, Huang et al. (2020) reported a revival of rainfall after 1999, but this revival does not persist in the present study. In the case of NWI (Fig. 2c), the multidecadal variability is more pronounced towards the recent periods with an increased amplitude and decreased interannual variability from the 1960s. A similar

Table 2  
Range of rainfall in each intensity class for the multidecadal periods over the homogeneous regions

Dry range (mm day <sup>-1</sup> )	Low range (mm day <sup>-1</sup> )	Moderate range (mm day <sup>-1</sup> )	High range (mm day <sup>-1</sup> )	Very high range (mm day <sup>-1</sup> )	Extreme range (mm day <sup>-1</sup> )
Northeast India 0–2.57	2.59–10.18	10.20–24.61	24.65–31.43	31.52–50.38	50.59–85.80
Northcentral India 0–0.81	0.82–5.83	5.84–17.04	17.07–21.86	21.90–30.33	33.50–60.44
Northwest India 0–0.12	0.12–2.50	2.50–11.87	11.90–15.26	15.29–21.32	21.50–33.40
Westcentral India 0–0.99	0.98–5.95	5.96–16.96	16.92–21.10	21.12–31.97	32.28–52.88
Peninsular India 0.41–1.54	1.54–6.38	6.4–15.83	15.85–19.38	19.41–27.85	28.10–54.00

Average range for the four multidecadal periods are given

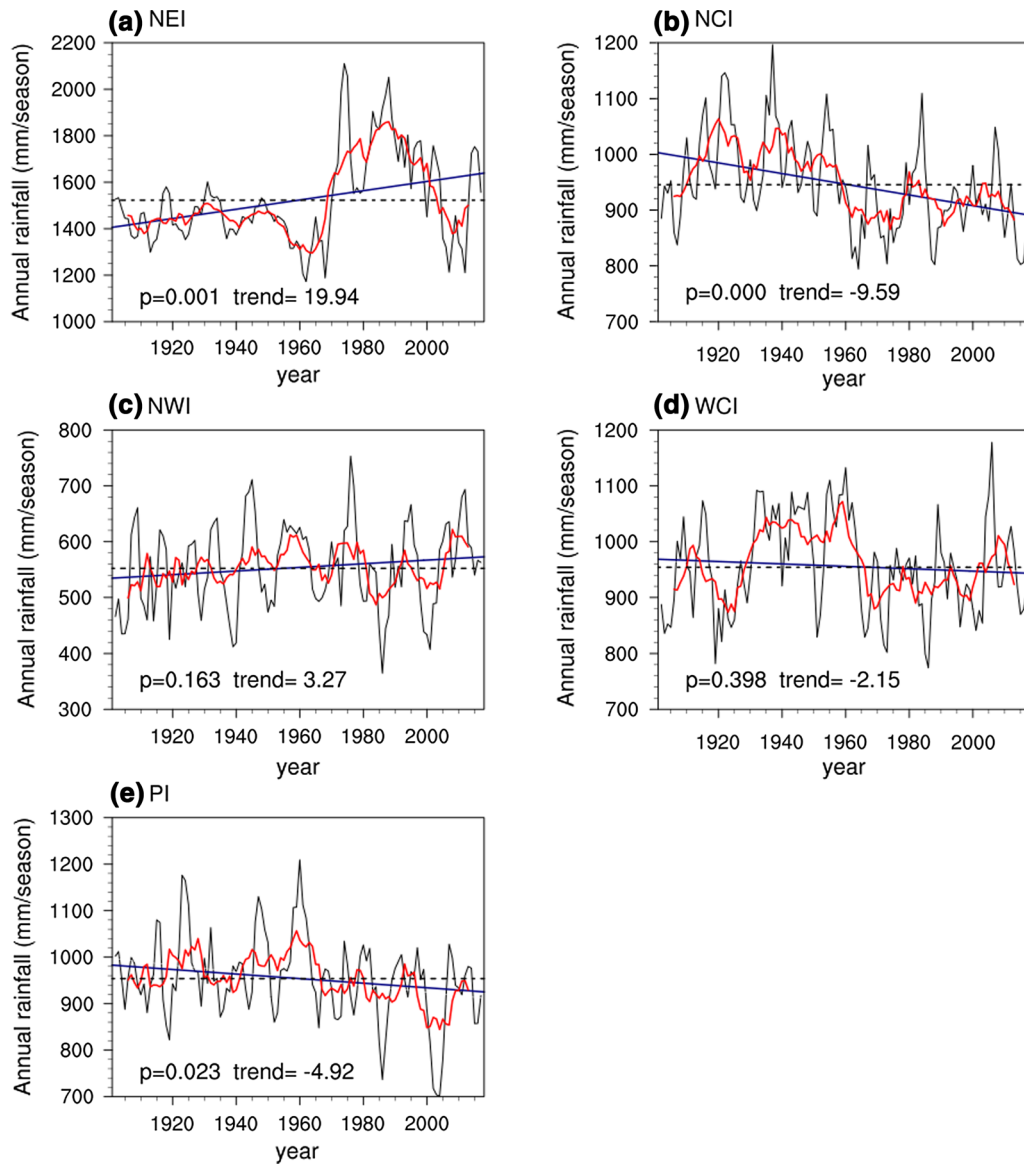


Figure 2

Long-term trend of monsoon rainfall for five homogeneous regions. Time series of summer monsoon rainfall (solid line) averaged in (a) Northeast India (NEI), (b) Northcentral India (NCI), (c) Northwest India (NWI), (d) Westcentral India (WCI), and (e) Peninsular India (PI). The red solid line represents the 11-year running mean, and the dashed line represents mean rainfall. The straight blue line shows the Sen's slope of long-term trend for 1901–2018. The  $p$ -value ( $p$ ) and trend value ( $t$ ) of the Sen's slope are given in the individual panels. The unit of trends is in  $\text{mm decade}^{-1}$ .

result of a decreasing trend in rainfall from the 1980s was reported in Chou et al. (2018); however, in the present study, we found a signature of recovery from 2005 onwards. In WCI (Fig. 2d), we identified an oscillatory pattern in the decadal variability, the amplitude and periodicity of which decreased after

1960. The above normal rainfall pattern is observed from the mid-1920s to mid-1960s, and rainfall is below normal from the mid-1960 to 2000. In both regions, epochs of above and below normal rainfall are almost symmetrical with respect to the mean, which attributes to the less significant trend value.

Similar to WCI, a similar pattern was identified in PI (Fig. 2e) in which multidecadal variability is changed to decadal time scale after 1960. It is important to highlight that during pre-1960, wet extremes of rainfall events are observed; however, during the post-1960 period, these wet extremes are replaced with dry extremes. In general, total rainfall received during the monsoon seasons in these regions clearly shows a spatial variability in the linear trends and other rainfall features. In all the regions, rainfall pattern changed since the 1960s, indicating the effect of climate shift (Baines & Folland, 2007; Joshi & Pandey, 2011).

In addition to the total rainfall, we also investigated the rainfall in six different intensity bins to explore the variabilities and trends of the individual intensity bins. It is important to note that variability and trends in total rainfall may be different from the variabilities of different intensity classes due to the contrasting variabilities and trends in different intensity classes. An elaborated view of the monsoon rainfall with respect to intensity bins is necessary, as changes in rainfall eventually affect the groundwater reserve, salt water intrusion in the coastal belts, soil moisture, agricultural production, drinking water, electricity generation, etc.

### 3.2. Variabilities and Trends of Seasonal Rainfall in Different Intensity Classes

In order to understand further features of rainfall variability, we classified the total monsoon rainfall into different intensity bins based on percentile value as described in Table 1. The long-term trend of rainfall in each intensity class over the five homogeneous regions is shown in Fig. 3. Significant trends were observed in different intensity bins in all the regions. The dry intensity bin (< 10th percentile) exhibits a significant increasing trend over NEI, NCI, and PI, whereas a significant decreasing trend is found in NWI. The low intensity bin (10–50th percentile) showed a significant decreasing trend in NEI and a significant increasing trend in WCI. Regarding the moderate intensity class (51–90th percentile), a significant decreasing trend is found in NEI, NCI, and PI, while in NWI, the trend is increasing. For the high intensity bin (91–95th

percentile), a significant increasing trend is noticed in NEI, with significant decreasing trends in NWI and WCI. For the very high intensity bin (96–99th percentile) a significant increasing trend is registered only in NEI; however, it is decreasing significantly in NCI, WCI, and PI. In the extreme bin (> 99th percentile), we observed significant increasing trends in NEI and WCI; non-significant trends were seen in all other regions. All the trends are significant at a 0.05 level, except for the moderate intensity class in PI and high intensity class in WCI which are significant at a 0.10 significance level. This analysis may be used to understand which category of rainfall would have contributed to the seasonal total rainfall trend. In addition to this, we found significant trends in certain intensity classes which were not identified in the long-term trend analysis of seasonal total rainfall. The results for NEI for very high and extreme cases are in accordance with the findings of Varikoden and Revadekar (2020).

The long-term average and 11-year running mean of rainfall in each intensity bin over NEI (Fig. 3a) has significant epochal variabilities since the mid-1950s. Dry-, low-, and moderate intensity classes have an interannual variability rather than a prominent multidecadal variability pattern before mid-1950s, and that for high, very high and extreme cases is before the mid-1960s. Rainfall from dry events is below normal, while low and moderate events are above normal till 1950, after which significant multidecadal variability is observed for the three events with dry and low in the same phase. High, very high- and extreme intensity classes showed a drastic increase after 1960, and therefore, distinct centennial scale variability is observed. In the post-1960 period, the embedded interannual variability is also dominant. In NCI (Fig. 3b), multidecadal variabilities are prominent for the dry, low, and moderate intensity classes. For dry and low intensity bins, the phase of multidecadal variability is opposite during the entire study period. However, the rainfall was above normal from 1901 to 1960 for the moderate-intensity bin, after which there was a decline to below-normal rainfall till 2000, which indicates a centennial mode of oscillation; this mode of periodicity is not reported so far in the studies of the Indian monsoon. Earlier studies reported lesser periodicities with 60–70 years

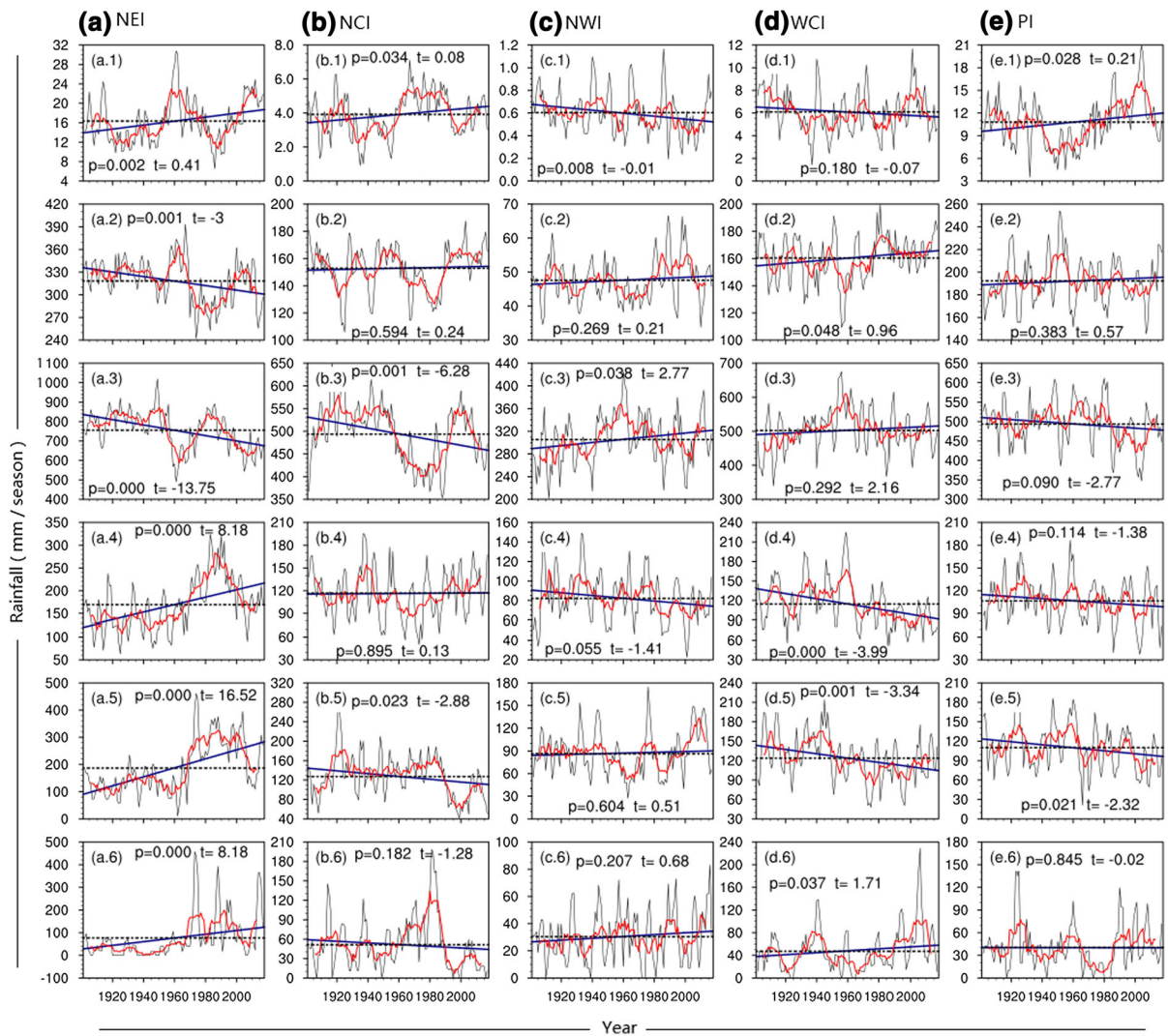


Figure 3

Long-term trend of monsoon rainfall in different intensities for the homogeneous regions. Time series of different intensities of monsoon rainfall (solid line) averaged in different homogeneous regions : (a) Northeast India, (b) Northcentral India, (c) Northwest India, (d) Westcentral India, and (e) Peninsular India. Each column from the top represents (1) dry, (2) low, (3) moderate, (4) high, (5) very high, and (6) extreme intensity classes. The red solid line represents the 11-year running mean, and the dashed line represents mean rainfall. The straight blue line represents the Sen's slope of the long-term trend for 1901–2018. The  $p$  value ( $p$ ) and trend value ( $t$ ) of the Sen's slope are given in the individual panels. The unit of trends is in  $\text{mm decade}^{-1}$ . Ordinates are not uniform in each row

of multidecadal variability with three decades of above followed by three decades of below normal monsoon (Kripalani & Kulkarni, 1997; Kripalani et al., 2003; Parthasarathy et al., 1994; Kumar et al., 1999; Goswami et al., 2015; Rajesh & Goswami, 2020). After 2000, the period of oscillation decreased to about 1/5th of the earlier periodicity. Interannual variability was highly pronounced for high, very

high, and extreme intensity bins in comparison with their multidecadal variabilities. Rainfall in the very high intensity class remained above normal for a long time (1901–1990) with high interannual variability; thereafter, below normal rainfall condition persists. In the case of the extreme intensity bin, the rainfall condition is about normal till 1960; after that, the dominance of multidecadal variability is observed.



Prominent interannual and multidecadal variabilities are observed in all the classes with varying trend values in NWI (Fig. 3c). Dry, moderate, and high intensity classes showed below normal rainfall, while low and very high intensity classes showed above normal rainfall in the recent period after the year 2000. In WCI (Fig. 3d), the low intensity class showed an above normal rainfall since 1980, and the high intensity class showed below normal rainfall since 1960. A significant decreasing trend in the frequency of moderate events over central India during the monsoon seasons from 1951 to 2000 was also observed, which is in accordance with the findings of Goswami et al. (2006). Very high and extreme intensity bins from 1950 showed rainfall below normal, which continued to 1990 and after a revival pattern was observed. Interannual variabilities are significant for dry, low, and moderate classes for the entire period for high and very high intensity bins towards recent multidecades. High interannual variability is observed for dry, low, and moderate intensities over PI (Fig. 3e), moreover, with dominant multidecadal variability in all the intensity classes. Low, moderate, and high intensity classes are observed with below normal rainfall after 1995, while the extreme intensity bin has shown above normal rainfall.

In general, it can be concluded that multidecadal variability as well as different harmonics in different time scale are distinct in rainfall intensity bins. Epochal modulation of the Indian monsoon rainfall amplitudes with three alternating decades of below-normal seasonal mean rainfall followed by three decades of above-normal seasonal mean rainfall (Kripalani et al., 2003; Goswami et al., 2006) are also identified in rainfall intensity bins over the homogeneous regions.

### 3.3. Periodicity of Rainfall Intensity Classes

Spectral analysis was carried out in order to study the periodicity of each intensity class for the different homogeneous regions (Fig. 4). The intensity classes show significant periodicities (within 0.05 significance level) in different time scales. Significant multidecadal periodicity above 50 years is observed in NEI (Fig. 4a) for moderate and high intensity bins,

in NCI (Fig. 4b) for dry, low, moderate, high, and extreme intensity bins, in NWI (Fig. 4c) for extreme intensity, in WCI (Fig. 4d) for low, high, and extreme intensity bins, and in PI (Fig. 4e) for dry, high, and extreme intensity bins. Significant multidecadal periodicity of 30–50 years is observed in the dry intensity class over NCI, in the moderate class over NEI and NWI, in the high intensity class over NEI and NWI, in the very high intensity class over all the regions, and in the extreme class over NEI. Significant decadal and interdecadal periodicities are also observed in several intensity bins: in NCI, for high and extreme (11 years), in NWI for dry, low (7–14 years), and extreme (19 years), in WCI for dry (13 years), low (14 years), and moderate (17 years), and in PI in low (9 years), high (7–9 years), and extreme (7 years) intensity bins. According to several studies, ISMR shows oscillations attributed to ocean–atmosphere interactions. On multidecadal, decadal, and interannual time scales, El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Atlantic Zonal Mode (AZM), Atlantic Multidecadal Oscillation (AMO), Indian Ocean Dipole (IOD), etc. are the main modes of global oscillations that have been linked to ISMR. ISMR has a significant positive (negative or inverse relationship) correlation with AMO and IOD (ENSO, PDO, AZM). As a result, these teleconnections have an impact on intensifying/weakening of rainfall, subsequently producing periodicities in rainfall intensity classes (Ashok et al., 2004; Joshi & Pandey, 2011; Goswami et al., 2016; Joshi & Kucharski, 2017; Malik & Brönnimann, 2018; Sabeerali et al., 2019; Seetha et al., 2020).

Very high and extreme intensity bins are showing similar periodicities in all the homogeneous regions, except NEI. The periodicity in NEI and NCI ranges between 40 to 60 years in majority of the intensity classes. Periodicities in high and very high intensity bins are observed in the decadal variability as well. In general, most of the intensity classes show significant multiple periodicities. The results clearly indicate the existence of interannual to multidecadal periodicities in addition to spatial heterogeneity. In order to understand further features on spatial heterogeneity, spatial correlation analysis was carried out and discussed in the next section.

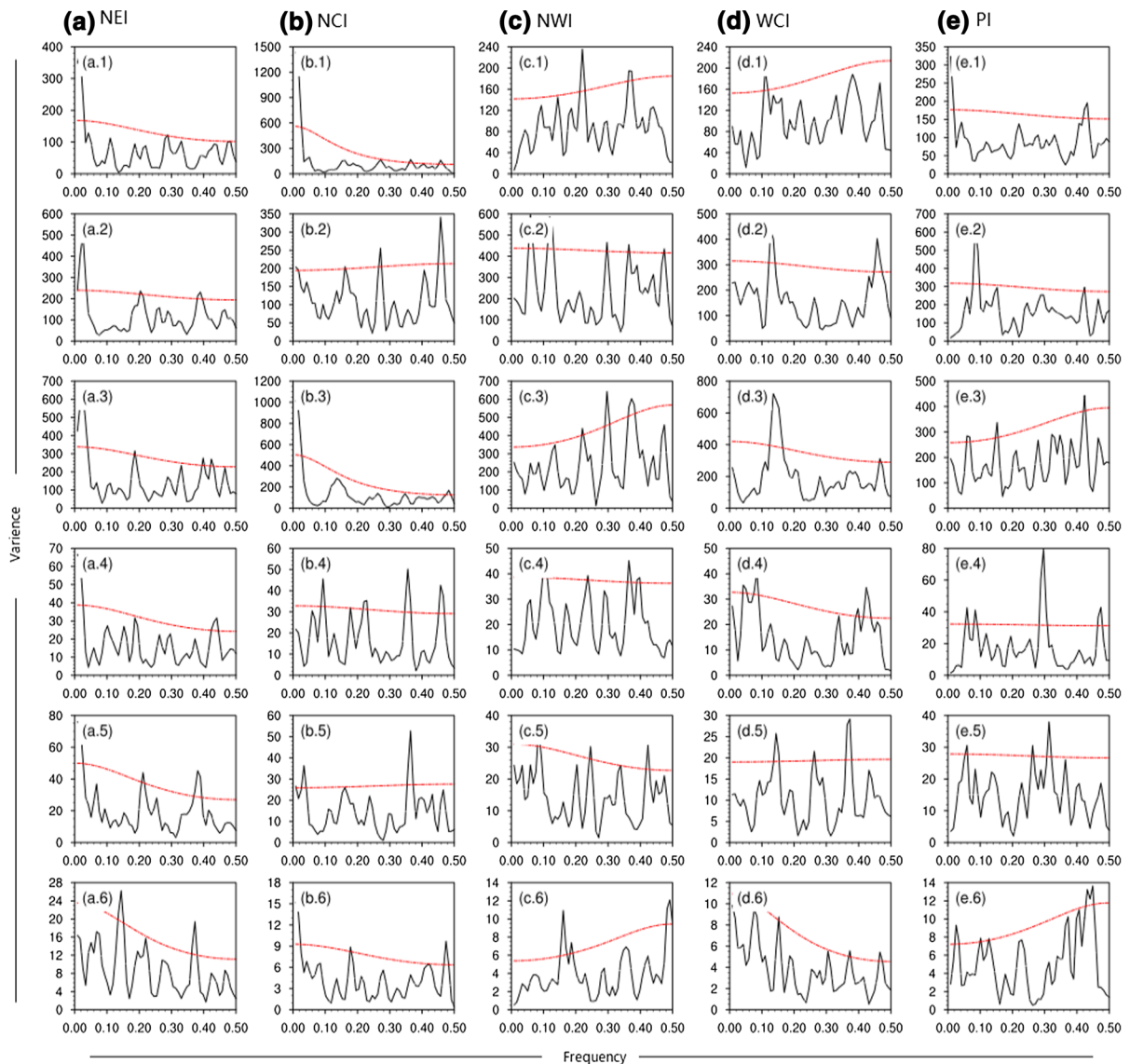


Figure 4

Periodicities of monsoon rainfall in different intensity classes for the five homogeneous regions. Frequency spectrum of different intensities for monsoon rainfall in different homogeneous regions : (a) Northeast India, (b) Northcentral India, (c) Northwest India, (d) Westcentral India, and (e) Peninsular India. Each column from the top represents (1) dry, (2) low, (3) moderate, (4) high, (5) very high, (6) extreme intensity classes. The red line represents the 0.05 significance bound. Ordinates are not uniform in each row

### 3.4. Spatial Coherence of Rainfall Intensity Classes

The spatial coherence of rainfall patterns in the five homogeneous regions is examined using linear correlation coefficient analysis and presented in Table 3. A positive value in the table indicates they are in coherence, and a negative value indicates they are out of phase. It is noticed that the dry intensity

class has a positive correlation between almost all homogeneous regions over the entire period (1901–2018). NWI and WCI, as well as WCI and PI, are in significant positive correlation with each other, which indicates they are coherent in producing the respective rainfall intensity classes. NEI shows an out-of-phase relationship with NCI and NWI in the

Table 3

The correlation values of different rainfall intensity classes between the homogenous regions for total and multidecadal periods

Regions	NEI-NCI	NEI-NWI	NEI-WCI	NEI-PI	NCI-NWI	NCI-WCI	NCI-PI	NWI-WCI	NWI-PI	WCI-PI
Dry										
<b>1901–2018</b>	0.09	−0.05	0.03	−0.07	<b>0.28</b>	<b>0.18</b>	0.05	<b>0.51</b>	0.15	<b>0.42</b>
1901–1930	−0.02	−0.25	0.22	0.01	<b>0.58</b>	<b>0.41</b>	0.15	<b>0.50</b>	0.30	<b>0.40</b>
1931–1960	−0.23	−0.09	0.06	−0.04	<b>0.55</b>	0.27	−0.06	0.22	−0.17	0.19
1961–1990	0.19	0.03	0.07	−0.33	<b>0.43</b>	<b>0.37</b>	0.31	<b>0.63</b>	<b>0.43</b>	<b>0.61</b>
1991–2018	0.35	0.07	−0.16	−0.04	<b>0.48</b>	0.24	−0.16	<b>0.57</b>	−0.09	0.29
Low										
<b>1901–2018</b>	0.06	−0.14	−0.05	−0.08	0.13	0.02	0.02	<b>0.39</b>	<b>0.23</b>	<b>0.22</b>
1901–1930	<b>0.39</b>	−0.23	−0.10	0.01	0.19	−0.12	0.04	0.32	<b>0.39</b>	0.33
1931–1960	0.17	0.01	0.01	0.04	0.17	0.10	0.01	<b>0.47</b>	0.17	<b>0.43</b>
1961–1990	−0.18	−0.18	−0.06	−0.07	0.10	−0.06	0.08	<b>0.54</b>	0.25	0.20
1991–2018	−0.09	−0.13	−0.02	−0.26	0.09	0.27	−0.08	0.27	0.19	−0.10
Moderate										
<b>1901–2018</b>	0.20	−0.09	0.06	0.07	0.09	0.02	−0.02	<b>0.52</b>	<b>0.32</b>	<b>0.50</b>
1901–1930	0.27	0.01	0.23	0.03	<b>0.48</b>	<b>0.36</b>	0.05	<b>0.54</b>	<b>0.38</b>	<b>0.60</b>
1931–1960	0.12	−0.14	0.33	0.27	−0.15	−0.12	0.03	<b>0.44</b>	0.12	<b>0.42</b>
1961–1990	−0.08	−0.01	−0.22	−0.13	0.09	−0.27	0.01	<b>0.44</b>	<b>0.46</b>	<b>0.59</b>
1991–2018	0.22	−0.09	−0.05	−0.02	0.13	0.36	−0.01	<b>0.68</b>	0.25	0.28
High										
1901–2018	−0.13	−0.05	<b>−0.18</b>	−0.02	−0.04	0.03	0.07	<b>0.36</b>	0.17	<b>0.20</b>
1901–1930	−0.24	−0.21	−0.12	−0.02	−0.13	−0.12	0.13	0.22	0.25	0.07
1931–1960	0.13	0.28	−0.11	−0.18	0.10	−0.01	0.02	<b>0.47</b>	0.20	<b>0.53</b>
1961–1990	−0.03	0.05	0.16	0.33	−0.28	0.22	0.04	<b>0.39</b>	−0.07	0.16
1991–2018	−0.32	−0.08	−0.24	−0.02	0.09	0.06	0.11	0.35	0.23	−0.20
Very high										
<b>1901–2018</b>	−0.11	−0.14	−0.13	−0.15	−0.11	0.06	0.09	0.17	0.13	0.08
1901–1930	0.08	−0.28	0.25	0.02	−0.15	0.02	−0.01	0.11	<b>0.39</b>	<b>−0.41</b>
1931–1960	−0.18	−0.07	0.00	0.19	−0.18	−0.07	0.0	0.33	−0.07	0.02
1961–1990	0.03	−0.03	<b>−0.42</b>	−0.22	−0.12	0.17	0.27	0.00	0.11	0.04
1991–2018	−0.31	−0.31	0.16	−0.24	0.37	0.02	0.09	0.29	0.06	0.21
Extreme										
<b>1901–2018</b>	−0.03	0.10	−0.08	−0.09	<b>−0.18</b>	−0.14	0.06	0.05	−0.01	−0.03
1901–1930	0.28	−0.16	−0.08	0.08	−0.25	0.01	<b>0.43</b>	0.22	−0.08	−0.20
1931–1960	0.03	0.16	−0.09	0.06	<b>−0.41</b>	0.04	0.15	−0.10	0.14	0.23
1961–1990	−0.21	−0.12	−0.17	−0.10	−0.12	−0.18	−0.02	−0.11	0.10	−0.11
1991–2018	−0.08	<b>0.44</b>	−0.10	−0.24	−0.08	−0.05	−0.03	0.16	−0.10	−0.18

The regions are represented as *NEI* Northeast India, *NCI* Northcentral India, *NWI* Northwest India, *WCI* Westcentral India, and *PI* Peninsular India. Bold values are at a 0.05 significance level

early multidecades, and this relationship is gradually reversed to in-phase, and then it is more strong and significant in the recent multidecades. A decrease in correlation value with WCI and PI towards the recent decades was also noticed. NCI shows a decrease in correlation value with all other regions towards the recent decades. This can be inferred as rainfall mechanism change in NEI and NCI towards the recent decades. The multidecadal trend showed a discontinuity followed by the correlation values for the period 1961–1990. This can be due to change in rainfall mechanism or change in the external factors

that influenced the rainfall over that multidecadal period. Overall, analysis shows a decrease in correlation within the regions towards the recent multidecades, and that can be interpreted as the rainfall events during the recent multidecades are more influenced by the local factors, as explained by Pielke et al. (2007) and Kishtawal et al. (2009). Similar results are seen in low and moderate intensity classes regarding the homogeneity and the decreasing correlation coefficient values towards the recent decades. Another important feature noted is NEI has a negative correlation with all other regions for

the low intensity class, and this may be due to the influence of local features. NWI and WCI as well as WCI and PI showed significant in-phase relationships with each other during the entire period. However, the correlation value has decreased in the period 1991–2018. For the moderate class, it is observed that for the entire period, NEI shows low correlation with all other regions, but for the recent periods, it turned out to be a negative value, and this may be due to the changes in rainfall mechanism such as urbanisation, land use and land change patterns, etc. Here, NWI and WCI, as well as WCI and PI, are showing significant positive correlations. For the high intensity class, NWI and WCI, as well as WCI and PI, have relatively lower correlation values compared with the above classes. Moreover, correlation values are decreasing towards the recent periods. Very high and extreme classes mostly have low values of correlations compared to others or are inversely related. In the case of high, very high, and extreme intensity bins, NEI showed a negative correlation with all other regions. WCI and PI have a very low correlation value for the early multidecadal period for the very high intensity class; however, this relationship has increased significantly in the recent decades.

In general, it is observed that there is a positive correlation between almost all the homogeneous regions for the dry, low, and moderate intensity classes. From this, it can be inferred that these rain events are coherent all over India or can be treated as caused by large-scale monsoon cloud bands. While extreme and very high intensity classes are more like localised phenomena, it may be due to their dependence on phenomena that are confined to the particular area. PI has low correlation value with the northern homogeneous regions. NEI has different rainfall mechanisms compared with all other regions for all intensity classes and shows variation towards the recent decades. This can be mainly due to anthropogenic and other synoptic activities (Fujinami et al., 2017; Goswami et al., 2010; Kuttippurath et al., 2021; Varikoden & Revadekar, 2020).

The correlation analysis of multidecadal variation from 1961 onwards indicates abrupt changes from the normal values, and it may be attributed to the effects of climate change. In other words, relationships have

been changing from inverse to in-phase in most of the regions as evidenced by the correlation values. It is also observed that the positive correlation values of large-scale events, such as dry, low and moderate intensities, are decreasing towards the recent multidecades, indicating that these events are out of phase and more localised in nature. From the changing correlation values between WCI and PI, it can be inferred that these areas have changes in the rainfall mechanism in the recent decades. In addition to the global warming, regional change in land use pattern in terms of urbanisation and agriculture have been taken place over the last few decades (Kishtawal et al., 2009; Paul et al., 2016; Pielke et al., 2007). Such land use transformation can produce significant changes in monsoon circulation by altering the regional evapotranspiration, surface radiative balance, moisture regime, and temperature regime over the Indian subcontinent (Feddeema et al., 2005; Douglas et al., 2009; Ghosh et al., 2009; Chou et al., 2018; Boyaj et al., 2020; Kuttippurath et al., 2021). This can lead to the spatial heterogeneity as well as the localization of rainfall events in India.

### 3.5. Characteristics in Rainfall Intensity Classes During Different Multidecades

Figure 5 shows the rainfall characteristics of ISMR for the five homogeneous regions of India over the four multidecadal periods for different rainfall intensity classes. In NEI (Fig. 5a1–a4), the contribution from the dry intensity class shows an increase from the first multidecadal period to the recent multidecadal period. From the third multidecade onwards, the contribution changes are more pronounced in the low, moderate, high, very high, and extreme intensity classes. The contribution of low intensity is decreased by 4%, and that for the moderate intensity by 10%. The contribution by the high intensity class was increased by 3%, and that for very high and extreme classes is about 5%. The contributions almost remain constant in the last two multidecades.

In NCI (Fig. 5b1–b4), the dry intensity class shows an overall increasing trend, and there are no considerable variations in all other rainfall intensity classes during the first two multidecadal periods.

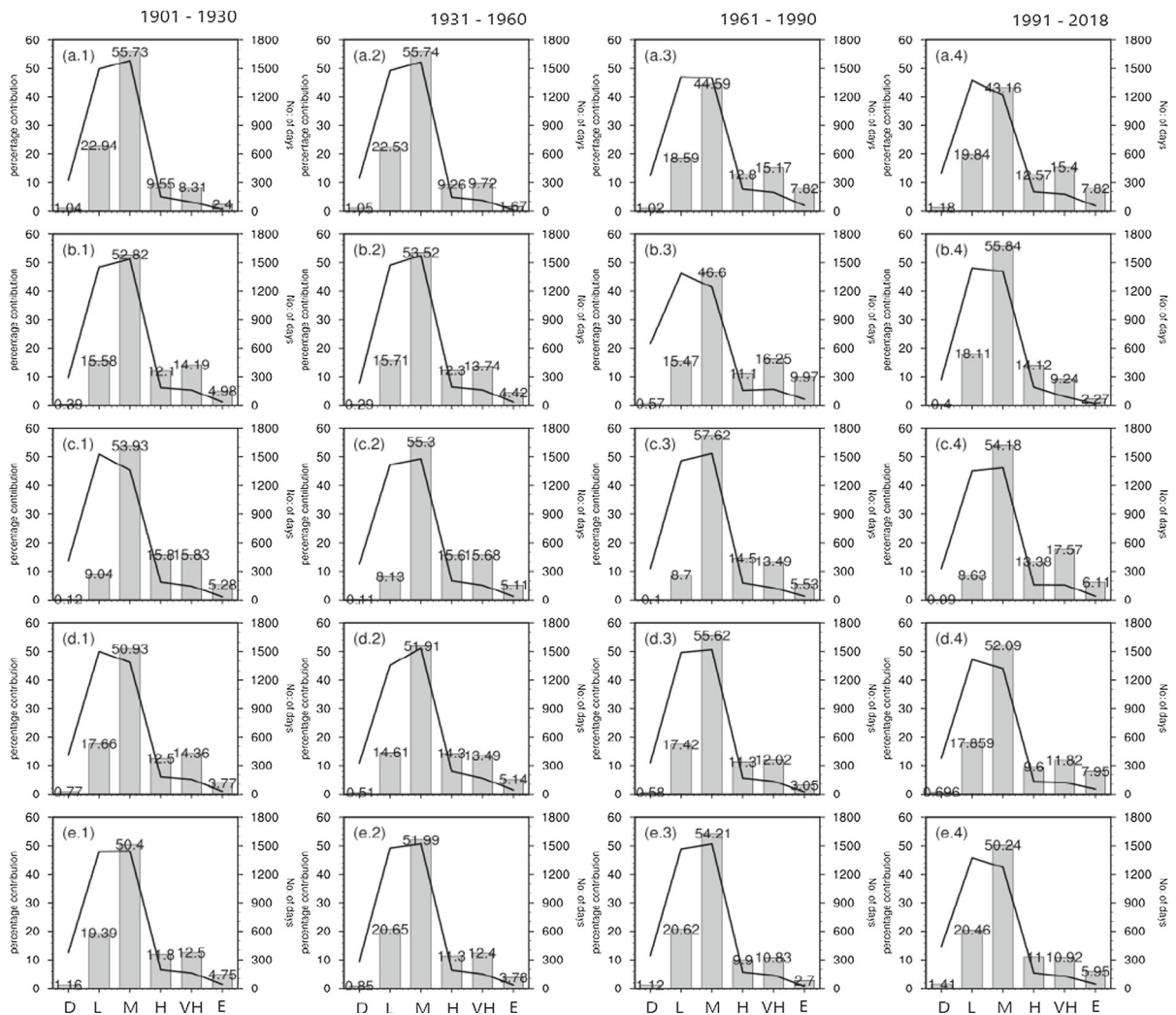


Figure 5

Rainfall characteristics in the multidecadal period over five homogeneous regions. The bar chart represents percentage contribution (left Y-axis), and the line graph represents the number of days (right Y-axis) of dry (D), low (L), moderate (M), high (H), very high (VH), and extreme (E) intensity classes during the four multidecadal periods: (1) 1901–1930, (2) 1931–1960, (3) 1961–1990, and (4) 1991–2018. Each row from the top represents different homogeneous regions : (a) Northeast India, (b) Northcentral India, (c) Northwest India, (d) Westcentral India, and (e) Peninsular India. The value inside the graph on each bar represents the percentage contribution by the intensity classes

During 1961–1990, changes in contribution are observed from all the intensity classes, with a notable change in dry and extreme classes. The dry and extreme intensity classes show a two-fold increase in occurrence, and for other events, the occurrences have shown a significant decrease. The study of Chou et al. (2018) has noted that the implementation of large-scale irrigation projects that started in the 1950s has resulted in land surface

cooling, which slowed large-scale atmospheric circulation resulting in variation in the ISMR pattern in this region. For the period 1991–2018, there is a dominant decrease in contribution by very high and extreme intensity classes. During this period, contributions from low, moderate, and high intensity classes have increased, and therefore, it can be inferred that rainfall is reviving in the recent epoch.

Significant changes are not observed in intensity classes during all the multidecadal periods in NWI (Fig. 5c1–c4). There is a slight decrease in contribution by the dry intensity class from the first epoch to recent. During the multidecadal period 1961–1990, the moderate intensity class showed an increase in its contribution (about 4%); high and very high intensity classes showed a decrease in contribution compared to the earlier epochs. During 1991–2018, the contributions from all intensity classes have decreased, except for the very high and extreme intensity bins. Very high and extreme intensity classes have shown their highest contribution during this period compared to other epochs.

In WCI (Fig. 5d1–d4), the low intensity class showed a low contribution (14%) over the 1931–1960 multidecadal period, and then it increased to 17% during 1961–2018. The moderate class does not have much variation, but it shows a slight increase during the period 1961–1990. The high-intensity class showed an increase in contribution during the period 1931–1960, and then it is constantly decreasing about 5% towards the recent multidecades. The very high intensity bin is showing a slight decrease in its contribution towards the recent period compared with the earlier epochs. The extreme intensity class has an oscillating pattern over multidecadal periods, with decreasing contributions in the first and third multidecades and increasing contributions in the second and fourth multidecades.

In PI (Fig. 5e1–e4), the dry events are increasing towards the recent periods. The contribution by the low intensity class is almost constant in all the multidecadal periods. The contributions by the moderate class over the first two multidecadal periods are almost the same (about 50%). During 1961–1990, it showed an increase of 4%, and then it came to its earliest contribution after 1990. High and very high intensity classes showed a constant contribution of about 12% in the first two multidecades. During 1961–1990, the contribution decreased to 10%, and that was the lowest contribution of these classes compared to other multidecades. The extreme intensity class showed a low contribution of about 3% during the 1961–1990 multidecadal period, and then it increased to 6% during 1961–2018.

In the last two multidecadal periods (1961–2018), the rainfall contribution in different intensity classes and spatial coherence patterns show drastic changes that can be attributed to the variation in rain-producing systems caused by climate change and changes in regional land usage (Kishtawal et al., 2009; Paul et al., 2016; Pielke et al., 2007). Warming associated with increasing greenhouse gas concentrations will cause an increase of the Asian summer monsoon precipitation variability (IPCC, 2001). The increase in spatial heterogeneity is also noted by Vinnarasi and Dhanya (2016) and Chou et al. (2018). It is noticed that more than 60 percent of total rainfall is contributed by moderate, low, and high intensity classes. The moderate event has a decreasing trend or remains constant in different homogeneous regions. This can lead to a decreasing trend in total rainfall towards the recent periods. Joseph and Simon (2005) found that the weakening of the monsoon is attributed to the weakening of the low-level jet stream (LLJ). Similarly, the weakening and northward shift of the LLJ core is attributed to the decreased rainfall by Sudeepkumar et al. (2018) and Varikoden et al. (2019).

Variation in the dry, very high, and extreme intensity classes creates changes in the contribution by major contributors such as low, moderate, and high intensity classes; therefore, these three can be inferred as responsible for contributing trend variation in the total rainfall received during each multidecadal period. Among the homogeneous regions, the percentage of rainfall contribution from dry events is more pronounced in NEI and PI in all the multidecades, but this is dominant during the first and last multidecades in the WCI. Increase in rainfall contribution by the extreme intensity class was found in NEI, NWI, and WCI for the multidecadal period 1991–2018, while NCI showed a decrease in the period, and these classes in NCI are showing drastic increase during 1961–1990.

#### 4. Summary and Conclusions

In this study, the trend and spatio-temporal variability of ISMR and different rainfall intensity classes are investigated in five homogeneous regions for

118 years. In the long-term trend analysis (1901–2018) of total rainfall we found:

- A significant increasing trend ( $19.9 \text{ mm decade}^{-1}$ ) in NEI and likewise found a significant increasing trend in high, very high, and extreme intensity classes in NEI;
- A significant decreasing trends in NCI ( $9.6 \text{ mm decade}^{-1}$ ) and PI ( $4.9 \text{ mm decade}^{-1}$ ) and also observed a significant increasing trend in the dry intensity class and a decrease in moderate and very high intensity classes in NCI and PI.

This finding is more helpful to understand which category of rainfall intensity is contributing to the changes in total rainfall trend. In addition, we found a significant decreasing (increasing) trend in the dry (moderate) intensity bin in NWI, in the WCI an increasing (decreasing) trend in the low and extreme (high and very high) intensity classes. It was observed that rainfall variability is higher in NEI and NCI and lower in WCI and NWI. From 1960 onwards, variability in rainfall patterns was also found in a majority of the intensity classes in the homogeneous regions.

Study on the periodicities of rainfall patterns in different intensity classes brings out significant multidecadal, decadal, and interdecadal variabilities. The very high intensity bin showed 30–50 years of periodicity in the entire homogeneous region. The extreme intensity class showed a similar range of periodicity, more than 50 years over large parts of India. In NCI, periodicity is ranging from 54 to 57 years, and it is showing in a majority of the intensity classes. In NEI, the periodicity ranges from 45 to 55, and it is dominant in the moderate, high, very high, and extreme intensity classes.

The spatial correlation values indicate that dry, low, and moderate intensity classes are coherent all over India or can be treated as large-scale rain events, while extreme and very high intensity classes are associated with localized phenomena and are caused by the geographic and dynamic features pertaining to the regions. The rainfall patterns are in phase over NWI, WCI, and PI, but out of phase over NEI. It may be due to the changing influence of local and large-scale features over the respective regions. The analysis also projects that the homogeneous rain events are becoming out of phase towards the recent

multidecades (1961–2018). The inter-regional correlation analysis between WCI and PI shows changes in correlation values towards the recent decades (1991–2018). The areas in which similar rainfall patterns observed in the earlier decades become out of phase in the recent decades (1961–2018).

Multidecadal features of rainfall intensity in different classes in different homogeneous regions show that more than 60 percent of total rainfall is contributed from the moderate, low, and high intensity classes. Modulations in dry, very high, and extreme intensity classes cause a change in the rainfall pattern of low, moderate, and high rainfall events, and therefore, it leads to significant changes in the total seasonal rainfall during each multidecadal period. The moderate event shows a slight decreasing trend, and this can lead to a decreasing trend of the total rainfall towards the recent period. Increase (decrease) in the contribution of rainfall from the extreme class is found in NEI, NWI, and WCI (NCI) during the multidecadal period 1991–2018. A drastic increase in contribution during 1961–1990 in NCI is also observed. In the last two multidecadal periods (1961–1990, 1991–2018), the rainfall contribution by different intensity classes and the patterns of spatial coherence show drastic changes.

It is critical to be aware of the spatial and temporal variability of rainfall, and it is important to note that seasonal total rainfall variability and patterns can vary from the variability of different intensity classes. Changes in rainfall necessitate a more detailed view of the monsoon rainfall with respect to intensity bin. In this study, we bring out spatial and temporal heterogeneity of different rainfall intensity bins over five regions of India, and the heterogeneity is increasing towards the recent decades. This change in rainfall pattern affects adversely in all fields. Therefore, it is better to evolve a new water management strategy to tackle the changing rainfall pattern. Furthermore, a scientific evaluation of rainfall intensity bins in different homogeneous regions will help to utilise the natural resources effectively.

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## REFERENCES

- Alexander, L., Zhang, X., Peterson, T., Caesar, J., Gleason, B., Klein Tank, A., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Rupa Kumar, K., Revadekar, J., Griffiths, G., Vincent, L., Stephenson, D., Burn, J., Aguilar, E., Brunet, M., ... Vazquez-Aguirre, J. (2006). Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research*. <https://doi.org/10.1029/2005JD006290>
- Ashok, K., Guan, Z., Saji, N. H., & Yamagata, T. (2004). Individual and combined influences of ENSO and the Indian Ocean dipole on the Indian summer monsoon. *Journal of Climate*, 17(16), 3141–3155.
- Baines, P. G., & Folland, C. K. (2007). Evidence for a rapid global climate shift across the late 1960s. *Journal of Climate*, 20, 2721–2744.
- Boyaj, A., Dasari, H. P., Hoteit, I., & Ashok, K. (2020). Increasing heavy rainfall events in south India due to changing land use and land cover. *Quarterly Journal Royal Meteorological Society*, 146, 3064–3085.
- Chou, C., Ryu, D., Lo, M., Wey, H., & Malano, H. (2018). Irrigation-induced land-atmosphere feedbacks and their impacts on Indian summer monsoon. *Journal of Climate*, 31, 8785–8801.
- Dash, S. K., Jenamani, R. K., Kalsi, S. R., & Panda, S. K. (2007). Some evidence of climate change in twentieth-century India. *Climate Change*, 85, 299–321.
- Dash, S. K., Nair, A. A., Kulkarni, M. A., & Mohanty, U. (2011). Characteristic changes in the long and short spells of different rain intensities in India. *Theoretical and Applied Climatology*, 105, 563–570.
- Douglas, E. M., Beltrán-Przekurat, A., Niyogi, D., Pielke, R. A., & Vörösmarty, C. J. (2009). The impact of agricultural intensification and irrigation on land-atmosphere interactions and Indian monsoon precipitation—A mesoscale modeling perspective. *Global and Planetary Change*, 67, 117–128.
- Feddema, J. J., Oleson, K. W., Bonan, G. B., Mearns, L. O., Buja, L. E., Meehl, G. A., & Washington, W. M. (2005). Atmospheric science: The importance of land-cover change in simulating future climates. *Science*, 310, 1674–1678.
- Fujinami, H., Sato, T., Kanamori, H., & Murata, F. (2017). Contrasting features of monsoon precipitation around the Meghalaya plateau under westerly and easterly regimes. *Journal of Geophysical Research: Atmospheres*, 122, 9591–9610.
- Fukushima, A., Kanamori, H., & Matsumoto, J. (2019). Regionality of long-term trends and interannual variation of seasonal precipitation over India. *Progress in Earth and Planetary Science*, 6, 1–20.
- Gadgil, S., & Gadgil, S. (2006). The Indian Monsoon, GDP and agriculture. *Economic and Political Weekly*, 41, 4887–4895.
- Ghosh, S., Luniya, V., & Gupta, A. (2009). Trend analysis of Indian summer monsoon rainfall at different spatial scales. *Atmospheric Sci. Lett.*, 10, 285–290.
- Ghosh, S., Vittal, H., Sharma, T., Karmakar, S., Kasiviswanathan, K., Dhanesh, Y., Sudheer, K., & Gunthe, S. (2016). Indian summer monsoon rainfall: Implications of contrasting trends in the spatial variability of means and extremes. *PLoS ONE*, 11, e0158670.
- Goswami, B. N., Kripalani, R. H., Borgaonkar, H. P., & Preethi, B. (2016). Multi-decadal variability in Indian summer monsoon rainfall using proxy data. *Climate Change: Multidecadal and beyond*. [https://doi.org/10.1142/9789814579933\\_0021](https://doi.org/10.1142/9789814579933_0021)
- Goswami, B. N., Mukhopadhyay, P., Mahanta, R., & Goswami, B. N. (2010). Multiscale interaction with topography and extreme rainfall events in the northeast Indian region. *Journal of Geophysical Research: Atmospheres*, 115, 1–12.
- Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M., & Xavier, P. K. (2006). Increasing trend of extreme rain events over India in a warming environment. *Science*, 314, 1442–1445.
- Guhathakurta, P., Rajeevan, M., Sikka, D. R., & Tyagi, A. (2014). Observed changes in southwest monsoon rainfall over India during 1901–2011. *International Journal of Climatology*, 35, 1881–1898.
- Guhathakurta, P., Sreejith, O., & Menon, P. (2011). Impact of climate change on extreme rainfall events and flood risk in India. *J. Earth System Sci.*, 120, 359–373.
- Guo, L., Turner, A., & Highwood, E. (2016). Local and remote impacts of aerosol species on Indian summer monsoon rainfall in a GCM. *Journal of Climate*, 29, 6937–6955.
- Huang, X., Zhou, T., Turner, A., Dai, A., Chen, X., Clark, R., Jiang, J., Man, W., Murphy, J., Rostron, J., Wu, B., Zhang, L., Zhang, W., & Zou, L. (2020). The recent decline and recovery of Indian summer monsoon rainfall: Relative roles of external forcing and internal variability. *Journal of Climate*, 33, 5035–5060.
- IPCC. (2001). *Climate change 2001: The scientific basis. Contribution of Working Group I to the third assessment report of the intergovernmental panel on climate change*. Cambridge University Press.
- Jain, S. K., Kumar, V., & Saharia, M. (2013). Analysis of rainfall and temperature trends in northeast India. *International Journal of Climatology*, 33, 968–978.
- Joseph, P. V., & Simon, A. (2005). Weakening trend of the southwest monsoon current through peninsular India from 1950 to the present. *Current Science*, 89, 687–694.
- Joshi, M. K., & Kucharski, F. (2017). Impact of Interdecadal Pacific Oscillation on Indian summer monsoon rainfall: An assessment from CMIP5 climate models. *Climate Dynamics*, 48, 2375–2391.



- Joshi, M., & Pandey, A. (2011). Trend and spectral analysis of rainfall over India during 1901–2000. *Journal of Geophysical Research*. <https://doi.org/10.1029/2010JD014966>
- Karmakar, N., Chakraborty, A., & Nanjundiah, R. (2017). Increased sporadic extremes decrease the intraseasonal variability in the Indian summer monsoon rainfall. *Science and Reports*, 7, 1–7.
- Kendall, M. G. (1975). *Rank correlation methods*. Charles Griffin.
- Kishtawal, C., Niyogi, D., Tewari, M., Pielke, R., & Shepherd, J. (2009). Urbanization signature in the observed heavy rainfall climatology over India. *International Journal of Climatology*, 30, 1908–1916.
- Kripalani, R. H., & Kulkarni, A. (1997). Climatic impact of El Niño/La Niña on the Indian monsoon: A new perspective. *Weather*, 52, 39–46.
- Kripalani, R. H., Kulkarni, A., & Sabade, S. S. (2003). Indian monsoon variability in a global warming scenario. *Natural Hazards*, 29, 189–206.
- Krishnan, R., Sabin, T. P., Ayantika, D. C., Kitoh, A., Sugi, M., Murakami, H., Turner, A. G., Slingo, J. M., & Rajendran, K. (2013). Will the South Asian monsoon overturning circulation stabilize any further? *Climate Dynamics*, 40, 187–211.
- Krishnan, R., Sabin, T., Vellore, R., Mujumdar, M., Sanjay, J., Goswami, B., Hourdin, F., Dufresne, J., & Terray, P. (2015). Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world. *Climate Dynamics*, 47, 1007–1027.
- Kulkarni, A. (2012). Weakening of Indian Summer Monsoon Rainfall in warming environment. *Theoretical and Applied Climatology*, 109, 447–459.
- Kumar, K. K., Rajagopalan, B., & Cane, M. A. (1999). On the weakening relationship between the Indian monsoon and ENSO. *Science*, 284, 2156–2159.
- Kumar, V., Jain, S. K., & Singh, Y. (2010). Analysis of long-term rainfall trends in India. *Hydrological Sciences Journal*, 55, 484–496.
- Kuttiipurath, J., Murasingh, S., Stott, P., Balan Sarojini, B., Jha, M., Kumar, P., Nair, P., Varikoden, H., Raj, S., Francis, P., & Pandey, P. (2021). Observed rainfall changes in the past century (1901–2019) over the wettest place on the Earth. *Environmental Research Letters*, 16, 024018.
- Lau, K. M., Kim, M. K., & Kim, K. M. (2006). Asian summer monsoon anomalies induced by aerosol direct forcing: The role of the Tibetan Plateau. *Climate Dynamics*, 26, 855–864.
- Li, Z., Lin, X., & Cai, W. (2017). Realism of modelled Indian summer monsoon correlation with the tropical Indo-Pacific affects projected monsoon changes. *Science and Reports*, 7, 1–7.
- Luwangleima, M., & Shrivastava, S. K. (2021). *Temporal and spatial variability of daily rainfall extremes in humid northeast Assam state of India hydrological extremes* (pp. 149–160). Cham: Springer.
- Malik, A., & Brönnimann, S. (2018). Factors affecting the inter-annual to centennial timescale variability of Indian Summer Monsoon Rainfall. *Climate Dynamics*, 50, 4347–4364.
- Mann, H. (1945). Nonparametric tests against trend. *Econometrica: Journal of the Econometric Society*, 13, 245–259.
- Meehl, G. A., & Washington, W. M. (1993). South Asian summer monsoon variability in a model with doubled atmospheric carbon dioxide concentration. *Science*, 260, 1101–1104.
- Menon, A., Levermann, A., & Schewe, J. (2013). Enhanced future variability during India's rainy season. *Geophysical Research Letters*, 40, 3242–3247.
- Mishra, V., Smoliak, B., Lettenmaier, D., & Wallace, J. (2012). A prominent pattern of year-to-year variability in Indian Summer Monsoon Rainfall. *Proceedings of the National Academy of Sciences*, 109, 7213–7217.
- Mohan, T., & Rajeevan, M. (2017). Past and future trends of hydroclimatic intensity over the Indian monsoon region. *Journal of Geophysical Research: Atmospheres*, 122, 896–909.
- Mukhopadhyay, P., Taraphdar, S., Goswami, B. N., & Krishnakumar, K. (2010). Indian summer monsoon precipitation climatology in a high-resolution regional climate model: Impacts of convective parameterization on systematic biases. *Weather and Forecasting*, 25, 369–387.
- Naidu, C. V., Durgalakshmi, K., Krishna, K. M., Rao, S. R., Satyanarayana, G. C., Lakshminarayana, P., & Rao, L. M. (2009). Is summer monsoon rainfall decreasing over India in the global warming era? *Journal of Geophysical Research*. <https://doi.org/10.1029/2008JD011288>
- Nair, P., Chakraborty, A., Varikoden, H., Francis, P., & Kuttipurath, J. (2018). The local and global climate forcings induced inhomogeneity of Indian rainfall. *Science and Reports*, 8, 1–12.
- Pai, D. S., Shridhar, L., Rajeevan, M., Sreejith, O. P., Satbhai, N. S., & Mukhopadhyay, B. (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.
- Parthasarathy, B., Munot, A. A., & Kothawale, D. R. (1994). All-India monthly and seasonal rainfall series: 1871–1993. *Theoretical and Applied Climatology*, 49, 217–224.
- Pattanaik, D., & Rajeevan, M. (2010). Variability of extreme rainfall events over India during southwest monsoon season. *Meteorological Applications*, 17, 88–104.
- Paul, S., Ghosh, S., Oglesby, R., Pathak, A., Chandrasekharan, A., & Ramsankaran, R. (2016). Weakening of Indian Summer Monsoon Rainfall due to changes in land use land cover. *Science and Reports*, 6, 1–10.
- Pielke, R., Adegoke, J., Beltrán-Przekurat, A., Hiemstra, C., Lin, J., Nair, U., Niyogi, D., & Nobis, T. (2007). An overview of regional land-use and land-cover impacts on rainfall. *Tellus B Chemical and Physical Meteorology*, 59, 587–601.
- Preethi, B., Mujumdar, M., Kripalani, R. H., Prabhu, A., & Krishnan, R. (2017). Recent trends and tele-connections among South and East Asian summer monsoons in a warming environment. *Climate Dynamics*, 48, 2489–2505.
- Rajeevan, M., Bhate, J., Kale, J. D., & Lal, B. (2005). Development of a high resolution daily gridded rainfall data for the Indian region. *Met. Monograph Climatology*, 22, 2005.
- Rajeevan, M., Gadgil, S., & Bhate, J. (2010). Active and break spells of the Indian summer monsoon. *Journal of Earth System Science*, 119, 229–247.
- Rajendran, K., Kitoh, A., Srinivasan, J., Mizuta, R., & Krishnan, R. (2012). Monsoon circulation interaction with Western Ghats orography under changing climate. *Theoretical and Applied Climatology*, 110, 555–571.
- Rajesh, P. V., & Goswami, B. N. (2020). Four-dimensional structure and sub-seasonal regulation of the Indian summer monsoon multi-decadal mode. *Climate Dynamics*, 55, 2645–2666.
- Roxy, M., 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. *Nature Communications*, 8, 1–11.
- Roxy, M., Ritika, K., Terray, P., Murtugudde, R., Ashok, K., & Goswami, B. (2015). Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land-sea thermal gradient. *Nature Communications*, 6, 1–10.
- Sabeerali, C. T., & Ajayamohan, R. S. (2018). On the shortening of Indian summer monsoon season in a warming scenario. *Climate Dynamics*, 50, 1609–1624.
- Sabeerali, C. T., Ajayamohan, R. S., Bangalath, H. K., & Chen, N. (2019). Atlantic Zonal Mode: An emerging source of Indian summer monsoon variability in a warming world. *Geophysical Research Letters*, 46, 4460–4467.
- Sahany, S., Venugopal, V., & Nanjundiah, R. S. (2010). Diurnal-scale signatures of monsoon rainfall over the Indian region from TRMM satellite observations. *Journal of Geophysical Research: Atmospheres*, 115, D02103.
- Seetha, C. J., Varikoden, H., Babu, C. A., & Kuttippurath, J. (2020). Significant changes in the ENSO-monsoon relationship and associated circulation features on multidecadal timescale. *Climate Dynamics*, 54, 1491–1506.
- Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of American Statistical Association*, 63, 1379–1389.
- Sen Roy, S., & Balling, R. C. (2004). Trends in extreme daily precipitation indices in India. *International Journal of Climatology*, 24, 457–466.
- Sheikh, M. M., Manzoor, N., Ashraf, J., Adnan, M., Collins, D., Hameed, S., Manton, M. J., Ahmed, A. U., Baidya, S. K., Borgaonkar, H. P., Islam, N., Jayasinghearachchi, D., Kothawale, D. R., Premalal, K. H. M. S., Revadekar, J. V., & Shrestha, M. L. (2015). Trends in extreme daily rainfall and temperature indices over South Asia. *International Journal of Climatology*, 35, 1625–1637.
- Shepard, D. (1968). A two-dimensional interpolation function for irregularly-spaced data. In Proceedings of the 1968 23rd ACM national conference (pp. 517–524).
- Singh, D., Tsiang, M., Rajaratnam, B., & Diffenbaugh, N. S. (2014). Observed changes in extreme wet and dry spells during the South Asian summer monsoon season. *Nature Climate Change*, 4, 456–461.
- Sudeepkumar, B., Babu, C. A., & Varikoden, H. (2018). Future projections of active-break spells of Indian summer monsoon in a climate change perspective. *Glob Planet Change*, 161, 222–230.
- Turner, A. G., & Annamalai, H. (2012). Climate change and the South Asian summer monsoon. *Nature Climate Change*, 2, 587–595.
- Varikoden, H., Babu, C. A., & Krishnakumar, K. (2013). long term trends of seasonal and monthly rainfall in different intensity ranges over Indian subcontinent. *Mausam*, 64, 481–488.
- Varikoden, H., Preethi, B., & Revadekar, J. V. (2012). Diurnal and spatial variation of Indian Summer Monsoon Rainfall using tropical rainfall measuring mission rain rate. *Journal of Hydrology*, 475, 248–258.
- Varikoden, H., & Revadekar, J. (2020). On the extreme rainfall events during the southwest monsoon season in northeast regions of the Indian subcontinent. *Meteorological Applications*, 27, e1822.
- Varikoden, H., Revadekar, J., Kuttippurath, J., & Babu, C. (2019). Contrasting trends in southwest monsoon rainfall over the Western Ghats region of India. *Climate Dynamics*, 52, 4557–4566.
- Vinnarasi, R., & Dhanya, C. (2016). Changing characteristics of extreme wet and dry spells of Indian monsoon rainfall. *Journal of Geophysical Research: Atmospheres*, 121, 2146–2160.

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