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Spatio-temporal change in rainfall over five different climatic regions of India

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ABSTRACT

The present study deals with the estimation of dependences, spatio-temporal trends, change points, and stationarity in rainfall and rainy day series (1901–2013) for five (out of six) different climatic regions of India. Only one-fourth of the station rainfall and rainy day datasets exhibits long-term dependence on an annual and seasonal basis. The presence of lag-one serial correlation is prominent for almost all the climatic regions of India. The significant decreasing trend is found mainly for the stations of semi-arid and humid sub-tropical regions. The magnitude of rainfall is decreasing for most parts of the study area by 10% for annual and monsoon seasons. The change point is presented in a smaller number of stations. Non-stationary behaviour is observed for the rainy day series of semi-arid and humid sub-tropical regions, which may increase the temporal variability of rainfall over the same regions. The findings of this study could be very useful for the planning and management of water resources of different climatic regions of India.

Key words: dependence, non-stationarity, rainfall, stationarity, trend analysis

HIGHLIGHTS

- We analyse short-term and long-term dependences, spatio-temporal trends, change point, and stationarity in rainfall and rainy day datasets over five different climatic regions of India.
- Change point detection for different climatic regions over parts of India.
- The trend stationarity and non-stationarity is comparatively lower in rainfall datasets than the rainy day datasets for annual and monsoon seasons.

INTRODUCTION

Rainfall is one of the most important factors of the Indian economy. In India, almost 80% of the rainfall occurs during the monsoon months (June to September). The monsoon rainfall occurs in every part of the country; however, the amount of rainfall varies drastically from place to place. The rainfall distribution is also highly varied with space and time. The Intergovernmental Panel on Climate Change (IPCC 2001) stated that the change of rainfall pattern due to global warming and the associated change in circulation is a matter of major concern. However, the global change in precipitation has been very low since 1901. An increase in precipitation was observed prior to 1951 in the northern hemisphere mid-latitude land areas. Estimates based on general circulation models under the RCP8.5 scenario suggest that the annual mean precipitation will possibly increase in the high latitudes and the equatorial Pacific Ocean by the end of this century (IPCC 2013). The available records show an increase in the frequency and intensity of extreme precipitation events in many parts of the world, and both are expected to increase in the future as well.

According to the IPCC, the seasonal average rainfall showed an inter-decadal variability with a falling trend over South Asia. The monsoon rainfall deficit was observed more frequently over some parts of South Asia (WGI AR5, IPCC 2013). In India, the average rainfall during the monsoon season and the number of monsoon depressions had decreased continuously. The extreme rainfall events had increased over central India and in many other areas (WGI AR5, IPCC 2013). The agricultural sector of India totally depends on the monsoon. A change in climatic conditions, particularly during monsoon months over the Indian region, can significantly affect the agricultural sector and food security of India. This could affect the livelihood of more than 50% of the country's population. The variability of Indian rainfall is also subjected to climate change. Therefore, climate change may affect the availability of water along with the risk of increase or decrease of floods or droughts over the country.

The estimation of the rainfall patterns on a regional basis for different climatic regions will help in understanding the global impact of climatic systems over the region. The rainfall trends on various spatial scales can provide futuristic scenarios, which are helpful in the planning and management of water resources of the region. The IPCC has also shown the need of trend analysis for the assessment of climate change (IPCC 2007). In India, a number of researchers had also studied the trend analysis of rainfall datasets in the past. However, no clear trend in annual average rainfall over India was reported by past studies (see, e.g., Mooley & Parthasarathy 1984; Sarker & Thapliyal 1988; Thapliyal & Kulshreshtha 1991; Lal 2001; Sinha Ray & De 2003; Ranade *et al.* 2008). However, some studies indicated the presence of a significant increasing or decreasing trend in annual or seasonal rainfall over different parts of India (Kothyari *et al.* 1997; Srivastava *et al.* 1998; Arora *et al.* 2006; Goswami *et al.* 2006; Pattanaik 2007; Guhathakurta & Rajeevan 2008; Kumar *et al.* 2010; Pal & Al-Tabbaa 2011; Subash *et al.* 2011; Jain & Kumar 2012; Mondal *et al.* 2014; Subash & Sikka 2014; Nageswararao *et al.* 2016; Dave & James 2017; Machiwal *et al.* 2017; Pandey *et al.* 2017; Malik *et al.* 2019, 2020a, 2020b; Malik & Kumar 2020). These studies have used different sets of data with varied data lengths. Most of the previous studies had been carried out using the sub-divisional or regional or gridded datasets. Some studies had also been conducted using a smaller number of station data. Furthermore, the earlier studies had not analysed the short-term and long-term dependences using Indian rainfall datasets. Therefore, in the present study, the rainfall data of 148 stations are analysed using various statistical tests. These stations are well distributed over five different climatic zones of India.

METHODS

Study area

In this study, the rainfall data of central, eastern, western, and northern India have been analysed. A map of the study area is shown in Figure 1. Five different climatic zones, namely, arid, humid sub-tropical, mountain, semi-arid, and tropical wet and dry, out of six climatic zones of India (according to Köppen climate classification), are covered in the study. Furthermore, the study area comprises the most populous states of India. The monsoon rainfall is one of the most important factors in all parts of the study area. Therefore, a weaker monsoon over the study area can create a number of water management problems. On the other hand, a monsoon with very high rainfall can create flooding.

Data used

The monthly rainfall, number of rainy days, and annual maximum rainfall (AMRF) data of 148 stations (Figure 1) are collected from the India Meteorological Department. These stations are well distributed over the study area. Out of the 148 stations, a total of 66 stations have more than 90 years of data, while the remaining stations have more than 60 years of data. However, only 40 stations have more than or equal to 100 years of rainfall data and also the end period of at least 2010 (Figure 1). Therefore, in this study, the maximum data are analysed for 1901–2013. The annual, monsoon, and non-monsoon rainfall series and number of rainy days' datasets are prepared from the monthly datasets.

Methodology

The variability of rainfall is obtained by calculating the coefficient of variation (CV). Then, the randomness of the rainfall is checked by using Anderson's correlogram test (Anderson 1942). The long-term dependence is measured by using the Hurst phenomenon (Hurst 1951). In this analysis, the significance of Hurst's coefficient 'H' is tested using a chart of empirical percentage points developed by Lye & Lin (1994). For rainfall trend estimation, the Mann–Kendall (MK) test (Mann 1945; Kendall 1955)/modified Mann–Kendall (MMK) test (Hamed & Rao 1998) is used for the nonrandom/random datasets. Theil–Sen's median slope estimator (Theil 1950; Sen 1968) is used to measure the change in rainfall magnitude during the analysis period. The detection of change point in rainfall has been carried out using Pettit and rank-sum tests. The stationarity behaviour of rainfall is also checked using the Kwiatkowsk–-Phillips–Schmidt–Shin (KPSS) test (Kwiatowski *et al.* 1992). The statistical tests mentioned in this analysis are well documented in the literature (Kwiatowski *et al.* 1992; Yue *et al.* 2002; Cunderlik & Burn 2004; Rao *et al.* 2004; Novotny & Stefan

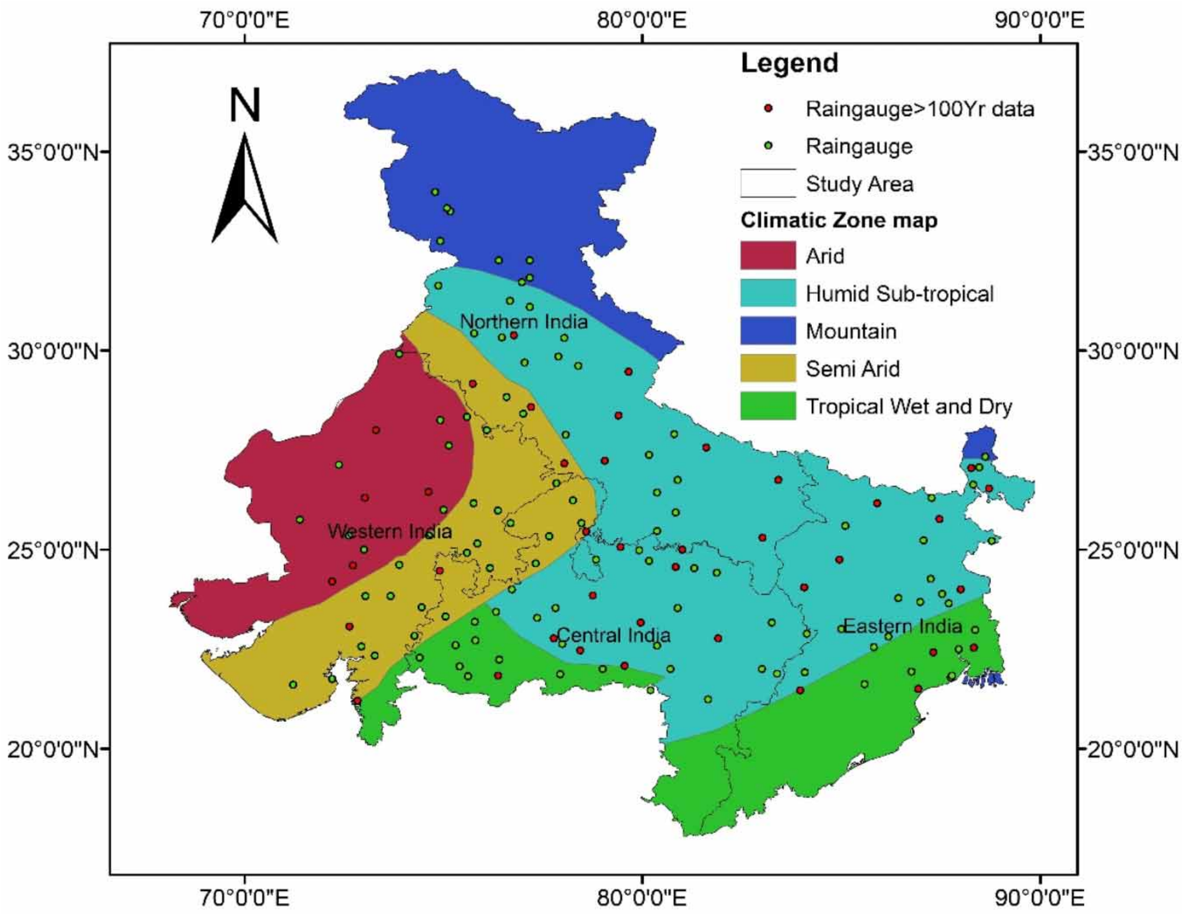

Figure 1 | Distribution of rainfall stations over the study area (central, eastern, western, and northern India).

2007; Kuriqi *et al.* 2020; Malik *et al.* 2020a, 2020b). In this study, all the statistics of the tests are checked for 5% significance level.

Anderson's correlogram test

The lag k autocorrelation coefficient for large datasets is estimated as:

$$r_k = \frac{\sum_{i=1}^{n-k} (x_i - \bar{x})(x_{i+k} - \bar{x}_{i+k})}{\left[\sum_{i=1}^{n-k} (x_i - \bar{x})^2 \times \sum_{i=1}^{n-k} (x_{i+k} - \bar{x}_{i+k})^2\right]^{1/2}} \quad (1)$$

where $\bar{x}$ and $\bar{x}_{i+k}$ are the sample mean of first $(n-k)$ and last $(n-k)$ terms, respectively. The randomness of the data can be checked by t-statistic with $(n-2)$ degree of freedom. Anderson (1942) provides a significance test for autocorrelation coefficient of lag k. The upper and lower bounds β of the autocorrelation coefficient of lag k with α level of significance for n observations are estimated as:

$$\beta = -\frac{1}{n-k} \pm Z_{1-(\alpha/2)}\left(\frac{(n-k-1)^{\frac{1}{2}}}{(n-k)}\right) \quad (2)$$

where $Z_{1-(\alpha/2)}$ is standard normal variate.

Hurst coefficient

The Hurst coefficient is used to measure the long-term dependences from a time series. The Hurst coefficient is estimated by Hurst's 'H', which is easy to assess. Hurst's H (Hurst 1951) is calculated as follows:

$$H = \frac{\log\left(\frac{R}{S}\right)}{\log\left(\frac{n}{2}\right)} \tag{3}$$

where R is the range of cumulative departure from the mean of a time series, S is the standard deviation of a time series, and n is the length of time series. R is calculated as follows:

$$R = \max\left(\sum_{i=1}^{n}(X_i - \bar{X})\right) - \min\left(\sum_{i=1}^{n}(X_i - \bar{X})\right) \tag{4}$$

The value of H lies in between 0 and 1. In general, the value of H more than 0.5 implies the presence of long-term dependence in the time series. However, the significance of the calculated Hurst's H should always be tested.

MK test

The MK test (Kendall & Stuart 1968) is a distribution-free, nonparametric test for the trend estimation of a time series. The MK test statistic is calculated as follows:

$$S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{5}$$

where x_i and x_j are observations $j > i$, and n is the length of dataset and the sign function is given by:

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} 1 & \text{if} \quad (x_j - x_i) > 0 \\ 0 & \text{if} \quad (x_j - x_i) = 0 \\ -1 & \text{if} \quad (x_j - x_i) < 0 \end{cases} \tag{6}$$

For independent and identically distributed data, the expected value $E(S)$ and the variance $\mathrm{Var}(S)$ are given by:

$$E(S) = 0 \tag{7}$$

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5)}{18} \tag{8}$$

If two or more data values are the same, then the tie correction is applied, and the sample variance is corrected as:

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18} \tag{9}$$

where m is the number of tied groups and t_i is the number of tied elements of extent i. For large datasets ($n \geq 10$), the test statistic follows normal distribution (Kendall & Stuart 1968) and the standard normal test statistic is estimated as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}} & \text{if} \quad S < 0 \end{cases} \tag{10}$$

MMK test

The autocorrelated data reduce the chance of significant trend detection in the MK test (Rao *et al.* 2004). To overcome this problem, the MMK (Hamed & Rao 1998) test is applied to the autocorrelated time series. In the MMK test, a variance correlation factor n/n_s^* is applied in the presence of significant autocorrelations as follows:

$$n/n_s^* = 1 + \frac{2}{n(n-1)(n-2)} \times \sum_{k=1}^{n-1} (n-k)(n-k-1)r_k \quad (11)$$

where n is the number of observations and n_s^* is the effective number of observations to account for autocorrelation in the data. The number of lags can be limited to three for significant autocorrelations (Hamed & Rao 1998). The corrected variance is then estimated as:

$$\mathrm{Var}^*(S) = \mathrm{Var}(S) \times n/n_s^* \quad (12)$$

where Var(S) is calculated from Equations (8) or (9), and the rest of the test is same as the MK test.

Theil–Sen median slope estimator

Theil–Sen's median slope estimator, Q (Yue *et al.* 2002; Cunderlik & Burn 2004), for n number of data is given by:

$$Q = \frac{(x_j - x_i)}{(j - i)} \quad \text{for } j > i \quad (13)$$

The Sen's slope, b, is given by:

$$b = \mathrm{median}\left[\frac{x_j - x_i}{j - i}\right] \quad \text{for } j > i \quad (14)$$

where x_j and x_i are the data values at time j and i ($j > i$), respectively.

Pettitt test

The Pettitt test (Pettitt 1979) is more sensitive to breaks in the middle of the hydrological time series and is less sensitive to outliers in the time series causing skewness in the data distribution. The test statistic (T_y) is expressed as:

$$T_y = 2\sum_{i=1}^{y} r_i - \{y \times (n+1)\} y = 1,\ 2,\ 3,\ \ldots..,\ n \quad (15)$$

where r_i is the rank of the i^{th} data point in the time series and n is the size of the series or the number of years. The statistically significant abrupt change (T_{CP}) occurs at a point (or year) in the series where the value of $|T_y|$ is found to be the maximum, as defined by:

$$T_{\mathrm{CP}} = \max_{1 \le y \le n} |T_y| \quad (16)$$

Rank-sum test

For a time series of size N, N_A and N_B are the number of observations before and after the breakpoint, and N is the sum of N_A and N_B. The observations are given a rank with the smallest value having a rank of 1. The test statistic, W_A, is the sum of the ranks of observations from one of the samples: W_A = sum of the ranks for observations from A. When the sample size is greater than 10, the test statistic W_A follows a normal distribution with mean and variance of $E(W_A)$ and $\mathrm{Var}(W_A)$, respectively:

$$E(W_A) = \frac{N_A(N_A + N_B + 1)}{2} \tag{17}$$

$$\mathrm{Var}(W_A) = \frac{N_A N_B(N_A + N_B + 1)}{12} \tag{18}$$

The standardised test statistic, Z, is calculated as follows:

$$Z = \frac{W_A - E(W_A)}{\sqrt{\mathrm{Var}(W_A)}} \tag{19}$$

and $Z \sim N(0, 1)$.

KPSS test

The KPSS test (Kwiatowski *et al.* 1992) is useful to verify the null hypothesis that a given time series is level or trend stationary. It is based on the assumption that a time series $X = (x_t, t = 1, 2, 3, \ldots, n)$ can be decomposed into the sum of a deterministic trend ξt (where ξ denotes slope), a random walk r_t, and a stationary error ε_t.

$$x_t = \xi t + r_t + \varepsilon_t \tag{20}$$

where t_r can be expressed as $r_t = r_{t-1} + u_t$ for all values of t; u_t are considered to be independent and identically distributed (*iid*) with mean zero and variance σ_u^2. The value of r_0 is considered to be fixed and serves the role of an intercept.

For a time series to be trend stationary, the random walk component r_t should be time invariant that impliesσ_u^2 should be zero. Hence, the null hypothesis is considered as $\sigma_u^2 = 0$ for stationarity test trend. Similarly, for a time series to be level stationary, the series should be stationary around a fixed level and this corresponds to the slope of the equation being zero. Hence, the null hypothesis should be $\xi = 0$.

The KPSS test statistic is computed as:

$$t_{\mathrm{KPSS}} = n^{-2} \sum_{t=1}^{n} S_t^2 / \hat{\sigma}^2(P) \tag{21}$$

where $S_t = \sum_{j=1}^{t} e_j$ denotes partial sum of residuals $\{e_j, j = 1, 2, 3, \ldots, n\}$, where $e_j = x_j - \bar{x}$ is referred to as residual; $\hat{\sigma}^2(P)$ denotes the error variance computed using Equation (22). Since the assumption of iid may not be strictly valid, the error variance is estimated as:

$$\hat{\sigma}^2(P) = \frac{1}{n} \sum_{t=1}^{n} e_t^2 + \frac{2}{n} \sum_{j=1}^{p} w_j(p) \sum_{t=j+1}^{n} e_t e_{t-j} \tag{22}$$

where p is the truncation lag, which corresponds to the number of lags up to which autocorrelation of the time series $X = (x_t, t = 1, 2, 3, \ldots, n)$ is significant, $w_j(p)$ is an optional weighting function that corresponds to the choice of a window. For the current study, Bartlett window (Bartlett 1951) has been considered, which is given by the following equation:

$$w_j(p) = 1 - \frac{j}{p+1} \tag{23}$$

A detailed explanation about this method can be found in Kwiatkowski *et al.* (1992).

RESULTS AND DISCUSSION

The monsoon rainfall is the main contributor to the annual rainfall (ARF) over the whole of India. Monsoon rainfall values show a wide variation in the study area with mean values ranging from 2,717 mm (in the Himalayan Mountains) to 152 mm (in the western part of India). The mean monsoon rainfall during 1901–2013 for the study area is shown in Figure 2(a). The figure indicates that the eastern part of India and the Himalayan region of the northern part of India get very high monsoon rainfall (more than 1,300 mm/year). The annual average rainfall of western India is very low, and almost all parts of the region receive less than 750 mm ARF during the analysis period. The variability of monsoon rainfall is shown in Figure 2(b). The CV indicates a higher value of 80.5% in the western parts of the study area ranging to a lower value of 15.2% in the mountain area. It can be observed that the regions with lower mean rainfall show higher variability and vice versa.

Long-term dependence in station data

The Hurst coefficient is used to measure the long-term dependence in annual and seasonal rainfall and rainy day series. The results of long-term dependence on annual and seasonal rainfall and the number of rainy days of 148 stations in different climate zones are given in Table 1. The results indicated that the significant long-term dependence is comparatively higher in the stations of semi-arid climatic zones. The stations of tropical wet and dry zones are mostly free from the effect of long-term dependence. The AMRF series are the least to show long-term dependence among other series. In conclusion, the significant long-term dependence is observed in a smaller number of stations (less than 25% of the stations) on the annual and seasonal rainfall as well as the number of rainy day series.

Presence of lag-one autocorrelation

Table 2 presents the number of stations showing serial correlation (r_1) for rainfall and rainy day series. It is observed that most stations (almost 80%) show the sign of serial correlation (r_1) in all the rainfall and rainy day series. In both annual and monsoon rainfall, 93% of the stations from arid regions show the presence of significant serial correlation. The lowest presence of significant serial correlation (71 and 67%) is observed in the tropical wet and dry climatic zone for annual and monsoon rainfall. The results clearly indicated that the presence of serial correlation is more dominant than long-term dependence in all the climatic zones.

Trends in rainfall and rainy day series

The summary of trend analysis for 148 stations distributed over the central, east, north, and west part of India is given in Table 3. The results indicate that less than 30% of stations only show a significant trend (increasing or decreasing) for all the rainfall and rainy day variables. It can be observed that only one station shows a significant increasing trend for both AMRF and NMRD (non-monsoon rainy day) in central India. There is no increasing trend observed for other variables of central India. A maximum of four stations shows an increasing trend in ARF and AMRF for north India and east India, respectively. The stations showing an increasing or decreasing trend in rainfall variables are minimal in east, north, and west India. However, the deceasing trend can be observed in the stations of central India, which is a similar finding of Goswami *et al.* (2006). The trend analysis results of AMRF series do not show any signal of increase or decrease. The trend analysis results of rainy day series are similar to the finding of rainfall series for all parts of India. However, the number of stations showing a decreasing trend is more for the rainy day series than the rainfall series. Overall, the stations showing a decreasing trend are more prominent than the stations showing an increasing trend in both the rainfall and rainy day series for all parts of India. The results are also depicted for all five climatic zones of India in Figures 3 and 4.

The results of trend analysis of rainfall variables for five different climatic zones of India are shown in Figure 3(a)–3(d). It can be seen from Figure 3(a) that for ARF, very few stations show an increasing or decreasing trend in mountain, arid, and tropical wet and dry climatic zones. However, a decreasing trend is dominant in the stations of semi-arid and humid sub-tropical climatic zones. The results are similar to the results of ARF for the rainfall of monsoon season (Figure 3(b)). The number of stations showing a decreasing trend in monsoon rainfall is more than ARF for the tropical wet and dry climatic zones. No pattern is observed for the stations showing an increasing trend. Figure 3(c) shows the trend analysis results of rainfall for non-monsoon season. It can be seen that no stations show any increasing or decreasing trend for the arid climatic zone. Only two stations of mountain and one station of humid sub-tropical zones show an increasing trend. Few stations of semi-arid climatic zones show an increasing trend. No pattern is observed for the stations showing a decreasing trend. The trend analysis results of AMRF are depicted in Figure 3(d). Only five stations of humid sub-tropical climatic zone and two stations from both semi-

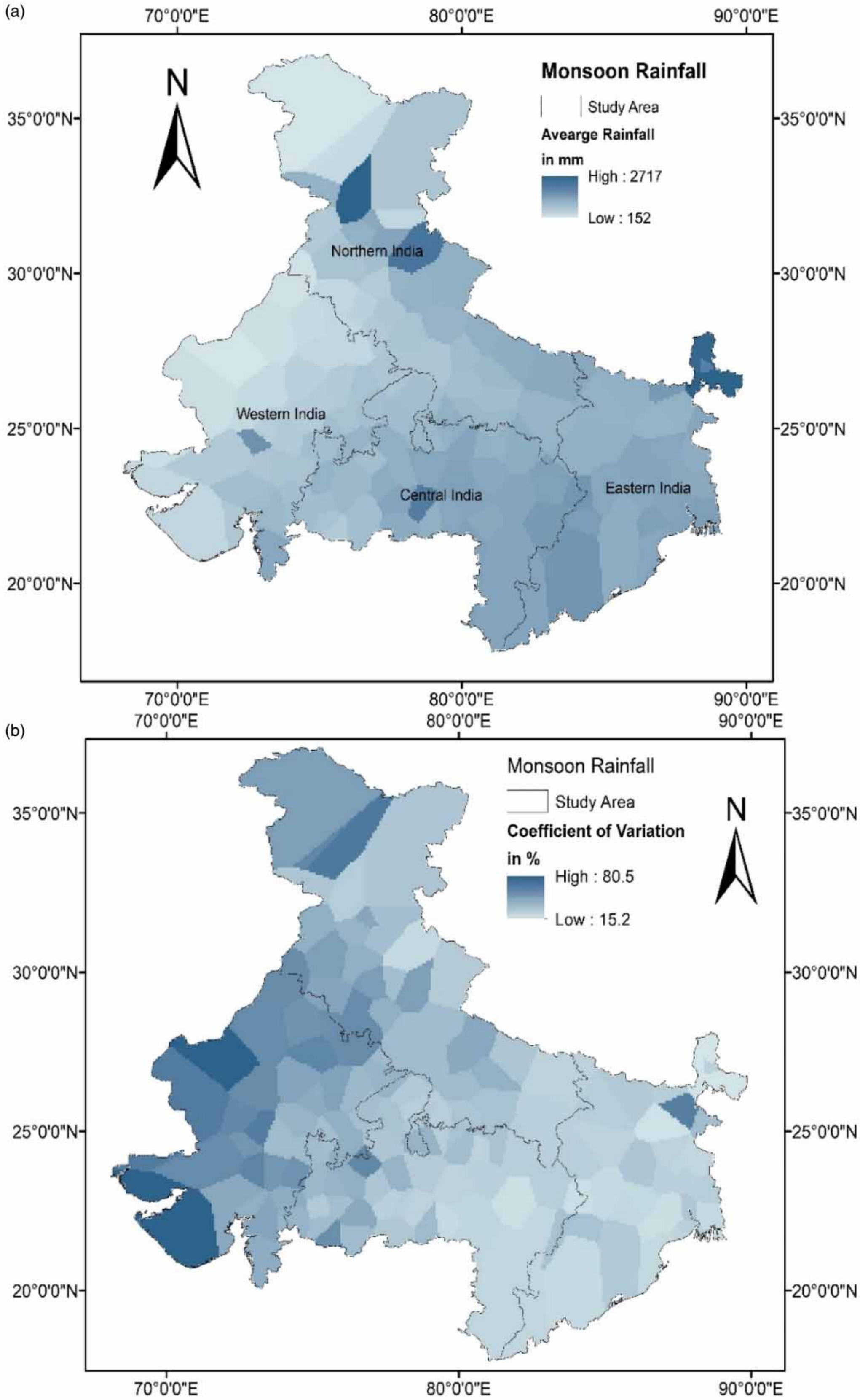

Figure 2 | Monsoon season rainfall and its variation in the study area during 1901–2013: (a) mean and (b) CV.

Table 1 | Summary of results of Hurst coefficient analysis indicating the presence of long-term dependence on the annual and seasonal rainfall and rainy day series

Climatic zone	Total station	ARF	MRF	NMRF	HVYRF	ARD	MRD	NMRD
Arid	14	3	3	2	1	3	4	4
Humid sub-tropical	72	12	11	11	6	17	16	9
Mountain	9	4	1	3	1	5	2	3
Semi-arid	32	10	9	6	1	8	9	5
Tropical wet and dry	21	3	2	1	1	4	3	5
Total	148	32	26	23	10	37	34	26

Note: ARF, annual rainfall; MRF, monsoon rainfall; NMRF, non-monsoon rainfall; HVYRF, annual maximum rainfall; ARD, no. of rainy days in a year; MRD, no. of rainy days in the monsoon season; NMRD: no. of rainy days in the non-monsoon season.

Table 2 | Summary of results of lag-one auto-correlation coefficient analysis indicating the presence of serial correlation in annual and seasonal rainfall and rainy day series

Climatic zone	Total station	ARF	MRF	NMRF	HVYRF	ARD	MRD	NMRD
Arid	14	13	13	10	11	9	11	11
Humid sub-tropical	72	60	57	55	59	60	61	60
Mountain	9	8	8	6	7	7	7	7
Semi-arid	32	24	27	24	24	22	25	24
Tropical wet and dry	21	15	14	17	16	18	20	12
Total	148	120	119	112	117	116	124	114

Note: ARF, annual rainfall; MRF, monsoon rainfall; NMRF, non-monsoon rainfall; HVYRF, annual maximum rainfall; ARD, no. of rainy days in a year; MRD, no. of rainy days in the monsoon season; NMRD, no. of rainy days in the non-monsoon season.

Table 3 | Summary of results of trend analysis in rainfall and rainy day series

	Increasing trend					Decreasing trend				
Variables	Central	East	North	West	Total	Central	East	North	West	Total
ARF	0	2	4	1	7	13	6	6	5	30
MRF	0	2	2	1	5	14	6	4	6	30
NMRF	0	1	3	3	7	4	2	2	1	9
AMRF	1	4	3	1	9	3	2	2	2	9
ARD	0	1	2	1	4	14	14	10	8	46
MRD	0	1	1	1	3	15	13	9	9	46
NMRD	1	0	1	3	5	8	3	3	3	17

Note: ARF, annual rainfall; MRF, monsoon rainfall; NMRF, non-monsoon rainfall; HVYRF, annual maximum rainfall; ARD, no. of rainy days in a year; MRD, no. of rainy days in the monsoon season; NMRD: no. of rainy days in the non-monsoon season.

arid and tropical wet and dry climatic zones show an increasing trend. However, no pattern exists for the stations showing an increasing trend.

The results of decreasing trend in ARF for the arid zone are in contrast to the findings of Kharol *et al.* (2013) and Machiwal *et al.* (2017). However, a similar finding of non-significant increasing or decreasing trends in the stations of the arid climatic zone for ARF has been reported in earlier studies (e.g., Guhathakurta & Rajeevan 2006). For all the climatic zones, most of the stations show non-significant increasing or decreasing trend, which is a similar finding reported by Machiwal & Jha (2008, 2016) for arid, semi-arid, and humid climatic zones of India. Some stations show an increasing trend in the upper portion of humid sub-tropical and semi-arid zones. Similar findings are also reported by Sinha Ray & Srivastava (2000) and Machiwal

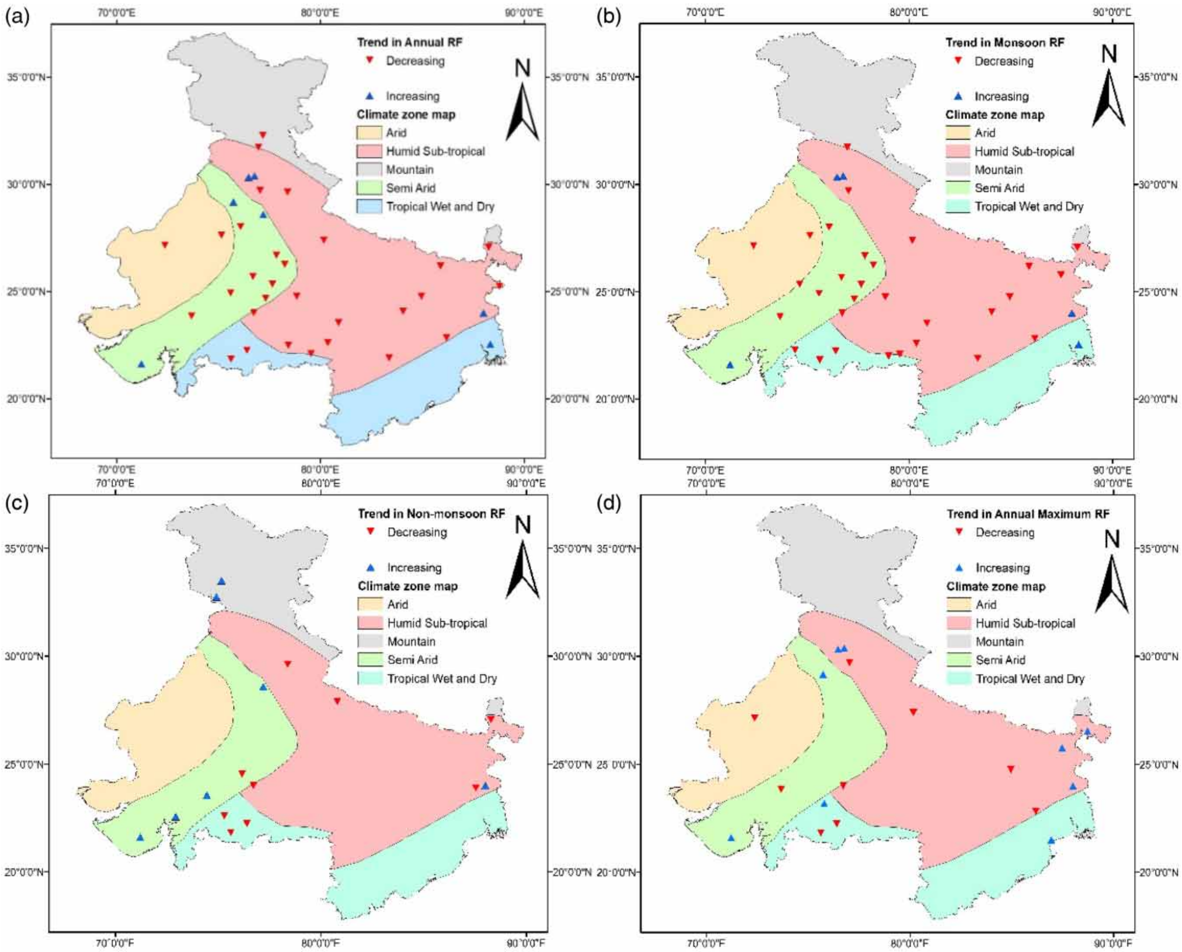

Figure 3 | Significant increasing or decreasing trend in long-term (1901–2013) data of (a) annual rainfall, (b) monsoon rainfall, (c) non-monsoon rainfall, and (d) annual maximum rainfall over different climatic zones of India.

et al. (2017). The stations of the north-western portion of India show a significant increasing trend in ARF. The results are similar to the findings of increasing rainfall trends in the same parts of India (e.g., Lal 2001; Rupa Kumar *et al.* 2006; Machiwal *et al.* 2017).

The results of trend analysis of rainy day variables for five different climatic zones of India are shown in Figure 4(a)–4(c). It can be observed from Figure 4(a) that only one station from each of mountain and humid sub-tropical zones and two stations from the semi-arid climatic zone of India show a significant increasing trend in the annual number of rainy days. The results also indicate that the significant decreasing trend is more prominent in the stations of arid, semi-arid, and humid sub-tropical climatic zones. Only one station from the humid sub-tropical zone and two stations from the semi-arid zone show a significant increasing trend for the number of rainy days in the monsoon season (Figure 4(b)). The results of significant decreasing trend in the monsoon number of rainy days are similar to the finding of the annual basis. However, the stations showing increasing or decreasing trends in NMRDs are not following any pattern (Figure 4(c)). It is observed from the results that mainly semi-arid and humid sub-tropical climatic zones indicate significant decreasing trends in rainfall and the number of rainy days for annual and monsoon seasons. The decreasing rainfall trend is going to affect the water availability of the region. The decreasing trend in the number of rainy days means that the intensity of the rainfall is going to increase or the amount of rainfall going to decrease. Both the situations are going to create water shortage over both the climatic zones of the study area.

Magnitude of change in rainfall series

The results of significant increasing or decreasing trend may not provide the actual picture of change in rainfall variables. According to the IPCC (2007), the change of magnitude is more important than the statistically significant trends for any

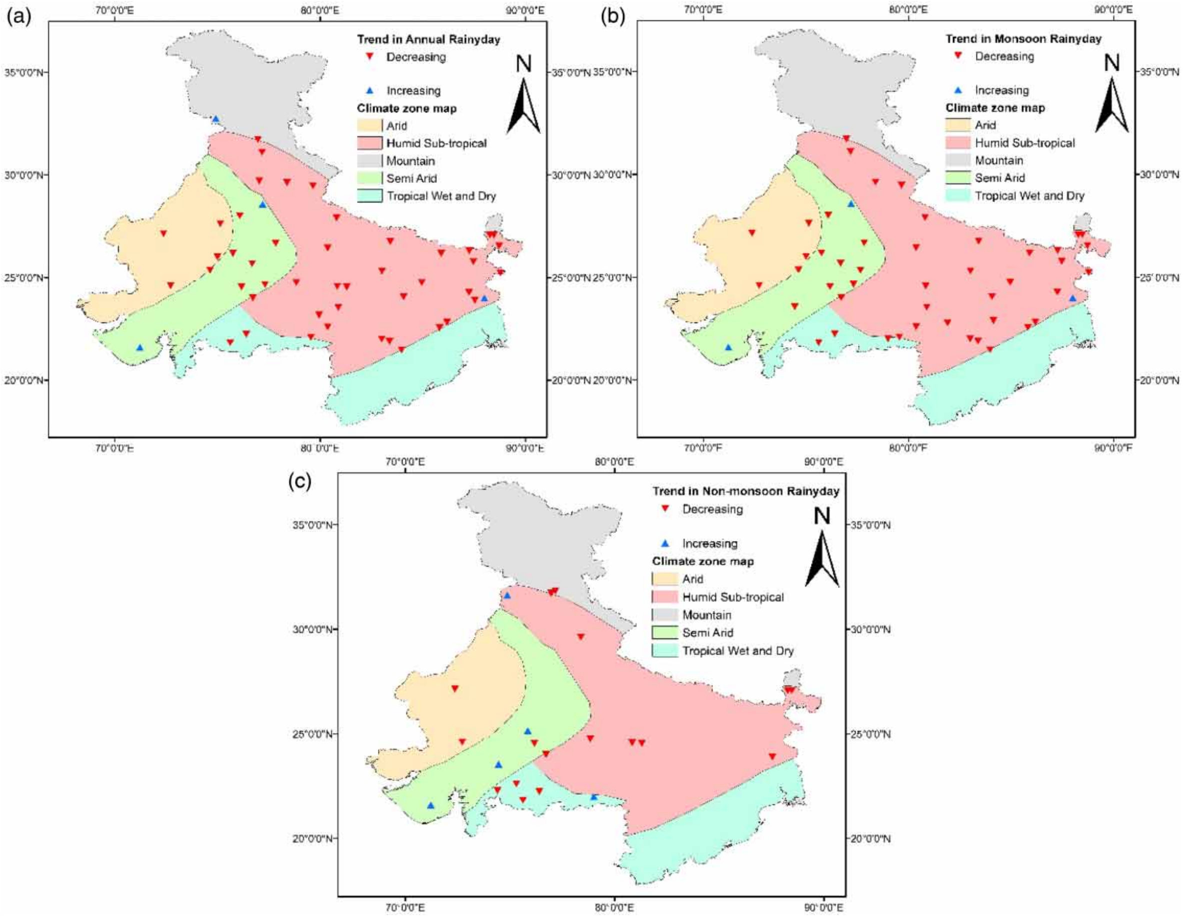

Figure 4 | Significant increasing or decreasing trend in long-term (1901–2013) data of the number of rainy day in (a) annual, (b) monsoon, and (c) non-monsoon season over different climatic zones of India.

climate change-related study. Therefore, the change in magnitude is analysed in the present study using Sen's median slope estimator. The change of magnitude per decade in percentage for rainfall series is shown in Figure 5. It can be observed that the maximum change (maximum increase) of magnitude of all the rainfall variables is in west India. The minimum change (maximum decrease) of magnitude of all the rainfall variables except non-monsoon rainfall is also in west India. An average percentage change in the magnitude of rainfall variables per decade (decreasing rainfall) is comparatively greater in central India than other parts of India.

The results showed that for annual and monsoon rainfall, the average percentage change of magnitude per decade is negative for all the parts of India. However, for non-monsoon season, the average percentage change in the magnitude of rainfall is positive for east (at 0.2%/decade) and west (at 0.7%/decade) India. For both central and northern India, all the rainfall variables show a decrease in rainfall. The AMRF is only increasing over east India (at 0.1%/decade). Western India shows a maximum decrease of AMRF at −2.3% per decade. These results clearly indicated that over east India, which experiences a very high average ARF, the AMRF is increasing. The resulting effect may increase the probability of the occurrence of floods during the monsoon season. However, the rainfall variables are decreasing all over the study area which could create various problems over this region.

The change in monsoon rainfall for four different regions, namely, central, eastern, northern, and western regions of India, is shown in Figure 6(a). Most parts of each of the four regions show a decrease of rainfall by up to 10%. A decrease of rainfall is also found of more than 10% for some parts of each of the four regions. However, an increase of rainfall up to 10% is also found for some other parts. Figure 6(b) shows the change in population density for four different regions, namely, central, eastern, northern, and western regions of India. It can be seen that the population density for all four regions increases

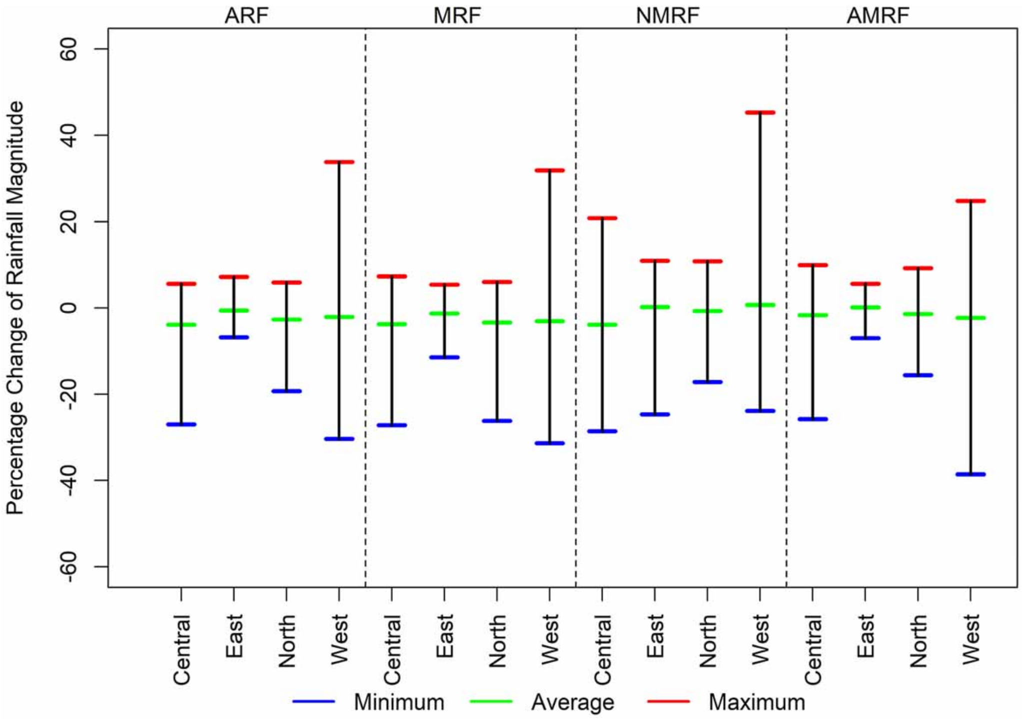

Figure 5 | Percentage change of magnitude of rainfall series per decade over central, east, north, and west India for the period of 1901–2013. ARF, annual rainfall; MRF, monsoon rainfall; NMRF, non-monsoon rainfall; HVYRF, annual maximum rainfall.

with decadal time. After the year 1950, the increase of population density is very high in eastern and northern regions of India, while a lesser increase of population density is observed for central and western regions of India. It is obvious that due to the increase in population, the demand for fresh water is going to increase and, at the same time, the magnitude of monsoon rainfall will decrease. According to a document published by NITI Aayog, Government of India, the country is undergoing the worst water crisis scenario. Not only that, almost 600 million people in the country are already facing severe water shortage. Furthermore, the problem related to drinking water is very severe and almost 75% of households in the country do not have drinking water on their premises. This situation will increase with time and create various problems due to the simultaneous impact of decreasing rainfall with the increase in population density. Therefore, it will require a more substantial strategy for managing the water resources of the country.

Change point detection

The results of change point detection using the Pettit test and rank-sum test are given in Table 4. The change point analysis is performed only for the stations having at least 100 years of data. Therefore, the change point analysis is applied for 40 stations over various climatic zones. The change point is selected when both the tests give the same results; otherwise, the change point is selected by plotting the datasets for those stations showing different results by the two tests. The results show that the significant change point is present in only 16 (40%), 15 (37.5%), and 9 (22.5%) stations out of 40 stations, for annual, monsoon, and AMRF, respectively. The change point detected by both the tests matches at 10 (62.5%), 10 (66.67%), and 5 (55.56%) stations for annual, monsoon, and AMRF, respectively. Therefore, it can be seen that the results of both the tests are in agreement for most of the stations.

The change point analysis was carried out using 40 stations, of which 5, 23, 7, and 5 stations are from arid, humid sub-tropical, semi-arid, and tropical wet and dry climatic regions of India. The results show that there is no change point detected for the stations of the arid climatic region. The change point is detected for only 9 (39.13%), 9 (39.13%), and 6 (26.09%) stations out of 23 stations for annual, monsoon, and AMRF in the humid sub-tropical climatic region. In the semi-arid region, the results show that only 4 (57.14%), 3 (42.86%), and 2 (28.57%) stations out of seven stations have change point for annual, monsoon, and AMRF. The results show that only 3 (60%), 3 (60%), and 1 (20%) stations have change point in annual,

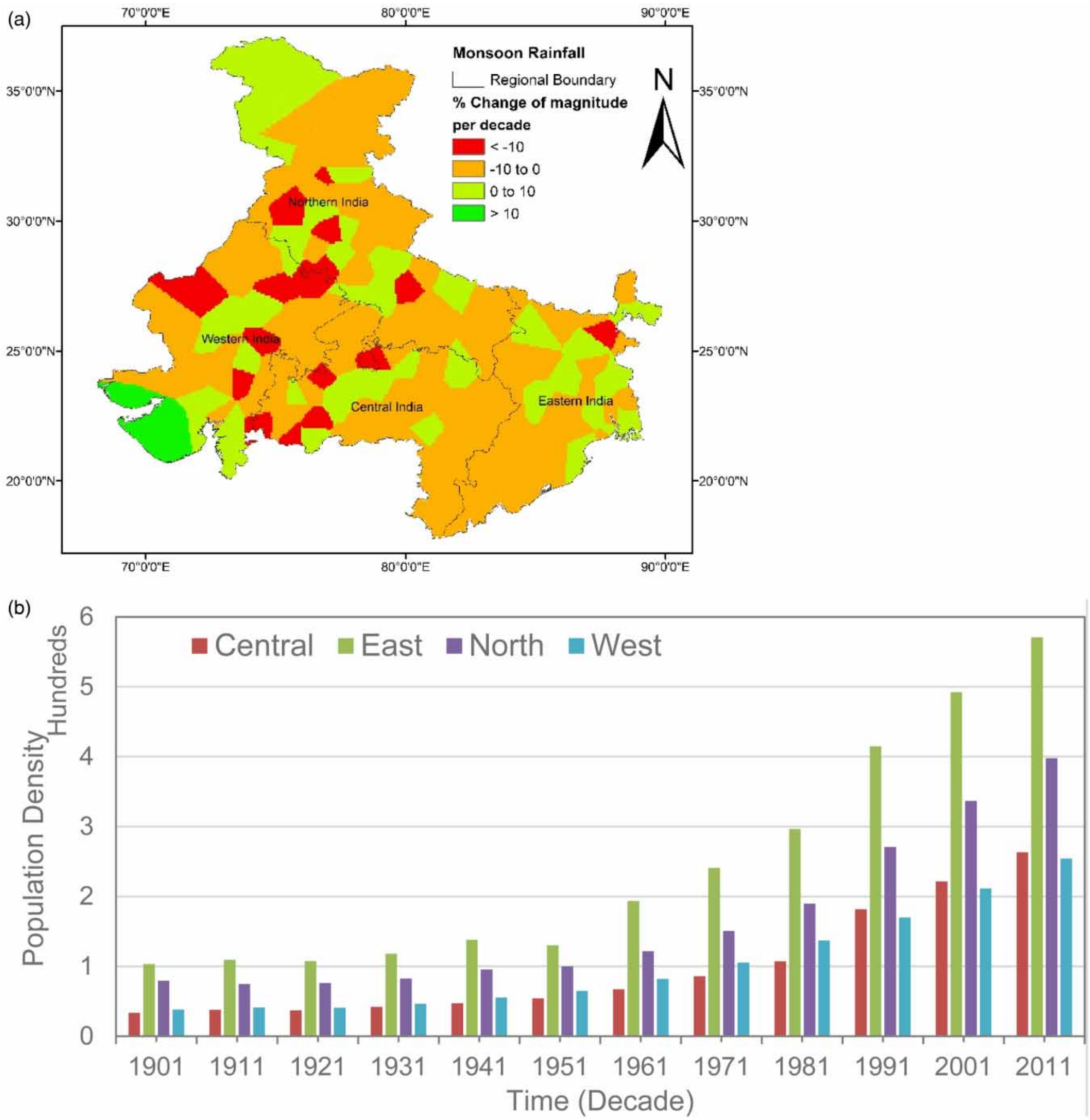

Figure 6 | Change in rainfall and population density over central, east, north, and west India: (a) magnitude of monsoon rainfall and (b) average population density (source of population density data: Census India, http://opengovernanceindia.org/rajrgid/statewise-census-data-in-india-1901-2011).

monsoon, and AMRF in the tropical wet and dry climatic region. The results indicated that the annual and monsoon rainfall are more prone to detect the change point in comparison to the AMRF. The detection of significant change point is greater for the stations of tropical wet and dry and semi-arid climatic regions than humid sub-tropical and arid climatic regions of India. The results also show that the change point detected for annual and monsoon rainfall is the same for all the stations, which clearly indicated that due to a change in monsoon rainfall, the ARF of all the same stations will change.

The results indicated that 11 stations experience a significant change in the period of 1950–1966 for annual and monsoon rainfall. However, no such period can be detected for AMRF. This change or shift in annual and monsoon rainfall may be linked to the increasing sea-surface temperatures and very heavy rain events. Rajeevan *et al.* (2008) reported that during the two decades of 1941–1960, the frequency of very heavy rainfall was below average. Moreover, according to the IPCC (2007), the sea-surface temperatures entered a cooling phase over the equatorial Pacific Ocean at the same time period of

Table 4 | Results of change point detection for at least 100 years' annual and seasonal rainfall series of different climatic regions of India

			Annual		Monsoon		Annual maximum	
S. No.	Rainfall station	Climatic zone	Pettit	Rank-sum	Pettit	Rank-sum	Pettit	Rank-sum
1	Abu	Arid	No	No	No	No	No	No
2	Ajmer	Arid	No	No	No	No	No	No
3	Bikaner	Arid	No	No	No	No	No	No
4	Deesa	Arid	No	No	No	No	No	No
5	Jodhpur	Arid	No	No	No	No	No	No
6	Allahabad	HST	No	No	No	No	No	No
7	Ambala	HST	**1942**	**1942**	**1942**	**1942**	No	No
8	Bahraich	HST	No	No	No	No	**1983**	**1983**
9	Bareilly	HST	No	No	No	No	No	No
10	Berhampore	HST	**1963**	**1963**	**1963**	**1963**	**1964**	**1964**
11	Daltonganj	HST	**1951**	**1951**	**1951**	**1951**	No	No
12	Darbhanga	HST	**1959**	**1959**	**1959**	**1959**	1962	**1961**
13	Darjeeling	HST	**1979**	**1979**	**1979**	**1979**	**1979**	**1979**
14	Gaya	HST	**1925**	1924	**1925**	1924	1947	**1945**
15	Gorakhpur	HST	No	No	No	No	1979	**No**
16	Hoshangabad	HST	**1950**	1949	**1950**	1949	No	No
17	Jabalpur	HST	**1962**	No	**1962**	No	No	No
18	Jalpaiguri	HST	No	No	No	No	No	No
19	Mainpuri	HST	No	No	No	No	No	No
20	Mukteshwar	HST	No	No	No	No	No	No
21	Nowgong	HST	No	No	No	No	No	No
22	Pachmarhi	HST	No	No	No	No	No	No
23	Pendra	HST	1965	**No**	1965	**No**	No	No
24	Purnea	HST	No	No	No	No	**1968**	1969
25	Sagar	HST	1935	**No**	1934	**No**	No	No
26	Satna	HST	NO	No	No	No	No	No
27	Seoni	HST	**1966**	**1966**	**1961**	**1961**	No	No
28	Varanasi	HST	No	No	No	No	No	No
29	Agra	Semi-arid	**1953**	**1953**	**1953**	**1953**	**1981**	**1981**
30	Ahmedabad	Semi-arid	No	No	No	No	No	No
31	Hissar	Semi-arid	**1951**	1950	No	No	No	No
32	Jhansi	Semi-arid	**1961**	**1961**	**1961**	**1961**	**1961**	**1961**
33	Neemuch	Semi-arid	**1946**	**1946**	**1946**	**1946**	No	No
34	New Delhi	Semi-arid	No	No	No	No	No	No
35	Surat	Semi-arid	No	No	No	No	No	No
36	Balasore	TWD	No	No	No	No	No	No
37	Khandwa	TWD	1944	**1945**	1944	**1945**	1948	**1949**
38	Kolkata	TWD	**1954**	**1954**	**1954**	**1954**	No	No
39	Midnapore	TWD	No	No	No	No	No	No
40	Sambalpur	TWD	1961	**1962**	1961	**1962**	No	No

Note: HST denotes humid sub-tropical zone; TWD denotes tropical wet and dry zone; bold font indicates the change point at 5% significance level.

1941–1960. The warming phase of the sea-surface temperatures was observed after the 1960s and was attributed to the increasing trend of very heavy rainfalls over India. Moreover, from Figure 6(b), it can also be found that after the year 1950, the population density increases very sharply for all the four parts (east, west, central, and north) of India. Therefore, the sharp increase after the 1950s may have impacted the changing behaviour of monsoon rainfall over the country.

Analysis of stationarity

The results of the KPSS test are given in Table 5. The analysis was carried out using 148 stations' rainfall and rainy day datasets for the entire time period of 1901–2013. The results indicated that most of the stations follow level stationarity for all

Table 5 | Results of the KPSS test for 148 station datasets for the period of 1901–2013

Variables	Level stationary	% of stations	Trend stationary	% of stations	Non-stationary	% of stations
Annual rainfall	119	80.4	26	17.6	3	2.0
Monsoon rainfall	119	80.4	25	16.9	4	2.7
Non-monsoon rainfall	139	93.9	5	3.4	4	2.7
Annual maximum rainfall	135	91.2	12	8.1	1	0.7
Annual rainy days	93	62.8	34	23.0	21	14.2
Monsoon rainy days	95	64.2	36	24.3	17	11.5
NMRDs	125	84.5	12	8.1	11	7.4

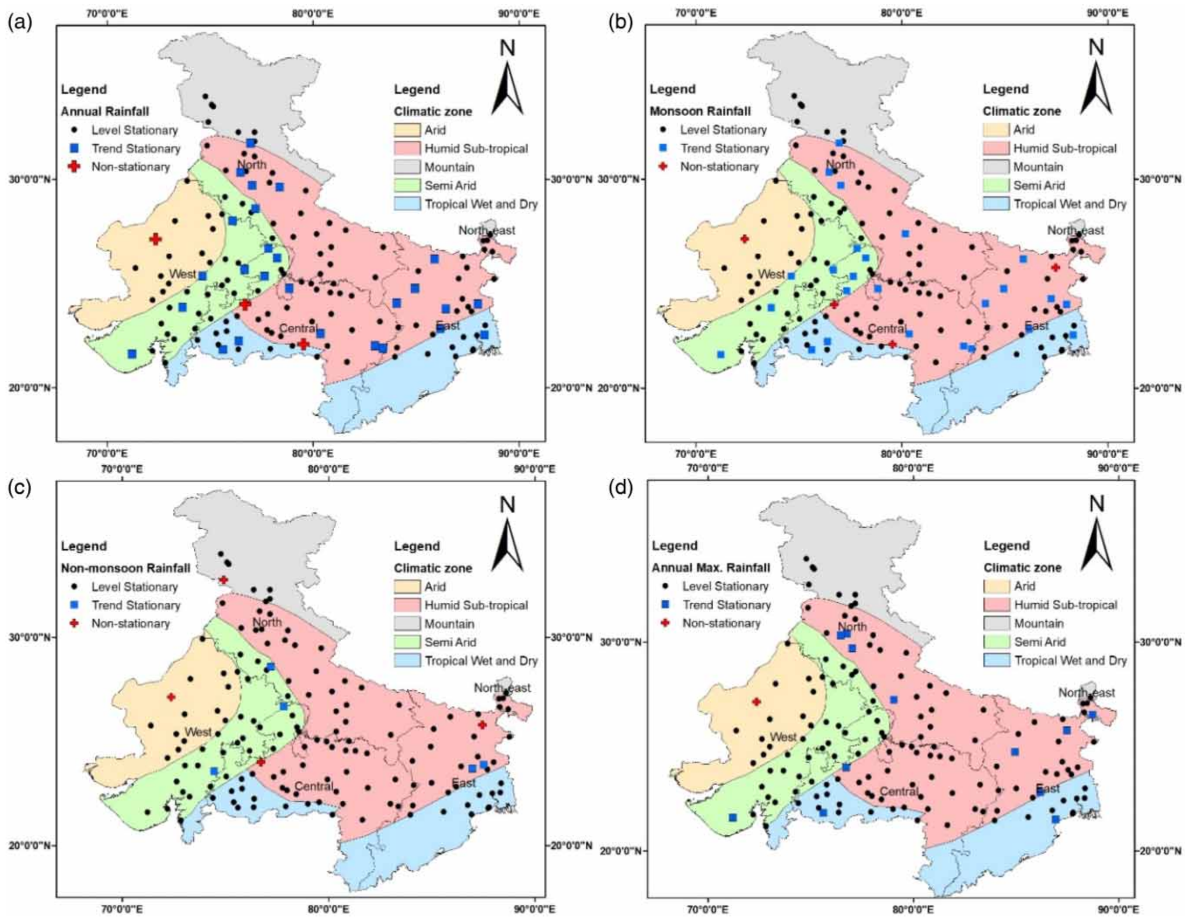

Figure 7 | Stationarity analysis of rainfall (1901–2013) series by the KPSS test for different climatic regions of India: (a) ARF, (b) monsoon rainfall, (c) non-monsoon rainfall, and (d) annual maximum rainfall.

rainfall and rainy day variables. The trend stationarity is found more for annual and monsoon season rainfall and rainy day series. For non-monsoon season, the percentage of stations showing level stationarity is maximum among the rainfall and rainy day series. More than 90% stations show level stationarity for annual maximum and non-monsoon rainfall series. It can be seen from the results that less than 3% of stations show non-stationarity in all the rainfall variables. Therefore, it is clear that the rainfall and rainy day series of the country are following stationary behaviour.

The spatial distribution of level stationarity, trend stationarity, and non-stationarity rainfall series obtained from the KPSS test is shown in Figure 7. It can be seen from Figure 7(a) that the stations of semi-arid climatic regions and near to those regions show trend stationarity. The trend stationarity is also found for the stations of humid sub-tropical climatic regions. Only three stations show non-stationarity, and there is no spatial pattern observed. The results are similar to the ARF for the monsoon season (Figure 7(b)). However, the non-monsoon and AMRF show level stationarity for almost all the stations. Those stations showing trend stationarity or non-stationarity in non-monsoon and AMRF do not follow any spatial trend. From the results, it is clear that the trend stationarity in ARF is mainly coming from monsoon rainfall. The results clearly indicated that the stations of the semi-arid region and near to that climatic region are going through a change and this may create multitudinous water-related problems for that region.

The spatial distribution of level stationary, trend stationary, and non-stationary rainy day series obtained from the KPSS test is shown in Figure 8. For annual and monsoon seasons, the rainy day series show that trend stationarity and non-stationarity are distributed over the semi-arid and humid sub-tropical regions (Figure 8(a) and 8(b)). However, the stations showing trend stationarity and non-stationarity do not follow any spatial pattern for the rainy day series of non-monsoon season (Figure 8(c)). The analysis clearly indicated that the rainy day series are more vulnerable than the rainfall series towards the trend

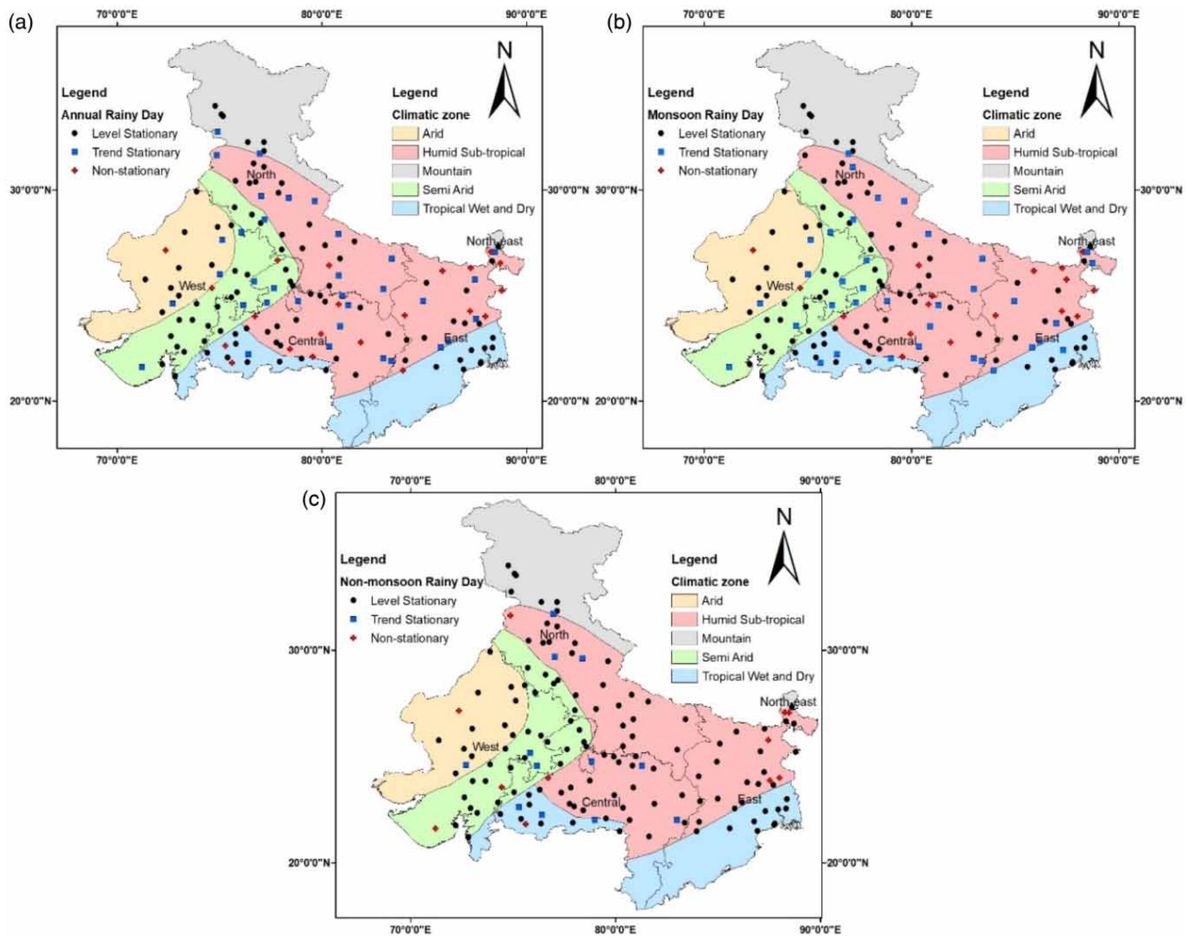

Figure 8 | Stationarity analysis of rainy day (1901–2013) series for annual and seasonal basis by the KPSS test for different climatic regions of India: (a) annual, (b) monsoon, and (c) non-monsoon season.

stationarity and non-stationarity. Due to this erratic behaviour of the rainy day series, the temporal variation in rainfall series over the semi-arid and humid sub-tropical regions is very high and will continue to increase the variation.

CONCLUSION

The spatio-temporal change in annual and seasonal rainfall and rainy day series of 148 stations has been analysed for five different climatic regions (arid, semi-arid, humid sub-tropical, mountain, and tropical wet and dry) of India. The long-term dependence, trends, change point detection, and stationarity of the rainfall and rainy day series are analysed using different statistical tests at 5% significance level. The results show that the presence of long-term dependence is very low for the rainfall and rainy day series for different climatic regions except in the semi-arid region. The lag-one serial correlation is prominent in the rainfall and rainy day series for all five climatic regions of India. The trend analysis results indicated that a smaller number of stations show a significant increasing trend, while some stations show a significant decreasing trend for annual and monsoon rainfall and rainy day series. The spatial distribution of rainfall and rainy day series confirms that the rainfall stations of the semi-arid and humid sub-tropical regions show a significant change, mainly in the decreasing side. A 10% decrease in the magnitude of annual and monsoon rainfall is found for almost the whole study area. The change point analysis is carried out using only 40 stations' data (which have at least 100 years' data) and shows that the stations having change point are very less in number. The analysis of stationarity shows that the higher percentage of stations follows level stationarity, while some stations, mainly in the semi-arid and humid sub-tropical regions, follow trend stationarity for all the rainfall variables. The trend stationarity and non-stationarity is more prominently visible in the rainy day series for annual and monsoon seasons.

The results of trend and stationarity analysis clearly indicate that the rainfall variables are not changing significantly. However, the rainy day series show a significant decreasing trend and non-stationarity for annual and monsoon seasons. The change in rainfall and rainy day series is more visible, mainly for the semi-arid and humid sub-tropical climatic regions of India. These two regions are the most populous part of the country and, therefore, the changing behaviour of rainfall can create various water-related problems for the same regions. Due to the non-stationarity in the rainy day variables, the variability of rainfall will also have an effect. Therefore, the water resources of these regions need a proper management strategy, and the present study can be very useful in this direction. However, the causes of the trend and non-stationarity have not been investigated, and a detailed study is required in this regard.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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