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Non-parametric Analysis of Long-term Rainfall and Temperature Trends in India

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SUMMARY

Long-term annual, seasonal and monthly trends in rainfall at 30 sub-divisional meteorological stations and temperature (maximum and minimum) in seven homogenous regional scales in India were investigated for trend analysis. The monthly (January–December), seasonal (winter, summer, monsoon/rainy and post-monsoon seasons) and annual rainfall series for each of the 30 meteorological sub-divisions along with monthly temperature series for all-India and seven homogeneous regions, viz., Western Himalaya (WH), Northwest India (NWI), North Central India (NCI), Northeast India (NEI), West Coast (WC), East Coast (EC) and Interior Peninsula (IP) were procured from Indian Institute of Tropical Meteorology, Pune, India (IITM: htpp://www.tropmet.res.in). Modified Mann-Kendall test (if the time series data are not serially independent), Sen's slope estimator and linear regression approaches were utilised for assessing the statistical significance of trend and variability in meteorological data. There are no significant trends in monthly rainfall at most of the synoptic stations in India. However, the maximum number of stations with negative trends have been observed in December (21 stations), and then in September (19 stations) and January (16 stations) and with positive trends in April (26 stations) and October (25 stations). For annual rainfall, 15 sub-divisional meteorological stations showed decreasing trends. Significant trends in annual rainfall have been noticed only at three stations (East Madhya Pradesh, Konkan and Goa and Coastal Karnataka) only. For seasonal trends, 20 sub-divisional meteorological stations showed decreasing trend in winter season (January and February). Nine sub-divisional meteorological stations showed decreasing trend in summer season (March, April and May), 16 sub-divisional meteorological stations showed decreasing trend in monsoon season (June, July, August, September) while eight sub-divisional meteorological stations showed decreasing trend in post-monsoon season (October, November and December). Significant trends in seasonal rainfall have been noticed in one sub-divisional meteorological station in winter season, three sub-divisional meteorological stations in summer, six sub-divisional meteorological stations in monsoon season and one sub-divisional meteorological station in post-monsoon. There was significant rising trend in maximum temperature in most of the months while minimum temperature in various regions showed increasing trends; but it had low significance level as compared to maximum temperature.

Keywords: Trend analysis, Rainfall, Temperature, Non-parametric test, Modified Mann–Kendall test, Sen's slope estimator.

1. INTRODUCTION

Effect of climate change on agriculture is multidimensional. Magnitude of change in temperature and rainfall pattern is impacting the natural vegetation over a region, which is facing a new challenge for survival. The fittest species are more likely to dominate in the changing pattern of climate, which could lead to emergence of new pests and diseases. Therefore, the spatial and temporal variability of these variables is important from both scientific and practical point of view. Rainfall, temperature and its associated seasonal

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patterns are critical components of agricultural production systems. Rising temperatures associated with climate change are likely to have a detrimental impact on crop production, livestock, fishery and allied sectors. Historically, climate analysis has been performed on continental and global scales (Pielke *et al*. 2000). However, with such local complexities, there is need to define local climate patterns. Local scale climate analysis can more accurately represent the complex climate that exists in India, and offers new insights into patterns in meteorological variables. Therefore, investigation of the climate change at local scale is necessary. Traditionally, climate patterns have been investigated using trend analysis on a point-by-point basis. Temperature and precipitation trends from one location would be compared with surrounding locations. This is appropriate when large distances separate monitoring locations. However, advanced spatial analysis is possible when monitoring locations are clustered in a local region. Spatially analyzing climate variables on a local scale provides improved insight into local patterns over both space and time. In the 1980s, several studies were published that investigated climate change on a national and global scale, using surface observations and remote sensing platforms (Diaz and Quayle 1980). However, there were few studies that investigated climate on a local scale, using the full suite of observing locations. Historically, climate researchers have used observations from a single location to represent the climate for a large area, sometimes even an entire state (Pielke *et al*. 2000). In view of the above, a number of studies have attempted to investigate the trend of climatic variables for the country. These studies have looked at the trends on the country scale, regional scales and at the individual stations. Many studies have attempted to determine the trend in rainfall and temperature on both country and regional scales because these two climatic variables are most important regarding climate change. Most of these deal with the analysis of annual and seasonal series for some individual stations or groups of stations. Jain and Kumar (2012) in their review paper, cited that there is no clear trend in average annual rainfall in India. Sen Roy and Balling (2004) analysed daily rainfall data for 1910-2000 at 129 stations and found generally increasing trend in a contiguous region extending from the northwestern Himalayas in Kashmir through most of the Deccan Plateau in the south and decreasing values in the eastern part of the Gangetic Plains and parts of Uttarakhand. Pal and Al-Tabbaa (2009) studied the trends in seasonal rainfall extremes in Kerala, using gridded daily data for 1954-2003. They found winter and post-monsoon extreme rainfall having an increasing tendency with statistically significant changes in some regions and decreasing trends in spring seasonal extreme rainfall. Kothawale *et al*. (2010) studied the association between El Niño Southern Oscillation (ENSO) and monsoon rainfall over India and reported a strong association between El Niño events and deficient monsoon rainfall. Nearly 60% of major droughts over India have occurred in association with El Niño events. Kumar *et al*. (2010) showed that the monsoon rainfall in India exhibited no significant trend over a long period of time, particularly in the all-India scale. Studies on climate change have shown an increase of 0.5-1% in rainfalls per decade in much of the Northern Hemisphere's mid and high latitude. Annual average of regional precipitation has increased between 7% and 12% for the areas in 30-85°N latitude and by about 2% for the areas in 0-55°S over the 20th century (Mosmann *et al*. 2004, Xu *et al*. 2003, Xu *et al*. 2005, Yu *et al*. 2006). Much of the research shows that there are decreasing or increasing trends in annual, seasonal and monthly rainfall but most of them are not significant trends. For example in Turkey, most regional mean, normalized, annual rainfalls have negative trends which are not significant (Kahya and Kalayc 2004, Raziei *et al*. 2005). Ramos (2001) showed that there is no significant trend in annual rainfall of Mediterranean area while González-Hidalgo *et al*. (2001) found a significant decrease in rainfall amount associated with a significant increase in variability in more humid areas of Valencia. IPCC report (2007) showed that significant trends have been observed in precipitation amounts in many regions from 1900 to 2005. Over this period, precipitation increased significantly in eastern parts of North and South America, northern Europe, northern and central Asia whereas precipitation declined in the Mediterranean coast, southern Africa and parts of southern Asia.

Most of the temperature trend studies in India focus on the analysis of annual and seasonal temperature data for a single station or a group of stations. Pramanik and Jagannathan (1954) studied the trends in the annual mean, maximum and minimum temperatures over the whole country who did not find any general tendency for an increase or decrease in these temperatures. Hingane *et al*. (1985) reveals that the mean annual temperature was found to be increasing over the west coast, interior peninsula, north central and northeastern regions of India along with the whole of India during the period 1901-1982. Pant and Hingane (1988) found decreasing trend in mean annual surface air temperature for 1901-1982 over the northwest Indian region consisting of the meteorological sub-divisions of Punjab, Haryana, west Rajasthan, east Rajasthan and west Madhya Pradesh. Rao (1993) analysed the data from seven stations for 1901-1980 and showed highly significant warming trend in the mean maximum, mean minimum and average mean temperatures of the Mahanadi river basin. Rupa Kumar *et al*. (1994) studied the trend analyses of maximum and minimum temperature at 121 stations in India for 1901-1987, which show that the increasing maximum temperature have increasing trend and there is no trend for minimum temperature, resulting in rise in mean and diurnal range of temperature. Arora *et al.* (2005), analysed the series of annual and season mean temperature, annual mean maximum temperature and annual mean minimum temperature using the data from 125 stations distributed throughout India. This study also showed that the percentage of significant trends was high and there is a rising trend in most cases. Bhutiyani *et al*. (2007) found increasing trend in maximum, minimum, mean and diurnal temperature range over the northwestern Himalayan region during the 20th century. Pal and Al-Tabbaa (2010) studied the long-term trends and variations in the monthly maximum and minimum temperatures in various climatological regions in India. Their result revealed increasing monthly maximum temperature, though unevenly, over the last century. Minimum temperature changes were found more variable than maximum temperature changes, both temporally and spatially, with results of lesser significance.

The present study focuses on investigating climate variability by analyzing trends of rainfall for various regions and different meteorological sub-divisions along with trends of temperature (maximum and minimum) for seven homogenous regions in India.

Table 1. Various meteorological sub-divisions along with covered area and mean rainfall

S. no	Sub-division	Sub-division no.	Area (km)^2	No. of rainfall Stations used	Mean rainfall (mm)
1.	Assam and Meghalaya	3	109096	10	3102.5
2.	Nagaland, Manipur, Mizoram, Tripura	4	70495	4	2742.1
3.	Sub-Himalayan W. Bengal	5	21625	5	3323.8
4.	Gangetic W. Bengal	6	66228	11	2226.9
5.	Odisha	7	155842	13	1988.1
6.	Jharkhand	8	79638	6	1862.6
7.	Bihar	9	94235	11	1729.3
8.	East Uttar Pradesh	10	146509	26	1712.9
9.	West U.P. Plains	11	96782	19	1304.6
10.	Haryana	13	45698	12	997.3
11.	Punjab	14	50376	10	1195.6
12.	West Rajasthan	17	195086	9	722.2
13.	East Rajasthan	18	147128	17	1337.1
14.	West Madhya Pradesh	19	175317	22	1420.3
15.	East Madhya Pradesh	20	135156	15	1748.5
16.	Gujarat	21	86034	11	1614.3
17.	Saurashtra and Kutch	22	109950	7	1240.5
18.	Konkan and Goa	23	34095	5	3974.3
19.	Madhya Maharashtra	24	115306	9	1107.5
20.	Marathwada	25	64525	5	1500.5
21.	Vidarbha	26	97536	8	1585.5
22.	Chhattisgarh	27	146138	6	2081.5
23.	Coastal Andhra Pradesh	28	93045	8	1501.1
24.	Telangana	29	114726	9	1484.1
25.	Rayalaseema	30	69043	4	1227.4
26.	Tamil Nadu	31	130068	15	1262.5
27.	Coastal Karnataka	32	18717	2	5552.2
28.	North Interior Karnataka	33	79895	6	1236.1
29.	South Interior Karnataka	34	93171	11	1323.1
30.	Kerala	35	38864	10	3944.7

2. MATERIALS AND METHODS

2.1 Data

2.1.1 Rainfall Data

Sub-divisional monthly rainfall data of India prepared by the Indian Institute of Tropical Meteorology (IITM: htpp://www.tropmet.res.in) were used in this study. A network of 306 stations (one representative station per district) over 30 meteorological subdivisions was used to prepare the sub-divisional data. The monthly (January-December) rainfall series for each of the 30 meteorological sub-divisions was also obtained. The monthly data were available for 141 years (1871-2011) for 30 sub-divisions. Various meteorological sub-divisions along with area covered and mean rainfall is given in Table 1. Rainfall data of six meteorological sub-divisions, namely Jammu and Kashmir, Uttaranchal, Himachal Pradesh, Arunachal Pradesh, Lakshadweep and Andaman & Nicobar Islands, were not available. As may be seen from Table 1 (Kumar *et al*. 2010), the area of studied sub-divisions varied from a minimum of 18717 km^2 (Coastal Karnataka) to a maximum of 195086 km^2 (West Rajasthan) with the number of rainfall stations varying from two (Coastal Karnataka) to 26 (East Uttar Pradesh). The 30 sub-divisions were combined into seven homogeneous regions as North Mountainous India (NMI), South Peninsular India (SPI), North Central India (NCI), North East India (NEI), North West India (NWI), East Peninsular India (EPI) and West Peninsular India (EPI). To investigate the change in rainfall for different seasons, a year was divided into four seasons viz., winter (December, Janurary and February), summer (March, April and May), monsoon season (June, July, August and September) and post-monsoon season (October and November). Trend analysis of the rainfall data for various regions and different meteorological sub-division for monthly, seasonal and annual was done seprately.

2.1.2 Temperature (Maximum and Minimum)

Monthly temperature series was used in the present study for all-India and seven homogeneous regions, viz., Western Himalaya (WH), Northwest India (NWI), North Central India (NCI), Northeast India (NEI), West Coast (WC), East Coast (EC) and Interior Peninsula (IP) over a network of 121 stations for the period 1901-2007 from the IMD. Details of data are available in http://www.tropmet.res.in/ (Kothawale and Rupakumar 2005).

2.2 Statistical Test for Trend Anlysis

Trend analysis of a time series consists of the magnitude of trend and its statistical significance. The magnitude of trend in a time series is determined by non-parametric method using Sen's estimator (1968). Sen's estimator has been widely used for determining the magnitude of trend in meteorological time series data. To ascertain the presence of statistically significant trend in climatic variables with reference to climate change, non-parametric Mann-Kendall (MK) test has been employed. According to Ahani *et al*. (2012), if a time series presents a linear trend, the true slope (change per unit time) can be estimated by using a simple nonparametric procedure developed by Sen (1968). Sen's slope estimator, the same as MK statistics, is a well-known statistical test (Dinpashoh *et al*. 2011, Tabari *et al*. 2011, Tabari *et al*. 2010a, Tabari *et al*. 2010b, Ahani *et al*. 2012). The total change during the observed period was obtained by multiplying the slope by the number of years (Tabari and Talaee 2011).

Mann (1945) presented a nonparametric test for randomness against time, which constitutes a particular application of Kendall's test for correlation commonly known as the Mann-Kendall test. The utility of the Mann-Kendall test (M-K test) is that it is considered robust, being insensitive to outliers and power transformations (Helsel and Hirsch 1992). Mann-Kendall test does not require any hypotheses on the variables and is more powerful than parametric tests. However, it is based on the hypothesis that the expected change in the series is a monotonic trend and not a break. However, if there is a break in the data series, no loss of power is observed in the M-K test in comparison with Pettitt's break test (Lemaitre 2002). Furthermore, if a climatic change affects a given series, a gradual change can be expected rather than a break that would result more from a meteorological change. The test is applied at the local scale and also at the regional scale to judge the regional significance of the changes detected. As stated by Zhai and Feng (2008), this test has a number of advantages: (i) the data do not need to conform to a particular distribution; thus extreme values are acceptable (Hirsch *et al*. 1993), (ii) missing values are allowed (Yu *et al*. 1993), (iii) relative magnitudes (ranking) are used instead of the numerical values, which allows for 'trace' or 'below detection limit' data to be included, as they are assigned a value less than the smallest measured value, and (iv) in time series analysis, it is not necessary to specify whether the trend is linear or not (Yu *et al.* 1993, Silva 2004). For M-K test, the null hypothesis is H_0 of no trend, *i.e.*, the observations of series are randomly ordered in time, against the alternative hypothesis, H_1, where there is an increasing or decreasing monotonic trend. The data values are evaluated as an ordered time series. Each data value is compared with all subsequent data values.

2.2.1 Mann–Kendall Non-parametric Test

To ascertain the presence of statistically significant trend in climatic variables such as temperature, relative humidity, rainfall and bright sunshine hours non-parametric Mann–Kendall (M-K) test has been employed. The null hypothesis (H_o) of M-K test states that the data ($x_1, x_2, x_3, \dots x_N$) has no trend versus the alternative hypothesis (H_1) of the existence of increasing or decreasing trend. The statistics (S) is defined as

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

where, x_j and x_i are data values at time j and i ($j > i$) and N is the number of data points. Assuming the $(x_j - x_i) = \theta$, value of sgn (θ) is computed as follows:

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & if \quad \theta > 0 \\ 0 & if \quad \theta = 0 \\ -1 & if \quad \theta < 0 \end{cases} \tag{2}$$

This statistics represents the number of positive differences minus the number of negative differences for all the differences considered. The test statistic Kendall's τ (Tau) can be computed as

$$\tau = \frac{S}{N(N-1)/2}$$

which has a range of –1 to +1 and is analogous to the correlation coefficient in regression analysis. The null hypothesis of no trend is rejected when S and τ are significantly different from zero. If a significant trend is found, the rate of change can be calculated using the Sen's slope estimator. For large samples the test is conducted using a normal distribution, with the mean and the variance as follows

$$E(S) = 0 \tag{3}$$

$$\operatorname{var}(S) = \frac{N(N-1)(2N+5) - \sum_{k=1}^{n} t_k(t_k-1)(2t_k+5)}{18} \tag{4}$$

where, n is the number of tied (zero difference between compared values) groups and tk the number of data points in the k^{th} tied group. The standard normal deviate (Z-statistic) is then computed as

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\operatorname{var}(S)}} & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \\ \dfrac{S+1}{\sqrt{\operatorname{var}(S)}} & \text{if} \quad S < 0 \end{cases} \tag{5}$$

If the computed value of $|Z| > z\alpha/2$, the null hypothesis (H_o) is rejected at α level of significance in a two-sided test.

For the Mann-Kendall test, the time series must be serially independent. However, in many real situations the observed data are auto-correlated. The autocorrelation in the observed data may cause misinterpretation of the trend test results.

The existence of positive serial correlation will increase the possibility of rejecting the null hypothesis of no trend while it is actually true, while negative serial correlation will decrease the possibility of rejecting the null hypothesis (Yue and Hashino 2003, Yue and Wang 2004). The Durbin–Watson statistic (Durbin and Watson 1950, 1971) is widely used to determine serial correlation in the time series data. The Durbin–Watson test is used to test if the residuals are independent, against the alternative that there is autocorrelation among them. The test statistic of the Durbin–Watson procedure is d and is calculated as follows

$$d = \frac{\sum_{t=2}^{n} \left(e_t - e_{t-1}\right)^2}{\sum_{t=1}^{n} e_t^2}$$

where e_t represents the observed error term (*i.e.*, residuals). It can be shown that the value of d will be between zero and four: zero corresponding to perfect positive correlation and four to perfect negative correlation. If the error terms, e_t and e_{t-1}, are uncorrelated, the expected value of d is 2. The further d is below 2 the stronger the evidence for the existence of positive first-order serial correlation and vice versa. If there is a serial correlation in the time series, it should be "pre-whitened" to eliminate the effect of serial correlation before applying the Mann–Kendall test.

2.2.2 Sen's Slope Estimator

Sen's estimator has been widely used for determining the magnitude of trend in meteorological time series data. If a linear trend is present in a time series, then the true slope (change per unit time) can be estimated by using a simple nonparametric procedure developed by Sen (1968). The slope estimates of N pair of data are first computed by

$$T_i = \frac{x_j - x_k}{j-k} \quad for \quad i = 1, 2, 3, ...N \tag{6}$$

where, x_j and x_k are data values at time j and k ($j > k$), respectively. If there are n values x_j in the time series we get as many as $N = n(n-1)/2$ slope estimates Si. The median of these N values of T_i is Sen's estimator of slope, which is calculated as

$$T_{Med} = \begin{cases} T_{\frac{N+1}{2}} & N \text{ is odd} \\ \frac{1}{2}\left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}}\right) & N \text{ is even} \end{cases} \tag{7}$$

A positive value of median indicates an upward (increasing) trend and a negative value indicates a downward (decreasing) trend in the time series. Finally, median is tested with a two-sided test at the $100(1-\alpha)\%$ confidence interval and the true slope may be obtained with the nonparametric test (Partal and Kahya 2006).

3. RESULT AND DISCUSSION

Durbin–Watson procedure are applied for testing the serial correlation in various data sets. This test revealed that majority of monthly series of rainfall and temperature appear to be have no significant serial correlation at $p < 0.05$. However some series showed significant serial correlation. Therefore, pre-whitening procedure have been applied before applying the Mann–Kendall test.

3.1 Trends in Rainfall

For each sub-divisional meteorological stations, monthly trends were analyzed using Mann-Kendall test and Sen's estimator. This showed that there were no significant trends in monthly rainfall at most of the synoptic stations in India. Kendall's τ (tau) statistics for monthly and annual rainfall for different sub-divisional meteorological stations in India are presented in Table 2. This table reveals that the maximum number of stations with negative trends have been observed in December (21 stations), and then in September (19 stations) and January (16 stations) and with positive trends in April (26 stations) and October (25 stations). For annual rainfall, 15 sub-divisional meteorological stations showed decreasing trends. Significant trends in annual rainfall have been noticed only at three stations (East Madhya Pradesh, Konkan & Goa and Coastal Karnataka) only.

For seasonal (Winter season, Summer season, Monsoon season, Post-Monsoon season) trends in rainfall, Sen's estimator and Kendall's statistic for various sub-divisional meteorological stations in India are given in Table 3. This table reveals that 20 sub-divisional meteorological stations show decreasing trend in winter season (December, January and February), nine sub-divisional meteorological stations show decreasing trend in summer (March, April and May), 16 sub-divisional meteorological stations show decreasing trend in monsoon season, three (June, July, August, September) and eight sub-divisional meteorological stations show decreasing trend in post-monsoon season (November and December). Significant trends in seasonal rainfall have been noticed at one sub-divisional meteorological station in winter season, three sub-divisional meteorological stations in summer season, six sub-divisional meteorological stations in monsoon season and one sub-divisional meteorological station in post-monsoon.

Sen's estimator and Kendall statistics for trends analysis in monthly and seasonal data of rainfall for different regions in India are presented in Table 4. This table indicates that January rainfall show increasing trend except for North, West and North-West India while rainfall in February show increasing trends except for North-Central India. March rainfall show increasing trends for North Mountainous, North-West India and West Peninsular India. April rainfall showed increasing trends except for Northeast India while May and June showed increasing trends except for South Peninsular India. July rainfall show significant increasing trends for Northeast India while August showed significant increasing trends for North-West India, East Peninsular India and West Peninsular India while decreasing trends (significant) for West Peninsular India. Rainfall in September showed significant increasing trends for

Table 2. Kendall's τ (tau) statistics for monthly and annual rainfall for different sub-divisional meteorological stations in India

Sub-divisional Zone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
North Assam	–0.131*	0.015	–0.078	0.013	–0.099	–0.084	0.004	–0.173*	–0.093	0.072	0.030	0.021	–0.110
South Assam	–0.095	–0.058	–0.090	–0.003	0.053	–0.082	–0.069	–0.176*	–0.109	0.013	–0.004	–0.046	–0.113
Himalayan West Bengal	–0.041	–0.011	–0.018	0.072	0.009	–0.133*	0.119*	–0.028	–0.056	0.088	0.124*	0.117*	–0.017
Gangetic West Bengal	0.076	0.029	0.006	0.097	0.016	–0.025	–0.053	0.057	–0.017	–0.050	–0.015	–0.086	0.099
Orissa	0.076	0.029	0.006	0.097	0.016	–0.025	–0.053	0.057	–0.017	–0.050	–0.015	–0.086	–0.020
Jharkhand	0.000	–0.060	–0.008	0.065	0.000	0.005	–0.084	–0.089	0.028	0.014	0.035	0.030	–0.032
Bihar Plains	–0.028	–0.014	0.012	0.071	0.107	–0.059	0.007	–0.069	0.003	0.036	0.080	0.069	–0.027
East Uttar Pradesh	–0.020	0.030	–0.013	0.147*	0.052	0.004	–0.067	–0.107	0.064	0.033	0.069	0.048	–0.050
West Uttar Pradesh Plains	–0.106	0.024	0.015	0.088	0.070	0.024	–0.065	–0.025	0.010	0.085	0.053	–0.012	–0.062
Haryana	–0.054	0.057	0.049	0.119*	0.041	0.055	0.007	0.097	0.020	0.018	0.134	–0.048	0.092
Punjab	–0.084	0.055	0.087	0.075	0.030	0.117*	0.041	0.067	0.065	0.097	0.158*	–0.041	0.106
West Rajasthan	–0.031	0.048	0.058	0.106	0.006	0.064	0.026	0.001	–0.026	0.038	0.003	–0.040	0.033
East Rajasthan	–0.089	0.020	0.017	0.089	–0.033	0.007	–0.039	0.020	–0.026	0.024	0.041	–0.101	–0.054
West Madhya Pradesh	–0.049	–0.009	0.078	0.056	0.016	–0.104	–0.051	0.090	–0.079	0.055	0.053	–0.063	–0.060
East Madhya Pradesh	–0.007	–0.025	0.016	0.052	0.042	–0.114	–0.159*	–0.007	–0.039	–0.006	–0.023	–0.030	–0.133*
Gujarat	–0.058	–0.039	–0.049	–0.060	–0.144*	–0.003	–0.056	0.074	–0.029	0.029	0.100	–0.065	–0.008
Saurashtra Kutch	0.003	–0.059	0.014	0.019	–0.059	0.040	–0.035	0.102	0.024	0.048	0.058	–0.062	0.075
Konkan and Goa	–0.016	–0.028	0.053	0.084	0.052	0.042	0.026	0.144*	0.043	0.082	0.017	0.009	0.140*
Madhya Maharashtra	0.049	0.003	0.058	–0.064	–0.026	0.062	–0.069	0.168*	–0.041	–0.022	–0.016	–0.062	0.020
Marathwada	0.056	0.066	0.121*	–0.022	0.031	–0.032	0.023	0.099	–0.114	0.086	0.056	–0.034	0.014
Vidarbha	0.065	0.055	0.089	0.050	–0.017	–0.056	–0.099	0.099	–0.114*	0.064	0.006	–0.015	–0.068
Chhattisgarh	0.013	–0.039	0.008	0.055	–0.002	–0.097	–0.166*	–0.097	–0.031	–0.027	–0.005	–0.014	–0.181
Coastal Andhra Pradesh	0.063	0.053	0.004	0.089	–0.026	0.039	0.093	0.084	–0.019	0.039	–0.001	–0.001	0.101
Telangana	0.125	0.107	0.018	0.046	0.070	0.009	0.042	0.132*	–0.083	0.115*	–0.016	–0.014	0.091
Rayalaseema	–0.010	0.055	0.055	0.100	0.056	0.061	0.081	0.052	–0.059	0.023	0.043	0.004	0.090
Tamil Nadu	–0.004	0.012	–0.002	0.019	–0.057	–0.069	0.083	–0.043	0.022	0.000	0.081	0.037	0.053
Coastal Karnataka	0.039	–0.023	0.071	0.027	0.049	0.070	–0.013	0.122*	0.000	0.059	0.024	–0.018	0.137*
North Interior Karnataka	0.052	0.037	–0.038	0.033	0.094	0.018	–0.047	0.134	–0.032	0.009	–0.038	0.002	0.058
South Interior Karnataka	0.029	0.022	–0.016	0.095	–0.071	–0.026	–0.056	0.073	0.071	0.006	0.005	–0.006	0.035
Kerala	0.095	0.079	0.057	0.092	–0.007	–0.139*	–0.078	0.053	0.097	0.099	0.109	–0.026	–0.002

* Trends statistically significance at $p < 0.05$

Table 3. Sen's estimator (T_{Med}) and Kendall's τ (Tau) for seasonal rainfall for sub-divisional meteorological stations in India

Sub-divisional	Winter season		Summer season		Monsoon season		Post-Monsoon season	
	TMed	TAU	TMed	TAU	TMed	TAU	TMed	TAU
North Assam	–0.040	–0.043	–0.298	–0.064	–1.046	–0.146*	0.200	0.070
South Assam	–0.079	–0.080	0.004	0.000	–1.244	–0.198**	0.072	0.024
Himalayan West Bengal	–0.026	–0.044	0.100	0.033	–0.639	–0.054	0.313	0.108
Gangetic West Bengal	0.005	0.007	0.123	0.042	0.611	0.091	0.132	0.046
Orissa	0.049	0.062	0.079	0.045	–0.261	–0.042	–0.202	–0.059
Jharkhand	–0.065	–0.061	–0.009	–0.004	–0.310	–0.049	0.089	0.034
Bihar Plains	–0.032	–0.047	0.206	0.121*	–0.431	–0.053	0.067	0.039
East Uttar Pradesh	–0.025	–0.032	0.051	0.071	–0.330	–0.047	0.034	0.024
West Uttar Pradesh Plains	–0.073	–0.086	0.067	0.099	–0.453	–0.072	0.064	0.075
Haryana	–0.018	–0.023	0.081	0.090	0.368	0.071	–0.024	–0.046
Punjab	–0.055	–0.039	0.081	0.076	0.626	0.105	0.004	0.007
West Rajasthan	–0.003	–0.013	0.025	0.060	0.015	0.003	0.001	0.012
East Rajasthan	–0.016	–0.055	0.005	0.012	–0.477	–0.078	–0.002	–0.006
West Madhya Pradesh	–0.007	–0.021	0.008	0.022	–0.502	–0.083	0.045	0.042
East Madhya Pradesh	–0.005	–0.005	0.016	0.023	–1.088	–0.149*	–0.024	–0.016
Gujarat	0.000	–0.057	–0.016	–0.132*	–0.104	–0.010	0.015	0.047
Saurashtra Kutch	0.000	–0.026	0.000	–0.009	0.428	0.059	0.007	0.036
Konkan and Goa	0.000	–0.045	0.030	0.070	1.827	0.122*	0.250	0.099
Madhya Maharashtra	0.000	–0.004	–0.029	–0.041	0.168	0.038	–0.002	–0.002
Marathwada	0.006	0.081	0.019	0.028	–0.117	–0.018	0.206	0.091
Vidarbha	0.031	0.062	0.031	0.039	–0.516	–0.072	0.048	0.030
Chattisgarh	–0.007	–0.010	–0.002	–0.002	–1.388	–0.190**	–0.083	–0.046
Coastal Andhra Pradesh	0.025	0.090	0.034	0.025	0.398	0.106*	0.023	0.004
Telangana	0.026	0.144*	0.094	0.098	0.257	0.041	0.193	0.083
Rayalaseema	0.000	–0.006	0.164	0.131*	0.200	0.042	0.103	0.027
Tamil Nadu	–0.010	–0.015	–0.026	–0.018	0.003	0.002	0.374	0.069
Coasta Karnataka	0.000	0.018	0.317	0.084	1.731	0.099	0.257	0.065
North Interior Karnataka	0.000	0.044	0.114	0.096	0.070	0.016	–0.006	–0.003
South Interior Karnataka	0.000	0.022	–0.023	–0.013	0.277	0.066	–0.004	–0.001
Kerala	0.049	0.075	0.210	0.046	–1.080	–0.078	0.739	0.133*

* Trends statistically significance at $p < 0.05$, ** Trends statistically significance at $p < 0.01$

Table 4. Sen's estimator (T_{Med}) and Kendall's τ (Tau) for monthly and seasonal data of rainfall for different regions in India

Region	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
All India	T_{Med}	0.002	0.006	–0.002	0.011	0.005	–0.028	0.138	0.111
	Tau	0.011	0.028	–0.013	0.053	0.011	–0.029	0.130	0.096
North Mountainous	T_{Med}	–0.076	0.055	0.219	0.044	0.077	–0.220	–0.368	–0.441
(NMI)	Tau	–0.053	0.041	0.146	0.051	0.081	–0.096	–0.087	–0.128*
South Peninsular India	T_{Med}	0.004	0.001	–0.011	0.014	–0.042	0.033	0.156	0.140
(SPI)	Tau	0.028	0.010	–0.043	0.022	–0.032	0.025	0.085	0.092
North Central India	T_{Med}	0.013	–0.005	–0.008	0.012	0.010	–0.164	–0.056	0.050
(NCI)	Tau	0.039	–0.012	–0.028	0.039	0.016	–0.076	–0.025	0.029
Northeast India	T_{Med}	0.002	0.013	–0.012	–0.037	0.027	–0.188	0.228	–0.169
(NEI)	Tau	0.010	0.028	–0.012	–0.033	0.017	–0.100*	0.103*	–0.089
North West India	T_{Med}	–0.010	0.006	0.008	0.006	0.001	–0.096	0.003	0.282
(NWI)	Tau	–0.043	0.028	0.053	0.079	0.006	–0.066	0.002	0.125*
East Peninsular India	T_{Med}	0.002	0.006	–0.003	0.009	0.010	–0.018	0.209	0.217
(EPI)	Tau	0.030	0.026	–0.014	0.023	0.016	–0.011	0.116	0.116*
West Peninsular India	T_{Med}	0.000	0.000	0.000	0.016	0.014	–0.023	0.178	0.351
(WPI)	Tau	0.025	0.040	0.008	0.062	0.023	–0.013	0.065	0.152*

Region	Statistic	Sep	Oct	Nov	Dec	Annual	JF	MAM	JJAS	OND
All India	T_{Med}	0.054	0.054	0.025	0.008	0.327	0.016	0.022	0.237	0.077
	Tau	0.048	0.072	0.057	0.037	0.108*	0.047	0.037	0.100	0.082
North Mountainous	T_{Med}	0.208	0.022	0.018	0.014	–0.358	–0.018	0.309	–0.850	0.148
(NMI)	Tau	0.081	0.030	0.088	0.020	–0.047	–0.008	0.129*	–0.115*	0.112*
South Peninsular India	T_{Med}	0.079	0.096	0.106	0.009	0.494	0.012	–0.013	0.298	0.232
(SPI)	Tau	0.058	0.052	0.060	0.012	0.103*	0.038	–0.008	0.090	0.075
North Central India	T_{Med}	0.213	–0.046	0.001	0.002	0.046	0.009	0.015	0.036	–0.009
(NCI)	Tau	0.111*	–0.037	0.020	0.033	0.011	0.015	0.016	0.009	–0.004
Northeast India	T_{Med}	0.034	0.108	0.016	–0.005	0.033	0.019	–0.018	–0.132	0.161
(NEI)	Tau	0.017	0.056	0.043	–0.035	0.006	0.034	–0.009	–0.031	0.075
North West India	T_{Med}	0.047	0.011	0.003	0.000	0.202	–0.003	0.023	0.183	0.045
(NWI)	Tau	0.023	0.036	0.084	0.013	0.049	–0.009	0.056	0.045	0.067
East Peninsular India	T_{Med}	–0.061	0.042	0.037	–0.002	0.504	0.035	0.011	0.340	0.096
(EPI)	Tau	–0.035	0.018	0.038	–0.043	0.105	0.074	0.010	0.096	0.032
West Peninsular India	T_{Med}	0.038	0.058	–0.006	0.000	0.633	0.006	0.030	0.540	0.075
(WPI)	Tau	0.017	0.041	–0.018	–0.036	0.122*	0.042	0.040	0.111*	0.046

* Trends statistically significance at $p < 0.05$

North-Central India while rainfall in October showed increasing trends except for North-Central India. November showed increasing trend except for West Peninsular India. December showed increasing trend except for Northeast India, East Peninsular India and West Peninsular India. Annual rainfall indicated significant increasing trends for All India, South Peninsular India and West Peninsular India while winter rainfall showed increasing trends except for North Mountainous and North-West India. Summer season rainfall showed significant increasing trends for North Mountainous regions. Monsoon season showed significant decreasing trends for North Mountainous and Northeast India. Rainfalls in post-monsoon season showed significant increasing trend for North Mountainous only. For each meteorological station, linear trends were also analyzed for each month and it was found that linear trend were not significant. This study also revealed that the cyclic component were absent in most of the monthly series.

3.2 Trends in Temperature

Trend analysis using Sen's estimator (T_{Med}) and Mann-Kendall Statistics (Tau) for monthly and annual data of maximum and minimum temperature for different regions in India are given in Tables 5-6, respectively. Monthly temperatures (maximum and minimum) data were on a regional scale only. Maximum temperature increased in all months at All India level while ECI experienced increase in maximum temperature in all months except May, June and August while IP showed increasing maximum temperature in January, February, July, September, November and December months. NCI indicated increase in maximum temperature in February, April, August, September, October, November and December while NEI showed increase in maximum temperature in most of the months except January, March and May. NWI region showed increase in maximum temperature in February, April, August, September, November and December. WCI showed increase in maximum temperature in each month. WH showed increase in maximum temperature in January, February, March, April, September and October. Minimum temperature showed increasing trends in February, March, November and December at all India scale while EC experienced increase in Minimum temperature in February, March, April, August, October, November and December while IP

Table 5. Sen's estimator (T_{Med}) and Kendall's τ (Tau) for monthly data of maximum temperature for different regions in India

	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
All India	T_{Med}	0.005	0.013	0.007	0.007	0.001	0.001	0.004	0.005	0.007	0.007	0.013	0.013
	Tau	0.168*	0.285**	0.136*	0.176*	0.052	0.035	0.148*	0.283**	0.250**	0.223**	0.398**	0.423**
East Coast (EC)	T_{Med}	0.009	0.011	0.008	0.005	0.002	0.000	0.004	0.003	0.006	0.005	0.012	0.013
	Tau	0.314**	0.370**	0.286**	0.160*	0.059	0.002	0.164*	0.124	0.237**	0.194*	0.425**	0.490**
Interior Peninsula	T_{Med}	0.007	0.011	0.005	0.004	0.000	0.000	0.006	0.000	0.007	0.003	0.011	0.011
(IP)	Tau	0.211**	0.301**	0.127	0.093	0.022	–0.002	0.169**	–0.005	0.185*	0.070	0.299**	0.355**
North Central	T_{Med}	0.000	0.011	0.006	0.008	0.000	0.000	0.008	0.007	0.007	0.008	0.015	0.013
India (NCI)	Tau	–0.012	0.185*	0.092	0.133*	0.004	–0.006	0.154	0.265**	0.166*	0.153*	0.362**	0.345**
Northeast India	T_{Med}	0.004	0.014	0.005	0.007	0.005	0.006	0.004	0.011	0.006	0.012	0.017	0.016
(NEI)	Tau	0.108	0.274**	0.111	0.130*	0.126	0.*	0.176*	0.457**	0.297**	0.343**	0.498**	0.458**
NWI Northwest	T_{Med}	0.005	0.011	0.006	0.009	–0.002	–0.002	0.000	0.007	0.007	0.004	0.009	0.010
India (NWI)	Tau	0.100	0.136*	0.074	0.133*	–0.046	–0.037	0.012	0.153*	0.132*	0.082	0.204**	0.194*
West Coast	T_{Med}	0.014	0.019	0.013	0.009	0.007	0.009	0.009	0.007	0.012	0.012	0.013	0.017
(WCI)	Tau	0.480**	0.490**	0.346**	0.334**	0.267**	0.237**	0.330**	0.318**	0.380**	0.337**	0.475**	0.589**
Western	T_{Med}	0.022	0.030	0.014	0.022	0.003	0.004	–0.002	0.003	0.010	0.010	0.004	0.009
Himalaya (WH)	Tau	0.203**	0.242**	0.142*	0.232**	0.033	0.065	–0.040	0.074	0.181*	0.155*	0.060	0.108

* Trends statistically significance at $p < 0.05$, ** Trends statistically significance at $p < 0.01$

Table 6. Sen's estimator (T_{Med}) and Kendall's τ (Tau) for monthly data of minimum temperature for different regions in India

	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
All India	T_{Med}	0.000	0.007	0.005	0.002	0.000	–0.002	0.000	0.000	0.000	0.003	0.010	0.007
	Tau	0.005	0.195*	0.158*	0.055	–0.037	–0.093	–0.006	0.010	–0.002	0.115	0.205**	0.212**
East Coast (ECI)	T_{Med}	0.003	0.006	0.007	0.004	0.001	0.000	0.001	0.001	0.000	0.003	0.005	0.007
	Tau	0.103	0.169*	0.268**	0.188*	0.068	0.004	0.104	0.149*	0.098	0.166*	0.138*	0.201**
Interior Peninsula	T_{Med}	0.002	0.007	0.007	0.002	0.000	0.000	0.003	0.002	0.003	0.004	0.008	0.007
(IP)	Tau	0.061	0.176*	0.279**	0.067	0.000	0.033	0.244**	0.213**	0.279**	0.181*	0.145*	0.143*
North Central	T_{Med}	0.000	0.007	0.005	0.001	–0.003	–0.006	0.000	0.000	0.000	0.006	0.014	0.011
India (NCI)	Tau	–0.003	0.160*	0.131*	0.035	–0.090	–0.143*	–0.068	–0.045	–0.052	0.133*	0.278**	0.247**
Northeast	T_{Med}	0.000	0.008	0.003	0.000	0.000	–0.002	–0.002	0.000	–0.005	0.002	0.010	0.010
India (NEI)	Tau	0.002	0.190*	0.079	0.020	–0.020	–0.120	–0.*	0.006	–0.241**	0.062	0.227**	0.283**
Northwest India	T_{Med}	–0.007	0.002	0.003	0.000	–0.003	–0.005	–0.003	–0.001	0.000	–0.001	0.003	0.000
(NWI)	Tau	–0.132	0.041	0.064	0.007	–0.069	–0.174**	–0.116	–0.067	0.002	–0.035	0.070	–0.023
West Coast	T_{Med}	–0.001	0.003	0.003	0.003	0.002	0.002	0.001	0.002	0.004	0.002	0.005	0.004
(WCI)	Tau	–0.049	0.099	0.114	0.109	0.108	0.151*	0.123	0.161*	0.246**	0.114	0.110	0.117
Western	T_{Med}	0.005	0.014	0.008	0.007	–0.002	0.003	0.002	–0.005	0.005	0.007	0.016	0.013
Himalaya (WH)	Tau	0.093	0.203**	0.160**	0.127	–0.040	0.076	0.059	–0.135*	0.081	0.156*	0.263**	0.190*

* Trends statistically significance at $p < 0.05$, ** Trends statistically significance at $p < 0.01$

showed increasing trends in minimum temperature during February, March, July, August, September, October, November and December. NCI indicated increase in minimum temperature in February, March, June, October, November and December while NEI showed increase in Minimum temperature in February, September, November and December. NWI region showed increase in Minimum temperature in June only. WC showed increase in Minimum temperature in June, August and September. WH showed increase in Minimum temperature in February, March, August, September, October, November and December.

4. CONCLUSION

The Mann-Kendall test and Sen's Slope estimator were applied for long-term annual, seasonal and monthly trends of rainfall in 30 sub-divisional meteorological stations along with regional scale and temperature (maximum and minimum) in seven homogenous regions of India were investigated.

For each meteorological station, linear trends were analyzed for each month and it was found that linear trend was not significant. This study also revealed that the cyclic component were absent in most of the monthly series.

Mann-Kendall test indicated that there are no significant trends in monthly rainfall at most of the synoptic stations in India. However, the maximum number of stations with negative trends have been observed in December (21 station), and then in September (18 stations) and January (16 stations) and with positive trends in April (26 stations) and October (25 stations). For annual rainfall 15 sub-divisional meteorological stations showed decreasing trends. Significant trends in annual rainfall have been noticed only at three stations (East Madhya Pradesh, Konkan & Goa and Coastal Karnataka) only.

For seasonal trends, decreasing trend were observed in 20 sub-divisional meteorological stations in winter season, eight sub-divisional meteorological stations in summer season, 16 sub-divisional meteorological stations in monsoon season, and eight sub-divisional meteorological stations in post-monsoon season.

The significant trends, in seasonal rainfall have been noticed in one sub-divisional meteorological station in winter season, three sub-divisional meteorological stations in pre-monsoon, six sub-divisional meteorological stations in monsoon season and one sub-divisional meteorological station in different post-monsoon.

It was also found that there was significant rising trend in maximum temperature in most of the months while minimum temperature in various regions also showed increasing trends. But it had low significance level as compared to maximum temperature. The tendency in increasing maximum temperature in December in particular and maximum and minimum temperatures in general for several regions could be indicative of the eventual climate change in this area.

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