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An investigation into observational characteristics of rainfall and temperature in Central Northeast India—a historical perspective 1889–2008

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Abstract Mann–Kendall non-parametric test was employed for observational trend detection of monthly, seasonal and annual precipitation of five meteorological subdivisions of Central Northeast India (CNE India) for different 30-year normal periods (NP) viz. 1889–1918 (NP1), 1919–1948 (NP2), 1949–1978 (NP3) and 1979–2008 (NP4). The trends of maximum and minimum temperatures were also investigated. The slopes of the trend lines were determined using the method of least square linear fitting. An application of Morelet wavelet analysis was done with monthly rainfall during June–September, total rainfall during monsoon season and annual rainfall to know the periodicity and to test the significance of periodicity using the power spectrum method. The inferences figure out from the analyses will be helpful to the policy managers, planners and agricultural scientists to work out irrigation and water management options under various possible climatic eventualities for the region. The long-term (1889–2008) mean annual rainfall of CNE India is 1,195.1 mm with a standard deviation of 134.1 mm and coefficient of variation of 11%. There is a significant decreasing trend of 4.6 mm/year for Jharkhand and 3.2 mm/day for CNE India. Since rice crop is the important *kharif* crop (May–October) in this region, the decreasing trend of rainfall during the month of July may delay/affect the transplanting/vegetative phase of the crop, and assured irrigation is very much needed to tackle the drought situation. During the month of December, all the meteorological subdivisions except Jharkhand show a significant decreasing trend of rainfall during recent normal period NP4. The decrease of rainfall during December may hamper sowing of wheat, which is the important *rabi* crop (November–March) in most parts of this region. Maximum temperature shows significant rising trend of 0.008°C/year (at 0.01 level) during monsoon season and 0.014°C/year (at 0.01 level) during post-monsoon season during the period 1914–2003. The annual maximum temperature also shows significant increasing trend of 0.008°C/year (at 0.01 level) during the same period. Minimum temperature shows significant rising trend of 0.012°C/year (at 0.01 level) during post-monsoon season and significant falling trend of 0.002°C/year (at 0.05 level) during monsoon season. A significant 4–8 years peak periodicity band has been noticed during September over Western UP, and 30–34 years periodicity has been observed during July over Bihar subdivision. However, as far as CNE India is concerned, no significant periodicity has been noticed in any of the time series.

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1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) in its fourth assessment report (AR4) indicates with very high confidence (90% probability of being correct) that human activities since industrialization have caused the planet to warm by about 1°C. With the doubling of carbon dioxide

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content in the atmosphere, this trend is projected to cause average global warming of around 3°C compared to the pre-industrial level. Studies on the extreme weather events over India shown that during summer, 60–70% of the coastal stations are showing an increasing trend in critical extreme maximum day temperature and increase in night temperatures. The frequency of heavy rains during the southwest monsoon showed an increasing trend over certain parts of the country. As reported by the IPCC, the Indian sub-continent will adversely be affected by enhanced variability of climate, rising temperature and substantial reduction of summer rainfall in some parts and water stress by 2020 (Cruz et al. 2007). Several studies were carried out by Chen et al. (1992), Chaudhary (1994), Kadioglu (1997), Izrael et al. (1997), Mirza and Dixit (1997), Rankova (1998), Ren et al. (2000), Brunetti et al. (2000a, b), Salinger and Griffiths (2001), Wibig and Glowicki (2002), Lu et al. (2004), Domroes and El-Tantawi (2005), Gadgil and Dhorde (2005) and Tomozeiu et al. (2006) to analyse the trends in long-term precipitation and temperature and its inter-annual, seasonal and decadal variability at different scales such as local, regional, national and continental spatial scales. Parthasarathy and Dhar (1974), Thapaliyal and Kulshrestha (1991), Rao and Kumar (1992), Rupakumar et al. (1992), Srivastava et al. (1992), Parthasarathy et al. (1993), Kothyari and Singh (1996), Kripalani and Kulkarni (1996, 2001), Sinha Ray and Srivastava (2000), Sadhukhan et al. (2000), Patra et al. (2005) and Kothawale et al. (2010) studied trends of annual and seasonal rainfall at various locations and at different scales over India.

Several countries in the tropical Asia region have reported increasing surface temperature trends (Rupakumar et al. 1994). An analysis of seasonal and annual surface air temperatures (Pant and Kumar 1997) has shown a significant warming trend of 0.57°C per hundred years over India. The warming is found to be mainly contributed by the post-monsoon and winter seasons. The monsoon temperatures do not show a significant trend in any major part of the country except for a significant negative trend over Northwest India. Also, data analysed in terms of daytime and night-time temperatures indicate that the warming was predominantly due to an increase in the maximum temperatures, while the minimum temperatures remained practically constant during the past century. Singh and Sontakke (2002) reported that in the Indo-Gangetic Plains (IGP) of India, the annual surface air temperature had a rising trend (0.53°C/100 years, significant at 1% level) during 1875–1958 and a decreasing trend (−0.93°C/100 years, significant at 5% level) during 1958–1997. The post-1958 period cooling of the IGP seems to be due to expansion and intensification of agricultural activities and spreading of irrigation network in the region. Based on over a hundred years of data collected by the India Meteorological Department over the Indian region, warming of about 0.5°C per 100 years on an all-India average basis was shown. Spatially, this is manifested as regions of higher values, and even pockets of cooling, over different parts of India. Future projections of climate change using global and regional climate models, run by the Indian Institute of Tropical Meteorology with different IPCC emission scenarios, indicate temperature changes of about 3–5°C and increase of about 5–10% in summer monsoon rainfall (NATCOM 2004). It is also projected that the number of rainy days may decrease by 20% to 30%, which would mean that the intensity of rainfall is expected to increase. Extremes in temperature and rainfall also show increase in their frequency and intensity by the end of the year 2100. Another study using daily rainfall data for over 50 years shows significant increasing trend in extreme rainfall events over central India (Goswami et al. 2006).

The wavelet transform is a recent advance technique in signal processing that has attracted much attention since its theoretical development (Grossman and Morlet 1984). Its use has increased rapidly as an alternative to the Fourier transform in preserving local, non-periodic and multi-scaled phenomena. To know the periodity of monsoon rainfall, Azad et al. (2007, 2008) used a combination of multi-resolution analysis and classical Fourier spectral methods and identified 17 peaks in the power spectral density of the Homogeneous Indian Monsoon rainfall time series constructed, and also found that it exhibits ten statistically significant periodicities at a confidence level of 99.9%. Santos et al. (2001) analysed the Matsuyama city rainfall data using wavelet transform to know the main frequency components in the time series revealing that the monthly rainfall in Matsuyama city is composed mainly by an annual frequency. The water and agricultural sectors are likely to be worst affected by changing climate. Under warmer climate, the arid and semiarid regions could experience severe water stress due to the decline in soil moisture. The amount of water evaporated from the land surface is an important criterion for the sustenance and development of vegetative life. The spatial distribution and magnitude of rainfall and temperature trends would be highly relevant and useful from an agricultural and water management point of view. Most of the studies are confined to only seasonal and annual or confined to India as a whole or for different homogenous regions. However, on a monthly basis, analysis has been very little. This study investigates the trends of rainfall in the data series of monthly, seasonal and annual rainfall for five central northeast meteorological subdivisions separately as well as for the Central Northeast (CNE) India homogenous region using Mann–Kendall non-parametric test. The slopes of the trend lines were determined using the method of least square linear fitting. The trends of maximum and minimum temperature of the North Central India homogeneous temperature region were also examined using the same methodology. An application of Morelet wavelet analysis was also carried out with monthly rainfall during June–September, total monsoon and annual rainfall to know the periodicity and to test the significance of periodicity using the power spectrum method.

2 Data and methodology

Based on the topography and climatologically prevailing conditions over the sub-continent, the India Meteorological Department has divided the country into 35 meteorological subdivisions. Figure 1 shows the homogenous rainfall and temperature regions and meteorological subdivisions over India. Out of these 35 meteorological subdivisions, five subdivisions that fall in the CNE India homogenous region—which is part of the high potential, low productivity potential zone (CPWF 2003)—were considered here for analysis. Table 1 indicates the names of the CNE India meteorological subdivisions, area covered and number of rain gauge stations considered for the analysis. They have considered 75 rain gauge stations well distributed over the region (Fig. 2) for preparing time series, one from each of the districts which is the small administrative area and area-weighted mean monthly rainfall of all the meteorological subdivisions, as well as for the whole country by assigning the district area as the weight for each representative rain gauge station. The detailed methodology adopted for quality, completeness and homogeneity was discussed in detail Parthasarathy et al. (1993, 1995a, b) and also available in www.tropmet.res.in.

The monthly rainfall data series from 1889 to 2008 of five meteorological subdivisions as well as the monthly temperature data series from 1914 to 2003 of homogeneous temperature region available from the website of Indian Institute of Tropical Meteorology (www.tropmet.ac.in) were used in this study. To prepare spatially well representative and homogeneity, available station temperature data have been converted to monthly anomaly time series for the period 1901–2003, with reference to the respective station normal values. The station-wise monthly temperature anomaly time series are first objectively interpolated onto a $0.5 \times 0.5°$ grid for the entire period of 1901–2003. Then, the climatological normals (1951–1980) of temperature at 388 stations have been interpolated onto the same grid, resulting in high-resolution grid point temperature climatology for the country. The gridded monthly anomaly values are then added to the gridded climatology based on 388 stations, finally producing a long-term gridded data set of actual temperatures for India for the period 1901–2003. All-India and regional monthly temperature series are computed by simple averages of the constituent grid point data of the respective regions (Kothawale and Rupa Kumar 2005).

According to the World Meteorological Organization (WMO), the normal precipitation at a given station at any scale can be assumed as the mean of the precipitation over a 30-year period (WMO 1989). Using these criteria, the data series under study have been subdivided into four periods 1889–1918 (NP1), 1919–1948 (NP2), 1949–1978 (NP3) and 1979–2008 (NP4). The 30-year averages for monthly, seasonal and annual rainfall and its standard deviation were calculated for each period, in order to find out the rainfall variation during different normal periods. The coefficient of variation for monthly, seasonal and annual rainfall for each normal period was calculated to know whether there is any variability of rainfall during the study period. Based on climatic features of the months, India Meteorological Department has defined four seasons, viz. winter (January and February), pre-monsoon (March–May), monsoon (June–September) and post-monsoon (October–December). The percent contribution of monthly and seasonal rainfall to annual rainfall was also calculated for each normal period, as well as for the entire data set to know whether there is any change in the shift of rainfall pattern. The analysis was done for each of the five meteorological subdivisions as well as for the homogeneous central northeast region. The monthly rainfall for the homogenous CNE India region was calculated by averaging the rainfall data of five meteorological subdivisions. In the case of temperature, the monthly data sets were pooled into seasonal based on India Meteorological Department criteria as mentioned above, and the data sets were divided into three normal periods: 1914–1943 (NPT1), 1944–1973 (NPT2) and 1974–2003 (NPT3).

For all data sets of monthly, seasonal and annual rainfall for the four normal periods and for the entire period 1889–2008 and monthly, seasonal and annual mean maximum and minimum temperature for the three normal periods and for the entire period 1914–2003, the Mann–Kendall non-parametric test, as described by Sneyers (1990), was applied in order to detect trends. The Mann–Kendal test has been widely used by several researchers to detect trends in hydrological time series data (Wilks 1995; Serrano et al. 1999; Brunetti et al. 2000a, b; Onoz and Bayazit 2003; Luo et al. 2008; Pal and Al-Tabbaa (2010)). The slopes of the trends were calculated by fitting the data series into method of least square linear fitting.

2.1 Mann–Kendall test

The Mann–Kendall test basically involves the ranks obtained by each data in the data series. The n time series values ($X1$, $X2$, $X3$,..., Xn) are replaced by their relative ranks ($R1$, $R2$, $R3$,..., Rn; starting at 1 for the lowest up to n; adopted from Kundzewicz and Robson (2000) and Chiew and Sirivardena(2005)).

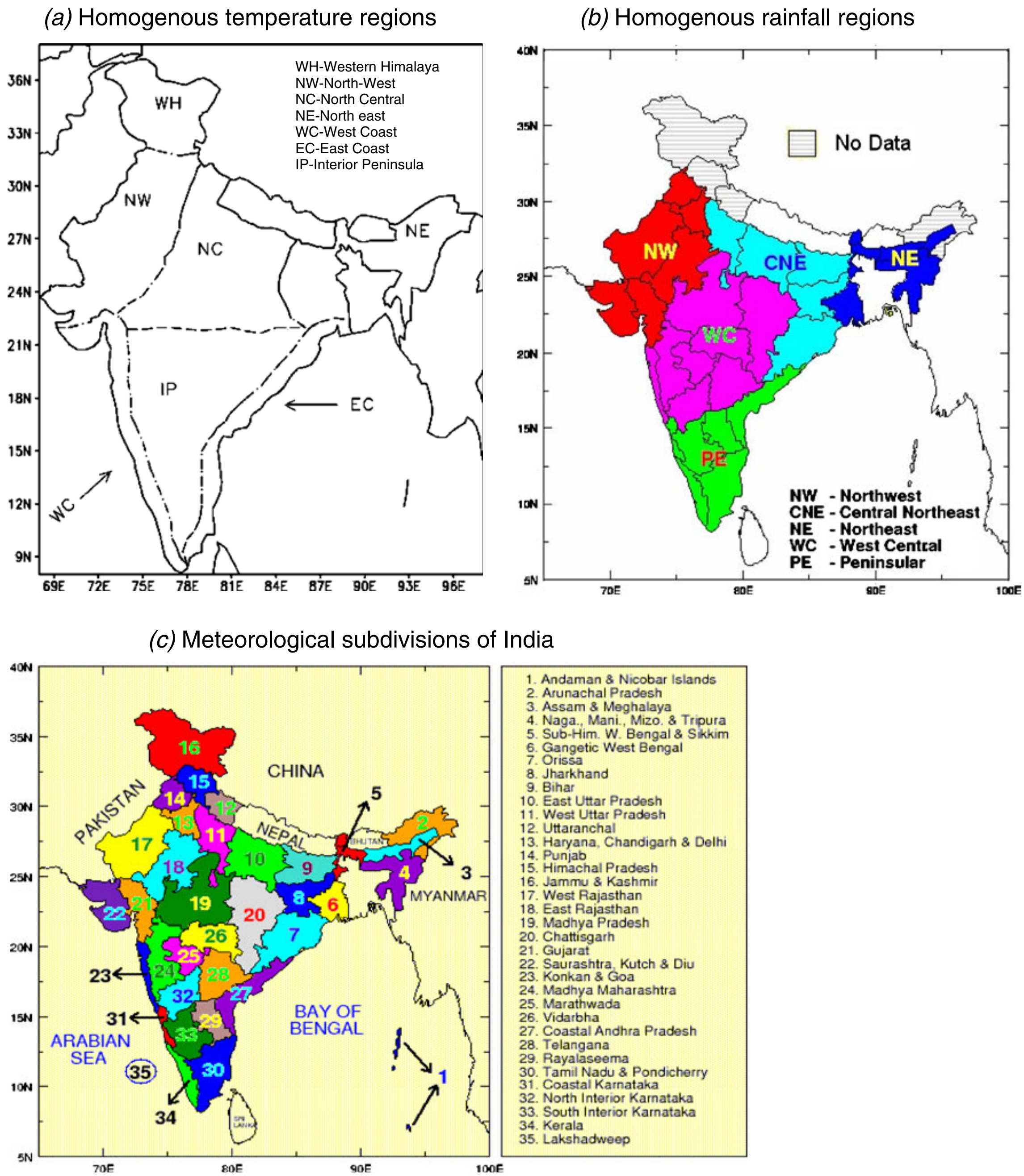

Fig. 1 **a** Homogenous rainfall regions, (**b**) homogeneous temperature regions and (**c**) meteorological subdivisions of India

Table 1 Characteristics of Central Northeast India homogeneous region

Sl. No.	Name of subdivision	Area (km^2)	Number of rain gauge stations
1	Western UP Plains	96,782	10
2	Eastern UP	146,509	26
3	Bihar	94,235	11
4	Jharkhand	79,638	6
5	Orissa	155,842	13
	Central Northeast India	573,006	75

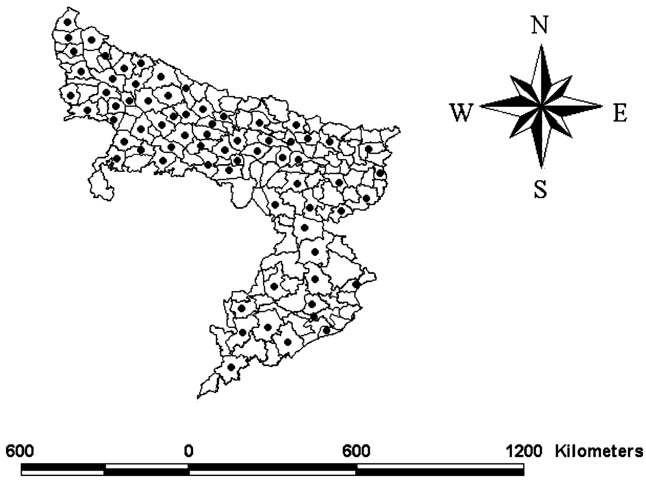

Fig. 2 Spatial distribution of rain gauge sites over the study region

The test statistic S is

$$S = \sum_{i=1}^{n-1} \left[\sum_{j=i+1}^{n} \operatorname{sgn}\left(R_j - R_i\right) \right]$$

where

$$\begin{aligned} \operatorname{sgn}(x) &= 1 \text{ for } x > 0 \\ \operatorname{sgn}(x) &= 0 \text{ for } x = 0 \\ \operatorname{sgn}(x) &= -1 \text{ for } x < 0 \end{aligned}$$

If the null hypothesis Ho (i.e. there is no trend in the data set) is true, then S is approximately normally distributed with

$$\begin{aligned} \mu &= 0 \\ \sigma &= n(n-1)(2n+5)/18 \end{aligned}$$

The z-statistic is therefore (critical test statistic values for various significance levels can be obtained from normal probability tables):

$$z = |S|/\sigma^{0.5}$$

A positive value of S indicates that there is an increasing trend and vice versa.

2.2 Wavelet transform

The wavelet transform can be used to analyse time series that contain non-stationary power at many different frequencies (Daubechies 1990). Assume that one has a time series, x_n, with equal time spacing ∂t and n=0…N−1. Also assume that one has a wavelet function,$\Psi(\eta)$ that depends on a nondimensional "time" parameter η. To be "admissible" as a wavelet, this function must have zero mean and be localised in both time and frequency space (Farge 1992). One of the most widely used continuous wavelets in geophysics is the complex Morlet wavelet (Morlet 1983), which consists of a plane wave modulated by a Guassian envelope (Torrence and Compo 1997):

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_o \eta} e^{-\eta^2/2}$$

where ω_o is the nondimensional frequency, here taken to be 6 to satisfy the admissibility condition (Farge 1992) More application of Wavelet analysis and methodology in detail were described by Torrence and Compo (1997).

3 Results and discussion

3.1 General rainfall statistics of the study area

The long-term (1889–2008) mean annual rainfall of CNE India is 1,195.1 mm with a standard deviation of 134.1 mm and a coefficient of variation of 11% (Table 2). The seasonal rainfall distribution indicates that 83.5% (997.6 mm) of the annual rainfall occurs during southwest monsoon (June–September) followed by 7.3% (87.6 mm) during post-monsoon season (October–December). Among the meteorological subdivisions, Orissa receives the highest annual rainfall of 1,490.1 mm with a standard deviation of 199.4 followed by Jharkhand (1,349.6 mm) with a standard deviation of 202.8 mm. The Western UP plains receives the lowest annual rainfall of 873.4 mm with a standard deviation of 178.1 mm. As far as different normal periods are concerned, it is clear that the normal seasonal rainfall for CNE India shows fluctuating rainfall pattern. The mean annual rainfall for the NP1 and NP2 are higher, while for the NP3 and NP4, the mean annual rainfall is lower compared to long-term period average. However, the same pattern is not followed in subdivisions (Fig. 3). The results show that for Jharkhand meteorological subdivision, all the normal periods except NP2 received lower annual rainfall. However, in the case of summer season, average rainfall received during the recent NP4 for all the subdivisions is higher compared to previous NP3 as well as the for the 120-year period.

The rainiest month during NP1 was August, July in NP2, August in NP3 and July in NP4 (Table 3) for CNE India rainfall. The same pattern has been observed for Eastern UP meteorological subdivision monthly rainfall also. However, July is the rainiest month for Bihar subdivision in all the normal periods except NP1 followed by August, while during NP1, it is vice versa. Results show that in Jharkhand subdivision, July is the rainiest month followed by August in all the normal periods. However, in the case of Orissa subdivision, August is the rainiest month during all the normal periods except NP2. The long-term average shows that August is the rainiest month followed by July.

Table 2 Mean seasonal rainfall (millimetre) and its standard deviation during 1889–2008, 1889–1918, 1919–1948, 1949–1978 and 1979–2008 for different subdivisions of Central Northeast India

Sl. No.	Name of subdivision	Rainfall and standard deviation				
		1889–2008 (long term)	NP1	NP2	NP3	NP4
JF (winter season)						
1	Western UP Plains	38.8±26.9	43.1±31.0	42.±25.3	33.2±24.0	36.2±26.7
2	Eastern UP	33.7±23.8	35.1±25.5	37.9±25.9	30.9±21.4	30.9±22.5
3	Bihar	32.0±25.3	32.3±27.2	36.8±21.8	29.±25.9	29.6±26.5
4	Jharkhand	45.4±36.1	48.0±44.9	61.7±35.7	37.4±26.5	34.7±29.8
5	Orissa	32.3±28.3	28.6±31.7	40.5±30.2	28.4±28.6	31.8±21.1
	Central NE India	36.4±21.6	37.4±26.9	43.9±20.1	31.8±19.3	32.6±17.7
MAM (summer season)						
1	Western UP Plains	34.3±24.6	35.4±25.2	26.0±21.2	29.6±17.8	46.1±29.1
2	Eastern UP	32.9±23.4	34.9±25.2	28.9±23.9	29.5±21.5	38.5±22.8
3	Bihar	82.7±40.0	86.8±35.4	65.9±35.3	73.1±37.5	105.1±41.7
4	Jharkhand	97.7±47.6	107.4±53.3	88.5±47.1	90.8±45.4	104.2±43.5
5	Orissa	119.4±63.7	126.6±68.6	105.9±52.1	102.4±39.9	142.9±80.8
	Central NE India	73.4±32.1	78.2±35.9	63.0±31.5	65.1±26.8	87.4±28.8
JJAS (monsoon season)						
1	Western UP Plains	759.0±167.4	733.9±187.4	759.6±163.2	804.3±144.6	738.2±170.5
2	Eastern UP	908.4± 191.1	902.4±196.0	939.7±202.6	890.8±174.9	900.9±195.9
3	Bihar	1,038.4±198.8	1,086.8±225.7	1,032.2±166.7	989.9±163.6	1,044.8±227.5
4	Jharkhand	1,104.1±175.0	1,087.3±158.1	1,150.0±150.6	1,089.2±176.2	1,090.0±209.9
5	Orissa	1,178.2±167.9	1,187.7±154.3	1,232.2±153.5	1,120.2±143.0	1,172.2±203.0
	Central NE India	997.6±112.0	999.6±100.2	1,022.7±108.0	978.9±105.2	989.2±132.8
OND (post-monsoon season)						
1	Western UP Plains	41.3±48.2	36.4±48.5	36.8±35.4	57.3±64.1	34.7±38.2
2	Eastern UP	57.2±64.8	64.0±97.8	53.3±41.4	63.6±61.9	47.7±43.5
3	Bihar	77.1±65.1	65.9±58.3	80.1±69.3	91.0±77.3	71.4±53.3
4	Jharkhand	102.3±71.0	92.8±76.2	115.0±67.1	102.7±72.0	98.6±70.1
5	Orissa	160.3±89.8	153.4±102.7	166.8±69.7	174.3±77.3	146.5±106.1
	Central NE India	87.6±51.4	82.5±61.6	90.4±43.2	97.8±53.1	79.8±46.2
Annual						
1	Western UP Plains	873.4±178.1	848.7±200.0	865.3±163.7	924.4±170.4	855.1±174.8
2	Eastern UP	1,032.2±206.6	1,036.4±243.7	1,059.8±192.9	1,014.8±201.2	1,018.0±191.5
3	Bihar	1,230.2±217.9	1,271.8±242.9	1,215.0±172.5	1,183.2±202.7	1,250.9±245.3
4	Jharkhand	1,349.6±202.8	1,335.5±190.3	1,415.1±153.0	1,320.1±230.6	1,327.5±223.3
5	Orissa	1,490.1±199.4	1,496.3±167.0	1,545.4±180.4	1,425.3±182.6	1,493.3±248.8
	Central NE India	1,195.1±134.1	1,197.7±135.3	1,220.1±108.2	1,173.6±146.8	1,189.0±145.3

NP1, 1889–1918; NP2, 1919–1948; NP3, 1949–1978; NP4, 1979–2008

3.2 Trends in monthly rainfall

There is a significant decreasing trend of 0.5 mm/year for Western UP subdivision and an increasing trend of 0.4 mm/year for Eastern UP subdivision during the recent normal period NP4 during January. However, Eastern UP and Bihar show a decreasing trend of 0.6 and 0.8 mm/year, respectively, during NP1. No significant trend of rainfall has been noticed in any of the normal periods as well as during the 120-year period over any subdivision as well as CNE India during February and March. During April, Eastern UP and Bihar subdivisions show an increasing trend of 0.02 and 0.07 mm rainfall/year, respectively, for the period 1889–2008. For May, a non-significant increasing trend of rainfall has been noticed for all the subdivisions during the recent normal period 1979–2008. However, Western UP, Bihar and CNE India show a significant increasing trend of 0.10, 0.19 and 0.10 mm/year, respectively, during 1889–2008. During June, all the meteorological sub-

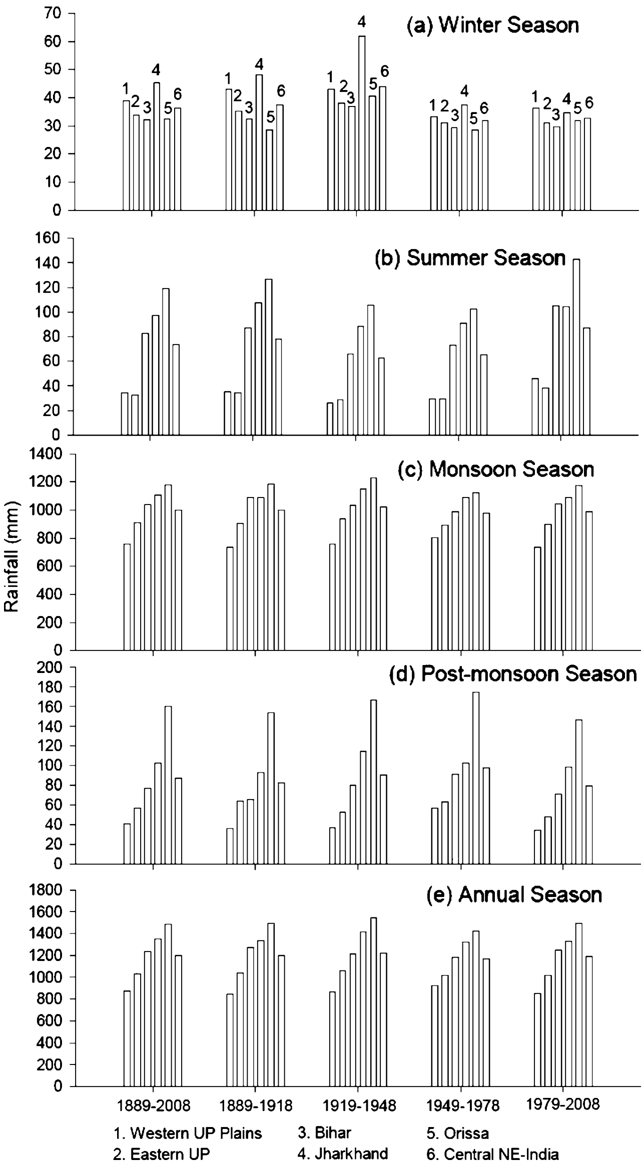

Fig. 3 Seasonal variation of rainfall over different subdivisions and Central Northeast India during different normal periods, NP1, NP2, NP3 and NP4 and period 1889–2008: NP1, 1889–1918; NP2, 1919–1948; NP3, 1949–1978; NP4, 1979–2008

divisions show an upward trend during the recent normal period 1979–2008, and even Western UP shows a significant increasing trend of 2.78 mm/day. However, for the long-term series, all the divisions except Eastern UP and Western UP plains show downward trend of rainfall.

The results show that during July, for the normal period NP1, there is a decreasing trend of rainfall for all the subdivisions and CNE India; moreover, there is a significant decreasing trend of 4.6 mm/year for Jharkhand and 3.2 mm/day for CNE India. Since rice crop is the important *kharif* crop (May–October) in this region, the decreasing trend of rainfall during the month of July may delay/affect the transplanting/vegetative phase of the crop, and assured irrigation is very much needed to tackle the drought situation. During the month of August, all the meteorological subdivisions show a decreasing trend during the period 1889–2008. Eastern UP and Bihar subdivisions show a decreasing trend of 0.50 mm rainfall/year for the entire period under consideration. However, when we look into different normal periods, there is a mix of increasing and decreasing rainfall activity for all the divisions as well as for the homogenous region for September. Eastern UP subdivision shows a significant decreasing trend of 2.8 mm/year during the recent normal period NP4. For October, all the subdivisions except Orissa as well as CNE India homogeneous region show an increasing trend during the period 1889–2008, but statistically not significant.

During the month of December, all the meteorological subdivisions except Jharkhand show a significant decreasing trend of rainfall during recent normal period NP4. The decrease of rainfall during December may hamper sowing of wheat, which is the important *rabi* crop (November–March) in most of this part of the region.

3.3 Seasonal trends of rainfall

All the subdivisions except Eastern UP and CNE India show an upward trend of annual rainfall during the recent normal period NP4, and even Jharkhand and Orissa subdivision show a significant increasing trend of 10.4 and 10.3 mm/year rainfall, respectively. However, when we look into the entire period of 1889–2008, all the subdivisions and CNE India show a non-significant decreasing trend of annual rainfall. During summer season, all the subdivisions recorded an upward trend of rainfall during the period 1889–2008 (Fig. 4) and even Western UP, Bihar subdivisions and CNE India show an increasing trend of 0.13, 0.24 and 0.12 mm/year, respectively, during the same period. All the subdivisions show an increasing trend of rainfall during the recent normal period NP4. During the post-monsoon season, Orissa and Jharkhand subdivisions show a significant increasing trend of 7.4 and 10.2 mm rainfall/year, respectively, during the recent normal period NP4.

3.4 Monthly temperature trends

The long-term (1914–2003) mean annual maximum and minimum temperature of North Central India is 30.7°C and 18°C, respectively. May is the hottest (39.1°C) month followed by April (36.7°C); January is the coolest (8.5°C) followed by December (8.9°C) during the period. The same pattern was observed during different normal periods: 1914–1943 (NPT1), 1944–1973 (NPT2) and 1974–2003 (NPT3) for maximum and minimum temperature. The

Table 3 Mean monthly rainfall and its percent contribution to annual over different meteorological subdivisions and Central Northeast India during normal periods and 1889–2008

Months	1889–1918	1919–1948	1949–1978	1979–2008	1889–2008
Central North East India					
January	14.4 (1.2)	20.6 (1.7)	16.9 (1.4)	13.4 (1.1)	16.3 (1.4)
February	23.0 (1.9)	23.4 (1.9)	14.9 (1.3)	19.2 (1.6)	20.1 (1.7)
March	17.0 (1.4)	13.5 (1.1)	15.1 (1.3)	15.3 (1.3)	15.2 (1.3)
April	16.8 (1.4)	15.5 (1.3)	14.7 (1.3)	19.5 (1.6)	16.6 (1.4)
May	44.5 (3.7)	34.0 (2.8)	35.2 (3.0)	52.6 (4.4)	41.6 (3.5)
June	181.5 (15.2)	148.2 (12.1)	144.8 (12.3)	177.8 (15.0)	163.1 (13.6)
July	301.4 (25.2)	344.7 (28.2)	307.0 (26.2)	314.6 (26.5)	316.9 (26.5)
August	313.9 (26.2)	317.7 (26.0)	312.4 (26.6)	293.3 (24.7)	309.3 (25.9)
September	202.7 (16.9)	212.2 (17.4)	214.7 (18.3)	203.5 (17.1)	208.3 (17.4)
October	64.5 (5.4)	67.7 (5.5)	82.9 (7.1)	58.5 (4.9)	68.4 (5.7)
November	13.0 (1.1)	16.0 (1.3)	10.5 (0.9)	12.6 (1.1)	13.0 (1.1)
December	5.0 (0.4)	6.7 (0.5)	4.4 (0.4)	8.7 (0.7)	6.2 (0.5)
Annual	1,197.7	1,220.1	1,173.6	1,189.0	1,195.1
Western UP Plain					
January	20.8 (2.4)	22.3 (2.6)	19.2 (2.1)	14.8 (1.7)	19.3 (2.2)
February	22.3 (2.6)	20.6 (2.4)	14.0 (1.5)	21.4 (2.5)	19.6 (2.2)
March	12.9 (1.5)	10.1 (1.2)	12.3 (1.3)	13.4 (1.6)	12.2 (1.4)
April	7.8 (0.9)	5.8 (0.7)	4.3 (0.5)	9.2 (1.1)	6.8 (0.8)
May	14.7 (1.7)	10.1 (1.2)	13.0 (1.4)	23.4 (2.7)	15.3 (1.8)
June	96.7 (11.4)	85.8 (9.9)	76.6 (8.3)	100.5 (11.8)	89.9 (10.3)
July	246.5 (29.0)	265.4 (30.7)	269.2 (29.1)	257.1 (30.1)	259.6 (29.7)
August	246.4 (29.0)	253.1 (29.2)	298.8 (32.3)	240.4 (28.1)	259.7 (29.7)
September	144.3 (17.0)	155.3 (18.0)	159.7 (17.3)	140.3 (16.4)	149.9 (17.2)
October	23.3 (2.7)	22.7 (2.6)	47.1 (5.1)	20.8 (2.4)	28.5 (3.3)
November	4.8 (0.6)	3.6 (0.4)	3.6 (0.4)	4.1 (0.5)	4.0 (0.5)
December	8.4 (1.0)	10.5 (1.2)	6.7 (0.7)	9.7 (1.1)	8.8 (1.0)
Annual	848.7	865.3	924.4	855.1	873.4
Eastern UP Plain					
January	15.7 (1.5)	18.9 (1.8)	19.0 (1.9)	14.7 (1.4)	17.1 (1.7)
February	19.4 (1.9)	19.0 (1.8)	11.9 (1.2)	16.2 (1.6)	16.6 (1.6)
March	9.7 (0.9)	8.3 (0.8)	9.6 (0.9)	7.4 (0.7)	8.8 (0.8)
April	5.5 (0.5)	7.6 (0.7)	5.2 (0.5)	7.8 (0.8)	6.5 (0.6)
May	19.7 (1.9)	13.0 (1.2)	14.7 (1.4)	23.3 (2.3)	17.7 (1.7)
June	130.8 (12.6)	104.5 (9.9)	107.0 (10.5)	137.2 (13.5)	119.9 (11.6)
July	283.2 (27.3)	331.1 (31.2)	291.6 (28.7)	292.8 (28.8)	299.7 (29.0)
August	308.1 (29.7)	297.7 (28.1)	306.6 (30.2)	260.2 (25.6)	293.1 (28.4)
September	180.4 (17.4)	206.4 (19.5)	185.5 (18.3)	210.7 (20.7)	195.8 (19.0)
October	51.8 (5.0)	40.1 (3.8)	54.6 (5.4)	34.4 (3.4)	45.2 (4.4)
November	7.4 (0.7)	5.7 (0.5)	3.7 (0.4)	4.5 (0.4)	5.4 (0.5)
December	4.8 (0.5)	7.4 (0.7)	5.3 (0.5)	8.8 (0.9)	6.6 (0.6)
Annual	1,036.4	1,059.8	1,014.8	1,018.0	1,032.2
Bihar					
January	12.7 (1.0)	17.6 (1.4)	18.5 (1.6)	11.7 (0.9)	15.1 (1.2)
February	19.6 (1.5)	19.2 (1.6)	10.7 (0.9)	17.9 (1.4)	16.8 (1.4)
March	12.6 (1.0)	9.6 (0.8)	11.6 (1.0)	10.1 (0.8)	11.0 (0.9)
April	15.5 (1.2)	15.1 (1.2)	14.7 (1.2)	22.0 (1.8)	16.8 (1.4)
May	58.7 (4.6)	41.3 (3.4)	46.9 (4.0)	73.1 (5.8)	55.0 (4.5)

Table 3 (continued)

Months	1889–1918	1919–1948	1949–1978	1979–2008	1889–2008
June	213.5 (16.8)	153.4 (12.6)	169.9 (14.4)	185.3 (14.8)	180.5 (14.7)
July	320.9 (25.2)	332.5 (27.4)	310.6 (26.2)	356.5 (28.5)	330.1 (26.8)
August	333.5 (26.2)	307.0 (25.3)	282.3 (23.9)	291.0 (23.3)	303.5 (24.7)
September	218.9 (17.2)	239.3 (19.7)	227.1 (19.2)	212.0 (16.9)	224.3 (18.2)
October	56.5 (4.4)	66.5 (5.5)	82.0 (6.9)	55.8 (4.5)	65.2 (5.3)
November	7.4 (0.6)	9.4 (0.8)	6.7 (0.6)	7.4 (0.6)	7.7 (0.6)
December	2.0 (0.2)	4.2 (0.3)	2.3 (0.2)	8.3 (0.7)	4.2 (0.3)
Annual	1,271.8	1,215.0	1,183.2	1,250.9	1,230.2
Jharkhand					
January	15.3 (1.1)	27.9 (2.0)	18.2 (1.4)	14.2 (1.1)	18.9 (1.4)
February	32.7 (2.5)	33.8 (2.4)	19.1 (1.4)	20.5 (1.5)	26.5 (2.0)
March	25.7 (1.9)	21.0 (1.5)	19.3 (1.5)	22.1 (1.7)	22.0 (1.6)
April	20.7 (1.6)	20.1 (1.4)	22.7 (1.7)	20.8 (1.6)	21.1 (1.6)
May	61.0 (4.6)	47.4 (3.4)	48.7 (3.7)	61.4 (4.6)	54.6 (4.0)
June	232.1 (17.4)	182.7 (12.9)	179.6 (13.6)	231.3 (17.4)	206.4 (15.3)
July	316.3 (23.7)	389.5 (27.5)	328.2 (24.9)	335.5 (25.3)	342.4 (25.4)
August	317.8 (23.8)	356.9 (25.2)	324.7 (24.6)	303.6 (22.9)	325.8 (24.1)
September	221.2 (16.6)	221.0 (15.6)	256.7 (19.4)	219.7 (16.5)	229.6 (17.0)
October	77.3 (5.8)	87.8 (6.2)	90.1 (6.8)	74.5 (5.6)	82.4 (6.1)
November	11.5 (0.9)	21.4 (1.5)	8.7 (0.7)	12.9 (1.0)	13.6 (1.0)
December	4.0 (0.3)	5.7 (0.4)	4.0 (0.3)	11.2 (0.8)	6.2 (0.5)
Annual	1,335.5	1,415.1	1,320.1	1,327.5	1,349.6
Orissa					
January	7.6 (0.5)	16.2 (1.0)	9.7 (0.7)	11.6 (0.8)	11.3 (0.8)
February	21.0 (1.4)	24.3 (1.6)	18.7 (1.3)	20.1 (1.3)	21.0 (1.4)
March	24.0 (1.6)	18.7 (1.2)	23.0 (1.6)	23.5 (1.6)	22.3 (1.5)
April	34.3 (2.3)	29.1 (1.9)	26.8 (1.9)	37.8 (2.5)	32.0 (2.1)
May	68.3 (4.6)	58.1 (3.8)	52.7 (3.7)	81.7 (5.5)	65.2 (4.4)
June	234.7 (15.7)	214.7 (13.9)	191.0 (13.4)	234.9 (15.7)	218.8 (14.7)
July	340.4 (22.7)	404.9 (26.2)	335.1 (23.5)	331.1 (22.2)	352.9 (23.7)
August	363.8 (24.3)	373.9 (24.2)	349.4 (24.5)	371.3 (24.9)	364.6 (24.5)
September	248.8 (16.6)	238.7 (15.4)	244.7 (17.2)	235.0 (15.7)	241.8 (16.2)
October	113.5 (7.6)	121.3 (7.8)	140.9 (9.9)	107.1 (7.2)	120.7 (8.1)
November	33.9 (2.3)	39.9 (2.6)	29.6 (2.1)	33.9 (2.3)	34.3 (2.3)
December	6.1 (0.4)	5.6 (0.4)	3.8 (0.3)	5.5 (0.4)	5.3 (0.4)
Annual	1,496.3	1,545.4	1,425.3	1,493.3	1,490.1

Figures in parenthesis indicate percent contribution of monthly rainfall to annual

month-wise significant inferences drawn from the application of Mann–Kendall test are as follows:

January Maximum temperature and minimum temperature show insignificant decreasing trend during 90-year period 1914–2003 (Fig. 5). The same pattern was observed for maximum temperature during NPT1 and NPT3, while there is a rising trend during NPT2. However, minimum temperature shows insignificant increasing trend during NPT1 and NPT3 and decreasing trend during NPT2.

February Maximum temperature shows significant (at 0.05 level) increasing trend of 0.009°C/year during the period 1914–2003 (Table 4). Linear approximation shows significant (at 0.01 level) rising trend of minimum temperature (0.05°C/year) during the recent normal period. This indicates that minimum temperature is more contributed to the rising of mean temperature.

March Maximum temperature shows insignificant increasing trend during 90-year period 1914–2003 and during all the

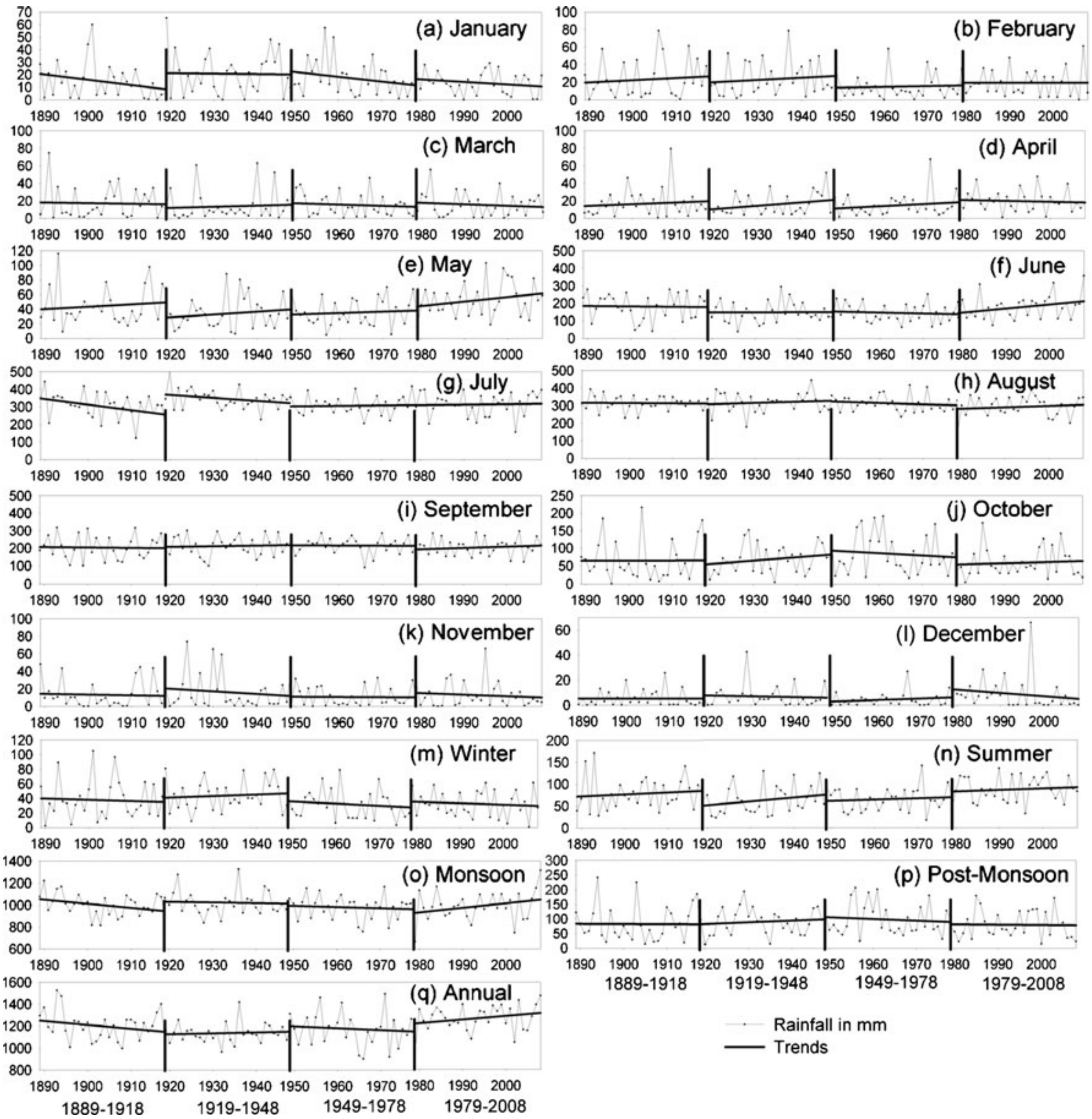

Fig. 4 Monthly, seasonal and annual trends of rainfall over different subdivisions and Central Northeast India during different normal periods NP1 (1889–1918), NP2 (1919–1948), NP3 (1949–1978) and NP4 (1979–2008)

normal periods. However, insignificant increasing trend of minimum temperature has been noticed during the period 1914–2003.

April Maximum temperature shows a significant (at 0.05 level) increasing trend of 0.01°C/year during the period 1914–2003.

May Maximum temperature shows significant (at 0.05 level) increasing trend of 0.045°C/year during NPT1. Linear approximation shows significant (at 0.01 level) decreasing trend of minimum temperature of the order of 0.06°C/year during NPT2.

June Minimum temperature shows significant (at 0.05 level) decreasing trend of 0.034°C/year during NPT2. Linear approximation shows significant (at 0.05 level) decreasing trend of minimum temperature (0.005°C/year) during the entire period of consideration.

July Maximum temperature shows significant (at 0.01 level) increasing trend of 0.014°C/year and 0.040°C/year during the period 1914–2003 and NPT2, respectively. Minimum temperature shows significant (at 0.01 level) decreasing trend of 0.022°C/year during NPT2. However, it shows significant (at 0.01 level) increasing trend of 0.034°C/year during the recent normal period 1974–2003.

August Maximum temperature shows significant increasing trend of 0.023°C/year (at 0.05 level) and 0.0097°C/year (at 0.01 level) during NPT3 and during 1914–2003, respectively.

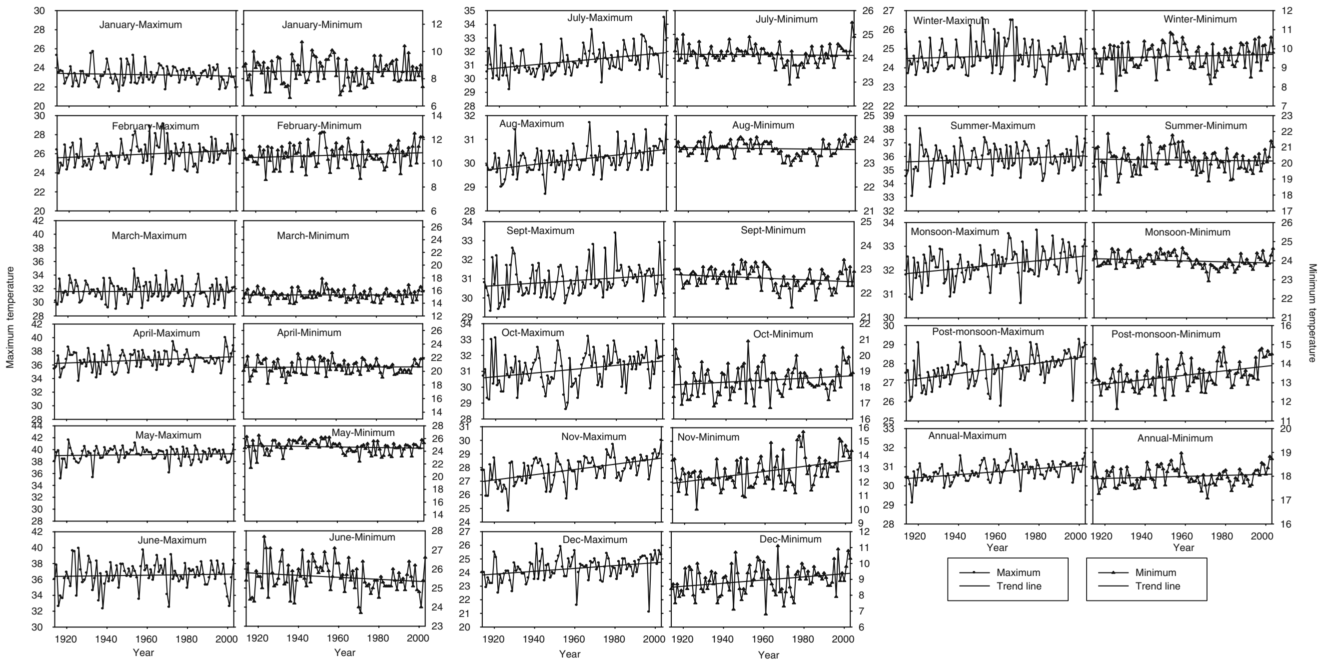

Fig. 5 Monthly, seasonal and annual maximum and minimum temperature variation during 1914–2003 and its trends over Central North India

Estimation of linear approximation shows significant (at 0.01 level) rising trend of minimum temperature (0.024°C/year) during NPT3 and significant (at 0.01 level) decreasing trend of minimum temperature (0.03°C/year) during NPT2.

September Maximum temperature shows significant rising trend of 0.0066°C/year (at 0.05 level) during the period 1914–2003. However, minimum temperature shows significant decreasing trend of 0.01°C/year (at 0.05 level) during 1914–2003 and 0.032°C/year (at 0.01 level) during NPT2. However, minimum temperature shows significant (at 0.05 level) rising trend of 0.016°C/year during the recent normal period NPT3.

October Maximum temperature shows significant rising trend of 0.012°C/year (at 0.01 level) during the period 1914–2003 and 0.029°C/year (at 0.05 level) during NPT1. Though, minimum temperature shows significant (at 0.05 level) increasing trend of 0.006°C/year during 1914–2003, while it shows insignificant falling trend during NPT1 and NPT2 and increasing trend during NPT3.

November Maximum temperature shows significant rising trend of 0.019°C/year (at 0.01 level) during the period 1914–2003 and 0.045°C/year (at 0.05 level) during NPT1. Though, minimum temperature shows significant (at 0.01 level) increasing trend of 0.019°C/year during 1914–2003, while it shows insignificant falling trend during NPT1 and increasing trend during NPT2 and NPT3.

December Maximum temperature shows significant rising trend of 0.011°C/year (at 0.01 level) during the period 1914–2003 and 0.025°C/year (at 0.01 level) during NPT3. Though, minimum temperature shows significant (at 0.01 level) increasing trend of 0.0099°C/year during 1914–2003, while it shows insignificant falling trend during NPT2 and increasing trend during NPT1 and NPT3.

3.5 Seasonal temperature trends

Maximum temperature shows significant rising trend of 0.008°C/year (at 0.01 level) during monsoon season and 0.014°C/year (at 0.01 level) during post-monsoon season during the period 1914–2003. The annual maximum temperature also shows significant increasing trend of 0.008°C/year (at 0.01 level) during the same period. Minimum temperature shows significant rising trend of 0.012°C/year (at 0.01 level) during post-monsoon season and significant falling trend of 0.002°C/year (at 0.05 level) during monsoon season. This rising feature of both maximum and minimum temperature ultimately increases the mean heating of the atmosphere and favours the cloud formation and eventually increases the rainfall activity. The post-monsoon season rainfall analysis also suggests that rainfall shows an increasing trend in all the meteorological subdivisions except Orissa and also for the CNE India homogeneous region. However, minimum temperature shows insignificant increasing trend during winter and insignificant decreasing trend during summer season during

Table 4 MK test results of maximum and minimum temperature for North Central homogeneous region

Months/seasons	1914–2003		1914–1943		1944–1973		1974–2003	
	Max	Min	Max	Min	Max	Min	Max	Min
January	N	N	N	P	P	N	N	P
February	P*	P	P	P	P	N	P	P**
March	P	P	P	N	P	N	P	P
April	P*	N	P	N	P	N	P	P
May	P	N	P*	P	N	N**	P	P
June	P	N*	P	P	N	N*	N	P
July	P**	N	N	N	P**	N**	P	P**
August	P**	N	P	P	P	N**	P*	P**
September	P*	N*	P	P	P	N**	N	P*
October	P**	P*	P*	N	P	N	P	P
November	P**	P**	P*	N	P	P	P	P
December	P**	P**	P	P	N	N	P**	P
Winter	P	P	P	P	P	N*	P	P*
Summer	P	N	P	N	P	N*	P	P
Monsoon	P**	N*	N	P	P	N**	P	P**
Post-monsoon	P**	P**	P**	N	P	N	P*	P*
Annual	P**	P	P	P	P*	N**	P	P**

P positive trend, *N* negative trend

*Statistically significant at 0.05 level

**Statistically significant at 0.01 level

the study period. The annual minimum temperature also shows insignificant increasing trend during the same period. When we look into different normal periods analysis, during the recent normal period 1974–2003, maximum temperature shows insignificant increasing trend during winter, summer and monsoon seasons and significant rising trend of 0.°C/year (at 0.05 level) during the post-monsoon season. However, minimum temperature also shows significant increasing trend of 0.026°C/year (at 0.05 level) during winter, 0.022°C/year (at 0.01 level) during monsoon and 0.028°C/year (at 0.05 level) during post-monsoon and insignificant increasing trend during summer season. The annual minimum temperature also shows significant rising trend of 0.023°C/year (at 0.01 level) during the recent normal period 1974–2003.

3.6 Wavelet power spectrum and global wavelet power spectrum

The global wavelet spectrum provides an unbiased and consistent estimation of the true power spectrum of the time series, and thus, it is a simple and robust way to characterise the time series variability. Global wavelet spectra should be used to describe rainfall variability in non-stationary hyetographs. For regions that do not display long-term changes in hyetograph structures, global wavelet spectra are useful for summarising a region's temporal variability and comparing it with rainfall in other regions. The global wavelet spectral shape is controlled primarily by the distribution of feature scales and appears diagnostic of the hydro-climatic regime despite a large range in watershed sizes because a clear qualitative difference could be found in the global wavelet spectra of hyetographs from different climatic regions. Figure 6 shows the power (absolute value squared) of the wavelet transform for the individual monsoon months and monsoon and annual rainfall at different subdivisions as well as CNE India. The parameters of the wavelet analysis were set accordingly used by Santos et al. (2001). The power gives information on the relative power at a certain scale and a certain time. It is clear that there is more concentration of power between different period (year) band for different set of data (monthly, monsoon and annual) of different subdivisions. The black contour in the same figure is the 5% significance level using a red noise background spectrum. The periodicity of the time series is verified by an integration of power over time, which shows different significant peak above the 95% confidence level for different subdivisions for the global wavelet spectrum, assuming red noise α=0.2787 or assuming white noise represented by the dashed lines.

No significant concentration of power has been noticed during the time series data except during September for Western UP. During September, significant power has been noticed between 4 and 8 years band. Interestingly, in Eastern UP subdivision, there is more concentration of power between 4 and 8 years band during August. Even though there is significant concentration of power between 4 and 8 years band during annual rainfall, the wavelet power spectrum could not show any patches (black contours). It is clear that there is more concentration of

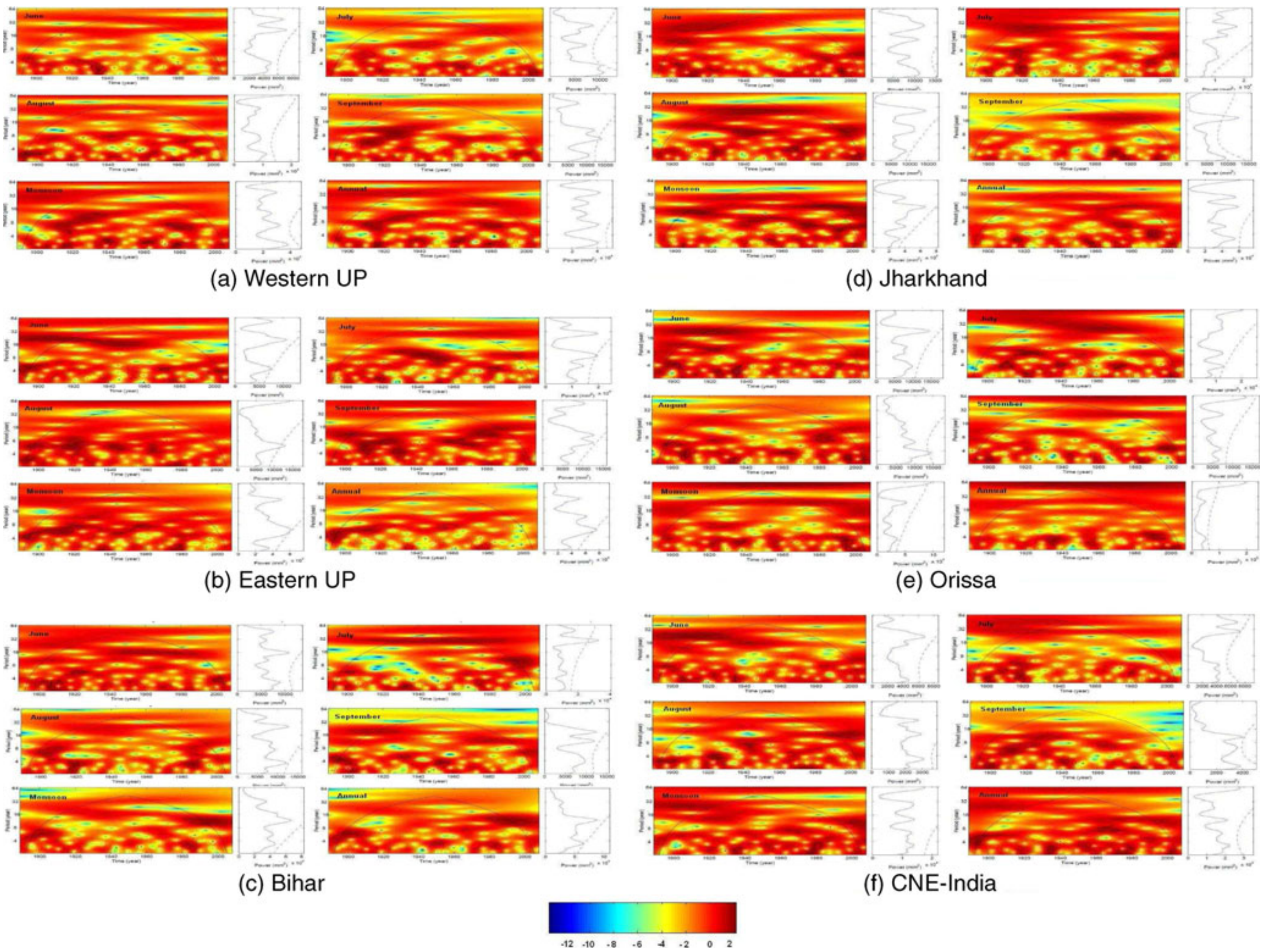

Fig. 6 The wavelet power spectrum for different sub-divisions (**a–f**). The *inverted cone* region is the cone of influence, where zero padding has reduced the variance. *Black contour* is the 95% significance level, using a red noise (α=0.2787) background spectrum. The *right side* graph of each wavelet power spectrum represents global wavelet power spectrum (*black line*). The *dashed line* is the 95% confidence level for the global wavelet spectrum

power between 30 and 34 years band during July for Bihar, with an average 32-year periodicity. As far as annual rainfall is concerned, there is more concentration of power between 10 and 14 years band with an average 12-year periodicity. However, for Jharkhand subdivision, there is more concentration of power between 12 and 24 years band during September. However, continuous patches are missing in other time series data. Monsoon and annual rainfall wavelet power spectrum show no significant power concentration within the region of cone of influence for Orissa subdivision which indicates that no periodicity has been noticed during the study period. However, there is significant concentration of power at the 4-year period during July. However, as far as CNE India is concerned, no significant power concentration has been noticed in any of the time series under study.

4 Summary and conclusions

The Mann–Kendall trend analysis provided some important features pertaining to the study area. The rising trend of maximum (0.014°C/year) and minimum temperature (0.012°C/year) during post-monsoon season may alter the crop growth window or calendar of important crops grown in this part of the region. As far as rainfall is concerned, there is a significant decreasing trend of 4.6 mm/year for Jharkhand and 3.2 mm/day for CNE India. Since rice crop is the important *kharif* crop (May–October) in this region, the decreasing trend of rainfall during July may delay/affect the transplanting/vegetative phase of the crop, and assured irrigation is very much needed to tackle the moisture stress situation. During summer season, western UP, Bihar subdivisions and CNE India show an increasing trend of 0.13, 0.24 and 0.12 mm/year, respectively, during the same period; this highlight the possibility of extreme/higher rainfall events during summer season. In order to study the periodicity of the monthly rainfall during individual monsoon months, total monsoon and annual rainfall of CNE India and different subdivisions, wavelet analysis is applied. The wavelet power spectrum shows different types of power concentration in different year bands, revealing different periodicity for different months, as well as monsoon seasonal and annual rainfall for different subdivisions. Interestingly, no significant periodicity has been noticed in any of the time series for CNE India. A significant average 6 years periodicity during September and 32 years periodicity during July have been noticed for Western UP and Bihar subdivisions, respectively. As with agricultural and water management point of view, monthly time scale may be higher, and future work should be explored to analyse 15-day composite rainfall data, so that under projected climate change and higher population growth scenarios of the study region, the planners and managers can chalk out strategy to tap maximum available natural resources at appropriate time to enhance agricultural productivity, thereby sustain food security. The inference figure out from the above analyses will be helpful to the managers, planners and agricultural scientists to work out irrigation and water management options under various possible climatic eventualities for the region.

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