INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **33**: 968–978 (2013)
Published online 5 April 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.3483

RMetS
Royal Meteorological Society

Analysis of rainfall and temperature trends in northeast India

S. K. Jain,[a]* Vijay Kumar[b,c] and M. Saharia[d]
[a] *WRD & M, Indian Institute of Technology, Roorkee, Uttarakhand, India*
[b] *Ministry of Earth Sciences, New Delhi, India*
[c] *Earlier at WRS Division, National Institute of Hydrology, Roorkee, India*
[d] *Department of Civil Engineering, National Institute of Technology, Silchar, Assam, India*

ABSTRACT: The northeast region (NER) of India covers an area of 0.26 million km^2. This region is one of the highest rainfall-receiving regions on the planet. Consequently, it has huge water and hydropower potential and analysis of rainfall and temperature trends would be of interest to water and energy planners. Trends in monthly, seasonal, and annual rainfall and temperature on the subdivision and regional scale for the NER were examined in this study. Trend analysis of rainfall data series for 1871–2008 did not show any clear trend for the region as a whole, although there are seasonal trends for some seasons and for some hydro-meteorological subdivisions. Similar analysis for temperature data showed that all the four temperature variables (maximum, minimum, and mean temperatures and temperature range) had rising trend. Notably for the post-monsoon season, the Sen's estimator of slope (°C/year) was 0.019, 0.011, and 0.015 for the maximum, minimum, and mean temperature, respectively. Copyright © 2012 Royal Meteorological Society

KEY WORDS rainfall; temperature; trend analysis; northeast India

Received 18 February 2011; Revised 4 January 2012; Accepted 11 March 2012

1. Introduction

Studies to detect climate change and its impact on the various sectors deserve urgent attention in light of the impact of climate change on agriculture, increased risk of hunger and water scarcity, rapid melting of glaciers, and decrease in river flows Intergovernmental Panel on Climate Change (IPCC, 2007). This study aims to determine trends in the monthly, annual, and seasonal total rainfall; maximum, minimum, and mean temperatures; and diurnal temperature range (DTR) for northeast region (NER) of India.

Although climate change is a broad area of research, the changing pattern of precipitation deserves urgent and systematic attention as it will affect the availability of food supply (Dore, 2005). Precipitation is a vital part of the hydrologic cycle and changes in its pattern would directly influence the water resources of the concerned region. Changes in rainfall quantity and frequency would alter the pattern of stream flows and demands (particularly agricultural), spatial and temporal distribution of runoff, soil moisture, and groundwater reserves. This will necessitate a review of our reservoir operation and water resources management policies. Trend analysis of rainfall in different spatial scales will lead to a better understanding of the problems associated with floods, droughts, and the availability of water for various uses with respect to future climate scenarios. Air temperature is also considered a good indication of the state of climate because of its ability to represent the energy exchange process over the earth's surface with reasonable accuracy (Vinnikov *et al*., 1990; Thapliyal and Kulshrestha, 1991).

2. Climate change in India

A large number of studies have been conducted for the Indian subcontinent and several investigators have concluded that the trend and magnitude of warming over India/Indian subcontinent over the past century is broadly consistent with the global trend and magnitude (Pant and Kumar, 1997; Arora *et al*., 2005; Dash *et al*., 2007). However, the DTR decadal trends over India are quite different from those observed over other parts of the globe because of the comparatively large increase in T_{max} over a major part of India (Srivastava *et al*., 1992; Rupa Kumar *et al*., 1994). Several studies relating to changing pattern of rainfall over India observed that there is no clear trend of increase or decrease in average rainfall over the country (Mooley and Parthasarathy, 1984; Thapliyal and Kulshrestha, 1991; Lal, 2001; Kumar *et al*., 2010). Although long-term trends in monsoon rainfall have not been observed on an all-India scale, several studies have found significant trends in rainfall on a regional scale (Koteswaram and Alvi, 1969; Jagannathan and Parthasarathy, 1973; Raghavendra, 1974; Chaudhary and

* Correspondence to: S. K. Jain, WRD & M, Indian Institute of Technology, Roorkee, Uttarakhand, India. E-mail: s_k_jain@yahoo.com

Abhyankar, 1979; Kumar *et al*., 2005; Dash *et al*., 2007; Kumar and Jain, 2010). Some studies have shown that, in general, the frequency of intense rainfall events in many parts of Asia has decreased, while the number of rainy days and total annual precipitation has decreased (Khan *et al*., 2000; Shrestha *et al*., 2000; Mirza, 2002; Lal, 2003; Min *et al*., 2003; Goswami *et al*., 2006; Dash *et al*., 2007).

3. Northeast India

The NER of India consists of the states of Assam, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, and Tripura, covering an area of 255 168 km^2. These states consist of a part of the east Himalayan region, which extends from Arunachal Pradesh eastwards to the Darjeeling hills of West Bengal. The area is characterized by rich biodiversity, heavy precipitation, and high seismicity. The climate is predominantly humid subtropical with hot, humid summers, severe monsoons, and mild winters. Along with the west coast of India, this region has some of the Indian subcontinent's last remaining rain forests. The region's lowland and moist to wet tropical evergreen forests are considered to be the northern most limit of true tropical rainforests in the world (Procter *et al*., 1998). Northeast (NE) India has 64% of the total geographical area under forest cover. The entire region is a part of Indo-Burma and Himalayan hotspots, 2 of 25 such hotspots in the world. An index map of the region is given in Figure 1.

NE India can be considered a separate macro-region within the Indian landmass (Winstanley, 1973; Parthasarathy *et al*., 1987). Agriculture products form important inputs to the economy of NE India and any changes in the spatial and temporal pattern of rainfall directly affects the monsoon-reliant agriculture ecosystem. The climate is subtropical and the region is characterized by wide variation of weather and climate. With an annual average rainfall of 2068 mm, it is one of the highest rainfall-receiving regions on the planet, which makes it an important site from a meteorological perspective. Cherrapunji (or Mawsynram), which is the wettest place on the Earth with annual rainfall of around 12 000 mm, falls in this region. On the other hand, a few places in Assam receive an annual rainfall of only up to 2000 mm. According to the data presented by Parthasarathy *et al*. (1995), the mean annual rainfall in the NER varies from 1577 to 6002 mm. The mean temperature varies from 5 to 30 °C and the mean relative humidity remains between 70% and 85% for most part of the year (Jhajharia *et al*., 2009). This region is drained by the mighty river Brahmaputra and its tributaries, with an average annual discharge of about 19 200 cumecs. Tea, besides paddy, forest products, such as bamboo, different types of fruit crops, and orchids are the main cash crops of NE India (Jhajharia *et al*., 2011).

Figure 1. Index map of the northeast region of India showing different meteorological subdivisions.

NE India is vulnerable to water-induced disasters because of its location in the eastern Himalayan periphery, fragile geo-environmental setting, and economic underdevelopment. The powerful hydrological and monsoon regime of the region, especially the Brahmaputra and the Barak (Meghna) river systems, are both a resource and a source of vulnerability.

High-resolution regional climate model (PRECIS) simulations for A1B emission scenario indicates that the projected mean annual rainfall in NE will vary from a minimum of 940 ± 149 to 1330 ± 174.5 mm, Ministry of Environment and Forest (MOEF, 2010). The increase with respect to 1970s is by 0.3–3%. The NE also shows a substantial decrease in rainfall in the winter months of January and February in 2030s with respect to 1970s with no additional rain projected to be available during the period March to May and October to December. In fact, recent data indicate the same pattern. However, the monsoon rainfall during June, July, and August is likely to increase by 5 mm in 2030s with reference to 1970s, a negligible rise indeed.

Jhajharia *et al*. (2009) suggest that two parameters, viz. sunshine duration and wind speed, strongly influenced changes in pan evaporation at various sites from different regions in NE India in different seasons.

Jhajharia and Singh (2010) observed decreasing trends in DTR ($DTR = T_{max} - T_{min}$) at four sites in NE for almost all timescales. However, the DTR trends were significant mainly at annual, seasonal (pre-monsoon and monsoon), and monthly (May, June, August, September, and November) timescales. Significant increasing trends in DTR are observed at three sites in the month of October and in the monsoon and post-monsoon seasons as well. Four sites showed significant increasing trends in T_{mean} in monsoon and post-monsoon seasons. Also, the post-monsoon changes in T_{max} and T_{min} were more than the monsoon changes, indicating an element of a seasonal cycle. Significant decreasing trends in the sunshine duration were observed at annual, seasonal (winter and pre-monsoon), and monthly (January–March) timescales.

Correlation analysis revealed that different meteorological parameters influence DTR in different seasons over different sites. DTR increases were found to be positively correlated with T_{max} and moderate negatively correlated with T_{min}. However, DTR decreases were found to have a positive correlation with sunshine duration, T_{max}, and E_{pan} and a negative correlation with T_{min}. Concomitant decreases in sunshine duration may be one of the potential causes of observed DTR decreases over NE India.

Jhajharia *et al.* (2011) estimated ET_0 using the Penman-Monteith (PM) method over the eight sites in NE India and NE India as a whole. The total annual ET_0 of the eight sites of NE region was in the range of about 900–1320 mm. The total monthly ET_0 was around 50–65 mm in December to February, reached peak in summer, and remained in the range of about 110–150 mm, it gradually decreased thereafter. The average seasonal total ET_0 for NE India as a whole varied from 105 mm in winter to 470 mm in monsoon. Statistically significant decreasing trends in ET_0 were observed for the annual duration; winter, pre-monsoon, and post-monsoon seasons and to some degree in the monsoon season. Temperature remained practically trendless in winter and pre-monsoon seasons and witnessed increasing trends in monsoon and post-monsoon seasons.

4. Methodology

For seasonal analysis, each year was divided into four climatic seasons (Rao, 1981), namely winter (January–February), pre-monsoon (March–May), southwest monsoon (June–October), and post-monsoon (November–December). Note that the southwest monsoon season in this region lasts for 5 months (June–October) in contrast to 4 months (June–September) for the whole of India, while the postmonsoon season lasts for only 2 months. Analysis of the data was carried out season-wise as well as year-wise for temperature (1901–2003) and rainfall (1871–2008). To detect local trends in the long time series for rainfall and temperature, analyses were performed by dividing them into smaller timescales – for rainfall, it is 1871–1950 and 1951–2008, and for maximum, minimum, and diurnal temperatures, it is 1901–1950 and 1951–2003.

In this study, the magnitude of trend in a time series was determined using a nonparametric method known as Sen's estimator (Sen, 1968) and statistical significance of the trend in the time series was analysed using Mann–Kendall (MK) test (Mann, 1945; Kendall, 1975).

4.1. Magnitude of trend

Sen's method assumes a linear trend in the time series and has been widely used for determining the magnitude of trend in hydro-meteorological time series (Lettenmaier *et al.*, 1994; Yue and Hashino, 2003; Partal and Kahya, 2006). In this method, the slopes (T_i) of all data pairs are first calculated by

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

where x_j and x_k are data values at time j and k ($j > k$), respectively. The median of these N values of T_i is Sen's estimator of slope, which is calculated as follows:

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

A positive value of β indicates an upward (increasing) trend and a negative value indicates a downward (decreasing) trend in the time series.

4.2. Significance of trend

To ascertain the presence of statistically significant trend in hydrologic climatic variables such as temperature, precipitation, and stream flow with reference to climate change, nonparametric MK test has been employed by a number of researchers (Douglas *et al.*, 2000; Yue *et al.*, 2003; Burn *et al.*, 2004; Singh *et al.*, 2008a,b; Kumar and Jain, 2011). The MK method searches for a trend in a time series without specifying whether the trend is linear or nonlinear. In this study, the MK test was also applied. The MK test checks the null hypothesis of no trend *versus* the alternative hypothesis of the existence of increasing or decreasing trend. Following Bayazit and Onoz (2007), no pre-whitening of the data series was carried out as the sample size is large ($n \geq 50$) and slope of trend was high (>0.01).

The statistics (S) is defined as (Salas, 1993) follows:

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \operatorname{sgn}(x_j - x_i) \tag{3}$$

where N is the number of data points. Assuming $(x_j - x_i) = \theta$, the value of $\operatorname{sgn}(\theta)$ is computed as follows:

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & \text{if} \quad \theta > 0 \\ 0 & \text{if} \quad \theta = 0 \\ -1 & \text{if} \quad \theta < 0 \end{cases} \tag{4}$$

This statistics represents the number of positive differences minus the number of negative differences for all the differences considered. For large samples ($N > 10$), the test is conducted using a normal distribution (Helsel and Hirsch, 1992) with the mean and the variance as follows:

$$E[S] = 0 \tag{5}$$

$$\operatorname{Var}(S) = \frac{N(N-1)(2N+5) - \sum_{k=1}^{n} t_k(t_k - 1)(2t_k + 5)}{18} \tag{6}$$

where n is the number of tied (zero difference between compared values) groups and t_k the number of data points in the kth tied group. The standard normal deviate (Z-statistics) is then computed as (Hirsch *et al.*, 1993) follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if} \quad S < 0 \end{cases} \tag{7}$$

If the computed value of $|Z| > z_{\alpha/2}$, the null hypothesis (H_0) is rejected at α level of significance in a two-sided test. In this analysis, the null hypothesis was tested at 95% confidence level.

4.3. Data used

As a whole, the Indian subcontinent has been divided into 36 meteorological subdivisions (these are the areas of homogenous climate, 34 in mainland and 2 on islands). The NER of India encompasses the following five subdivisions:

1. Assam and Meghalaya,
2. Arunachal Pradesh,
3. Nagaland, Manipur, Mizoram, and Tripura (NMMT),
4. Sub-Himalayan West Bengal and Sikkim (SHWBS), and
5. Gangetic West Bengal.

4.4. Rainfall

The subdivisional monthly rainfall data of India prepared by the Indian Institute of Tropical Meteorology (IITM, htpp://www.tropmet.res.in) was used to carry out this study. We used the data for the four subdivisions from the NER of India (the data for Arunachal Pradesh was not available). The station rainfall data were obtained from the India Meteorological Department (IMD). The data from IMD are released after rigorous quality checks and pre-processing so as to provide error-free data for analysis and design. As such, these data may be considered the most reliable long series of data for the study area. The data for 138 years (1871–2008) were used.

In addition, the subdivisions of India were combined into five homogeneous regions by IITM, of which we utilized the series for NER in our study. General statistical features of the different subdivisions and the whole study area are given in Table I. The area-weighted monthly rainfall (by assigning the subdivision area as the weight) series of the four regions, including NE, along with the combined data of 30 subdivisions, are available at http://www.tropmet.res.in.

It is noted that the density of the stations is low in the region. Furthermore, the coefficient of variations of the rainfall for the different subdivisions is quite low and it is still lower for the whole region.

4.5. Temperature

The temperature series for NE India was derived from the Indian Regional Monthly Surface Air Temperature data set published by IITM with data being sourced from IMD. All-India and regional monthly temperature series are computed by simple averages of the constituent grid point data of the respective regions, the details of which are available in the study by Kothawale and Rupakumar (2004). Maximum (T_{max}) and minimum (T_{min}) temperature series for the years 1901–2003 were used in this study along with computed values of DTR ($T_{max} - T_{min}$) and average temperatures (T_{avg}).

5. Results

The results of trend analysis for the rainfall and the temperature data are discussed in the following sections.

5.1. Rainfall data

Results of rainfall data analysis are presented for the monthly, seasonal, and annual data.

5.1.1. Trend analysis of monthly rainfall data

As expected, rainfall trends show large variability in magnitude and direction of trend from one subdivision to another. When the entire available data series for the period 1871–2008 was considered for trend detection at monthly scale, of 48 values (12 months × 4 subdivisions), 20 values were negative and 28 were positive (Table II). Among the subdivisions, two subdivisions, namely Assam and Meghalaya and NMMT, the value of Sen's estimator is statistically significant for only one

Table I. Meteorological subdivisions whose data were used and statistical properties of annual rainfall.

S. No.	Subdivision/ region	Subdivision number	Area (km^2)	Number of rainfall stations	Minimum rainfall (mm)	Maximum rainfall (mm)	Mean rainfall (mm)	CV*
1	Assam & Meghalaya	3	109096	10	1772.3	3084.9	2346.4	0.11
2	Nagaland, Manipur, Mizoram & Tripura	4	70495	4	1418.1	2742.1	1980.2	0.12
3	Sub-Himalayan West Bengal & Sikkim	5	21625	5	1705.9	3323.8	2504.2	0.13
4	Gangetic West Bengal	6	66228	11	1083.6	2182.2	1538.6	0.15
Northeast India		3, 4, 5, 6	267444	30	1576.0	2625.9	2067.8	0.09

* CV: coefficient of variation.

Table II. Sen's estimator of slope (mm/year) for monthly rainfall.

S. No.	Subdivision/region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1871–2008													
1	Assam & Meghalaya	−0.04	0.04	−0.15	0.01	−0.23	−0.18	0.14	**−0.50**	−0.22	0.29	0.03	0.01
2	Nagaland, Manipur, Mizoram, & Tripura	−0.01	−0.03	−0.14	0.04	0.14	−0.21	−0.14	**−0.52**	−0.25	0.05	−0.01	0.00
3	Sub-Himalayan West Bengal & Sikkim	0.00	0.00	−0.01	0.12	0.00	**−0.67**	**0.80**	−0.23	−0.24	0.29	**0.02**	0.00
4	Gangetic West Bengal	0.01	0.00	0.01	0.06	−0.07	−0.13	0.10	0.12	**0.41**	0.10	0.01	0.00
Northeast India		−0.02	0.01	−0.10	0.06	−0.06	−0.22	0.14	**−0.32**	−0.05	0.20	0.03	0.00
1871–1950													
1	Assam & Meghalaya	−0.07	0.05	−0.47	0.17	0.71	**1.16**	−0.15	−0.28	−0.02	**0.66**	0.03	0.00
2	Nagaland, Manipur, Mizoram, & Tripura	−0.02	0.04	**−0.60**	0.17	0.15	0.25	−0.23	−0.43	−0.60	0.09	−0.03	0.00
3	Sub-Himalayan West Bengal & Sikkim	−0.04	0.08	−0.07	0.18	0.42	−0.30	0.18	0.27	0.20	0.66	**0.03**	0.00
4	Gangetic West Bengal	0.03	0.02	−0.06	0.03	−0.20	−0.20	0.48	0.73	0.05	0.16	0.00	0.00
Northeast India		−0.02	0.03	**−0.42**	0.16	0.26	0.64	−0.06	−0.12	−0.21	0.38	0.06	−0.01
1951–2008													
1	Assam & Meghalaya	−0.07	**0.56**	0.20	**1.28**	**−2.03**	**−1.62**	−0.74	−0.75	0.53	−0.51	0.00	−0.03
2	Nagaland, Manipur, Mizoram, & Tripura	−0.08	0.22	0.36	0.56	0.88	**−2.74**	−0.55	−0.56	1.26	−0.82	0.01	0.01
3	Sub-Himalayan West Bengal & Sikkim	0.00	**0.19**	−0.02	**0.85**	−0.05	−0.60	0.84	0.37	1.91	0.42	0.03	**0.04**
4	Gangetic West Bengal	0.03	0.17	0.20	0.38	**1.19**	1.06	**1.44**	0.77	0.00	−0.38	0.04	0.03
Northeast India		−0.03	**0.32**	0.21	**0.72**	−0.20	**−0.91**	0.18	−0.17	0.77	−0.17	−0.07	0.01

Bold values indicate statistical significance at 95% confidence level as per the Mann–Kendall test (+ for increasing and − for decreasing).

month each. For SHWBS, Sen's estimator is statistically significant for three months. Of these, one month has large positive value and one month has large negative value. The Gangetic West Bengal subdivision has one month with rising trend, which is statistically significant. For the whole NE region, positive and negative values were evenly balanced and the declining trend for only one month is statistically significant.

Since the available data series was quite long (about 140 years), it was split in two parts, 1871–1950 and 1951–2008, to ascertain the temporal variation in trends in the series. For the period 1871–1950, of the 48 slope values, 17 were negative (declining trend). Although the values of Sen's estimator are comparatively larger, the values for very few months are statistically significant. Assam and Meghalaya subdivision has a large positive value of the Sen's estimator for the months of June and October and these were statistically significant; NMMT and SHWBS subdivisions had one rising and one declining statistically significant trend and no trend value was statistically significant for Gangetic West Bengal. For the whole NER, positive and negative values were evenly balanced and the declining trend for only one month was statistically significant.

For the period 1951–2008, of the 48 slope values, only 16 had negative sign and many values were statistically significant. Assam and Meghalaya subdivision had high positive as well as high negative values of the estimator and two positive and two negative values were statistically significant. The subdivision of NMMT had very high negative significant value for the month of June. Most of the statistically significant values for the SHWBS subdivision had high magnitude. For Gangetic West Bengal, all the values (except one) were positive and the values for two months were statistically significant. The data for the whole NER had six months of positive Sen's estimator value and six months of negative value for this period.

5.1.2. *Trend analysis of seasonal rainfall*

Trend analysis was also performed on seasonal scale to examine if there are trends in the data at this scale. Figure 2 shows the plots of seasonal and annual rainfall for the region for the period 1871–2008; trend lines for the data have also been drawn. It is noticed from the figures that the rainfall for the monsoon season has the least scatter among all the seasons. Annual rainfall also does not show much scatter but rainfall for winter and post-monsoon seasons have large variation from one year to the other. For the period 1871–2008, the various subdivisions had small positive or negative trends in different seasons, but the trends were significant only in three instances in monsoon and post-monsoon (Table III). Of 16 slope values, 11 were negative. Among the statistically significant values, one had a declining trend and the other two had rising trend. In the monsoon season, NMMT subdivision had high negative slope and Gangetic West Bengal had high positive slope; both are statistically significant. SHWBS subdivision had a small positive significant slope in the post-monsoon season.

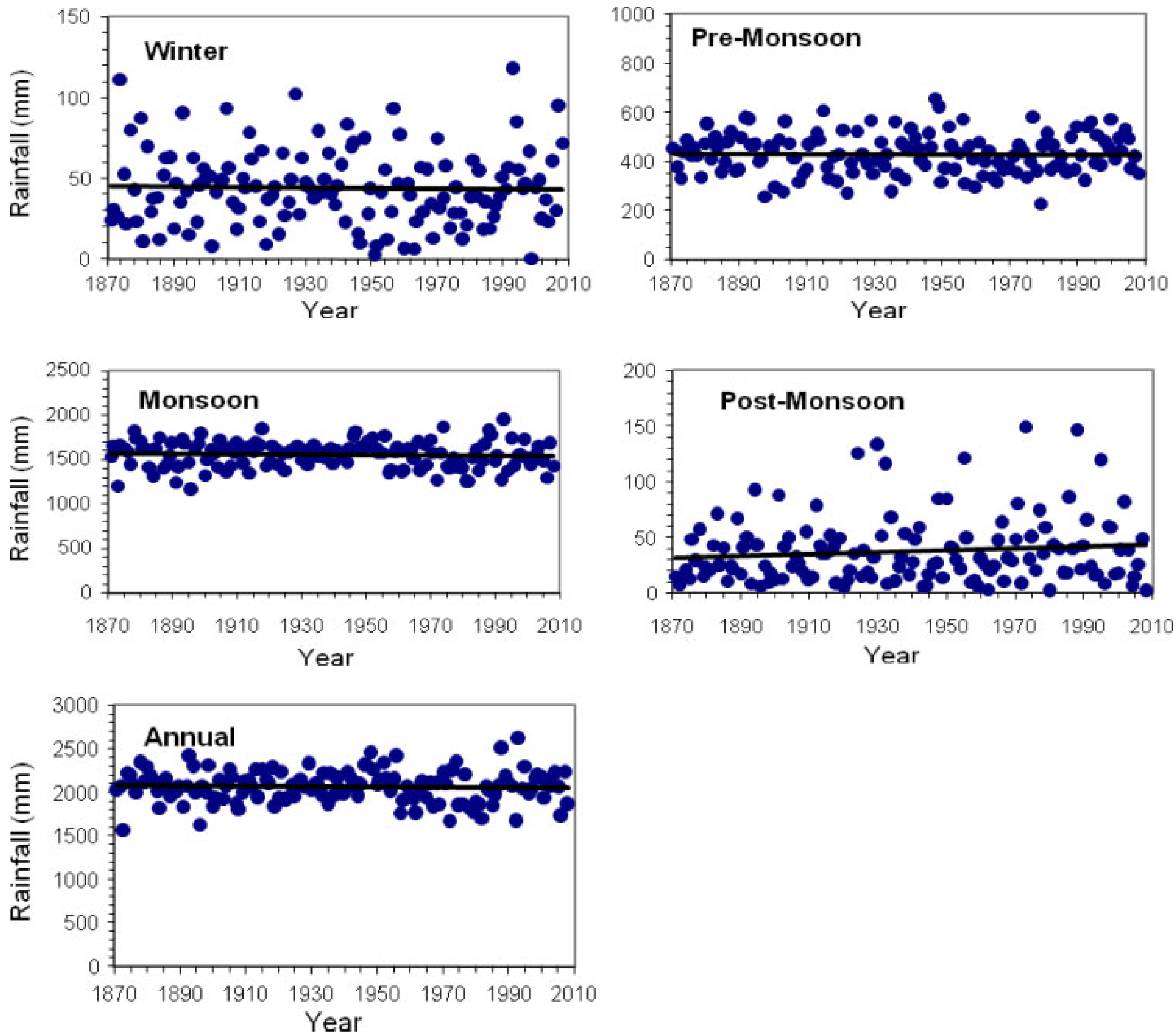

Figure 2. Plots of seasonal and annual rainfall and trend lines for the region for the period 1871–2008. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

For the period 1871–1950, of 16 slope values, only 5 were negative and none of the subdivisions had significant slope, although some of the values had high magnitude. None of the slope values for the whole NER was statistically significant.

Data for the period 1951–2008 showed high slope values for the various subdivisions. Most notable were the statistically significant positive slopes for Gangetic West Bengal. For the whole NER, two seasonal slope values were positive and two were negative. Thus, for the whole NER, seasonal slopes were mostly negative for the period 1871–2008, these were mostly positive for the period 1871–1950, and were both positive and negative for 1951–2008. But none of the slopes for the whole region was statistically significant.

5.1.3. Trend analysis of annual rainfall

For the annual data of various subdivisions, three values were negative and one was positive for the period 1871–2008, three values were positive and one was negative for the period 1871–1950, and there was a balance between negative and positive values for the period 1871–2008. Among these, only one value was statistically significant.

For the entire data series for the whole NER, the value of the Sen's estimator was −0.2, while it was 0.83 for the period 1871–1950 and 0.66 for the period 1951–2008 (Table III). Intuitively, it is difficult to explain as to why a large series shows a declining trend, but a rising trend is seen when it is split into two parts. To explore this behaviour, the statistical properties of the Sen's estimators were examined. In the Sen's method, the slopes of all data points are calculated and their median value is the Sen's estimator of slope. When the statistical properties of the data are determined, it is seen that these data have high skewness and they cannot be considered to be normally distributed. If we compute the mean values of the slopes for the entire series and the two parts of the series, these turn out to be −0.116, 1.38, and −0.241, respectively. These values give an intuitively reasonable estimate because the whole series has a decreasing slope, while the first part has a rising slope and the second a falling slope.

Table III. Sen's estimator of slope (mm/year) for annual and seasonal rainfall.

S. No.	Subdivision/region	Annual	Pre-monsoon	Monsoon	Post-monsoon	Winter
1871–2008						
1	Assam & Meghalaya	−0.66	−0.23	−0.68	0.03	−0.01
2	Nagaland, Manipur, Mizoram, & Tripura	−0.87	0.05	**−0.94**	−0.01	−0.05
3	Sub-Himalayan West Bengal & Sikkim	−0.05	0.07	−0.37	**0.04**	−0.01
4	Gangetic West Bengal	0.97	0.08	**1.01**	0.02	0.03
Northeast India		−0.20	−0.03	−0.39	0.05	−0.01
1871–1950						
1	Assam & Meghalaya	1.47	0.37	0.83	0.03	0.04
2	Nagaland, Manipur, Mizoram, & Tripura	−1.08	−0.21	−0.84	−0.03	0.01
3	Sub-Himalayan West Bengal & Sikkim	1.30	0.65	0.60	0.03	0.04
4	Gangetic West Bengal	1.15	−0.11	1.16	0.00	0.12
Northeast India		0.83	0.15	0.35	0.09	0.07
1951–2008						
1	Assam & Meghalaya	−3.01	−0.72	−2.92	−0.08	**0.46**
2	Nagaland, Manipur, Mizoram, & Tripura	−0.32	1.85	−3.03	0.23	0.21
3	Sub-Himalayan West Bengal & Sikkim	2.96	0.77	1.93	0.10	0.18
4	Gangetic West Bengal	**7.54**	**2.00**	**4.62**	0.06	0.36
Northeast India		0.66	1.02	−0.93	−0.04	0.37

Bold values indicate statistical significance at 95% confidence level as per the Mann–Kendall test (+ for increasing and − for decreasing).

Figure 3 shows the Box and Whisker plots of Sen's slopes of the seasonal and annual rainfall time series. The lower and upper ends of the box denotes the 25 and 75 percentile values, the line inside the box represents the median, and the whiskers show the minimum and the maximum values. For all the data series, the median line is close to zero, implying that there is no clear trend in the data. For all the five series in the figure, the distance between the median to minimum is less than the distance between the median to maximum. Thus, the variability of the Sen's slopes till the median is more at all timescales.

Overall, no clear pattern of the values of the Sen's estimator for rainfall for the NER of India has emerged, either spatially or temporally, and thus, one can conclude that the rainfall series for this region for the period 1871–2008 does not have any significant trend.

5.2. Trend analysis of temperature data

Figure 4 shows the plots of seasonal and annual maximum temperature as well as trend lines for the region for the period 1901–2003. Among the seasons, the post-monsoon season has the least scatter of the data, while the winter season shows the most scatter.

Analysis of monthly maximum temperature for the period 1901–2003 shows rising trend for all the months and the trend is statistically significant for 10 months as seen from Table IV. At the time, the minimum temperature data had mostly increasing trend; three months had increasing trend, which was significant and two months had decreasing significant trend. For all the months, the mean temperature had a rising trend, which was statistically significant for five months. Temperature range data also had rising trend for all the months, and it was statistically significant for all but one month, which implies that the range of temperatures is increasing.

As in the case of rainfall data series, the temperature data were also split in two parts to ascertain the temporal trends. For the period 1901–1950, all the temperature variables, maximum temperature, minimum temperature, mean temperature, and temperature range, had rising trend (except one value). All the trend values for the month of December were significant. For the period 1951–2003, the temperature variables had a mixture of rising and falling trends, but the maximum temperature had statistically significant positive slope for four months.

When we look at the trend of seasonal temperature data (Table V), all the values have shown rising trend and all the seasonal trends in maximum temperature and mean temperature are statistically significant. Similarly, the data for 1901–1950 are dominated by rising trend for all the seasons, whereas a mixture of rising and falling trends is seen for the data of 1951–2003.

Trend analysis of annual data showed that all the four temperature variables had rising trend for the data pertaining to 1901–2003 and 1901–1950, while the data for 1951–2006 had either the falling trend or no trend. For all the scenarios, the post-monsoon season had many statistically significant values.

Figure 5 shows the Box and Whisker plot of slopes of maximum temperature series. Here also, the mean lies close to zero, showing no large trend in the data at annual and seasonal levels. For all the five series in the figure, the distance between the median to minimum is nearly the same as the distance between the median to maximum. Thus, the variability of the Sen's slopes is nearly uniformly distributed at all timescales. Note that the range of variability of Sen's slopes is more for the winter season than for any other season or the annual maximum temperature series.

The findings of this article are supported by the results of a few recently published studies on trends in pan

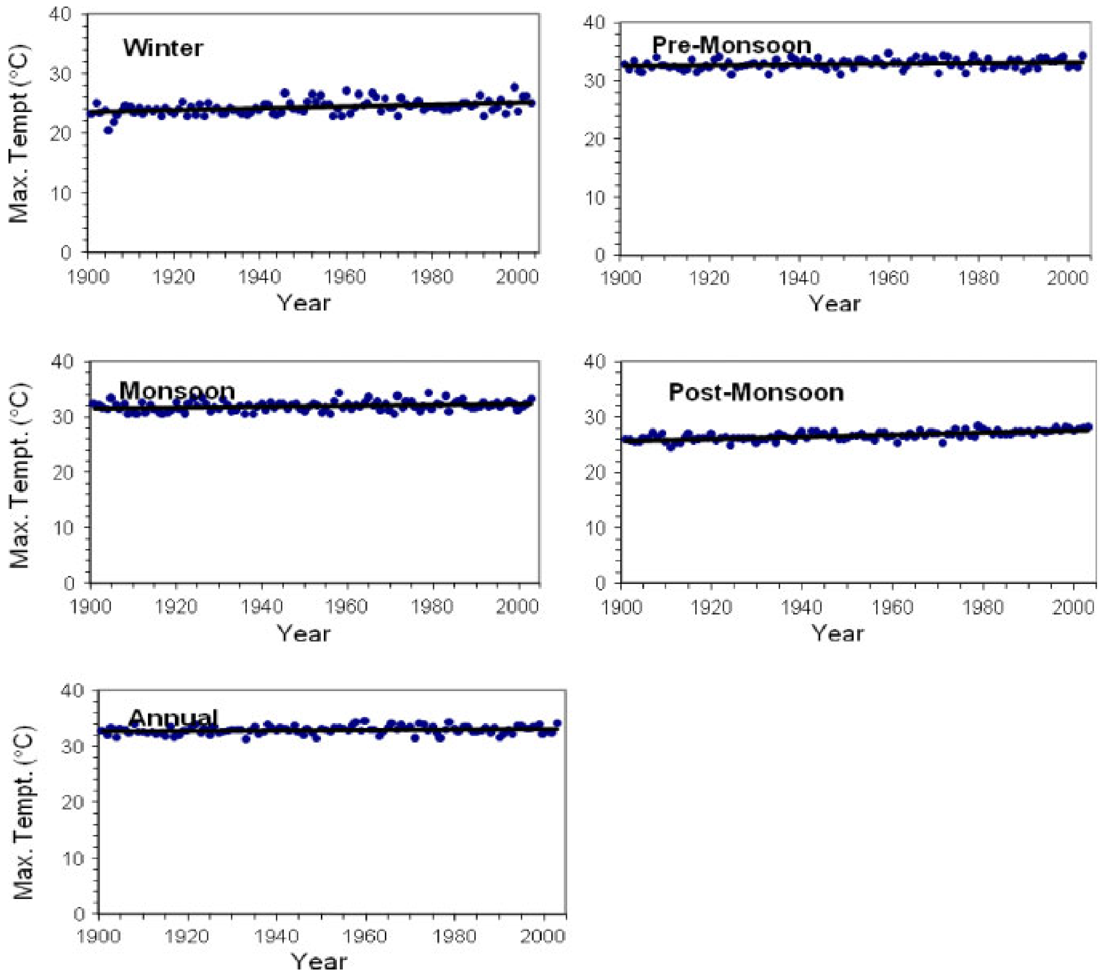

Figure 3. Plots of seasonal and annual maximum temperature for the region for the period 1901–2002; trend lines for the data have also been drawn. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

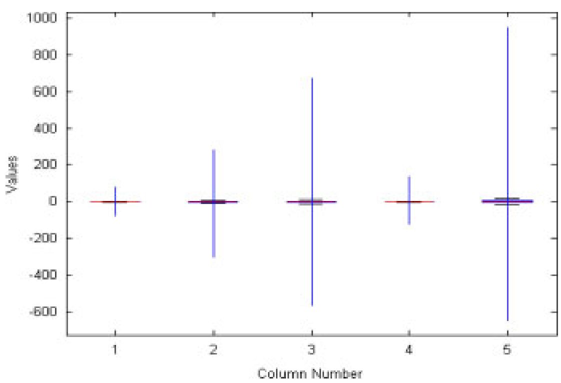

Figure 4. Box–Whisker plot of Sen's slopes of seasonal and annual rainfalls. Columns 1–5 refer to winter, pre-monsoon, monsoon, post-monsoon, and annual, respectively. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

evaporation/reference evapotranspiration (ET_0)/sunshine duration/temperature from some sites of NE India as reviewed earlier.

On the basis of the above, one can state that the maximum and average temperatures in the region are showing a rising trend and the increase is notably significant in statistical terms for the post-monsoon season (November and December). This behaviour of the data indicates the presence of an element of seasonal cycle in the temperature trends over NE India.

6. Summary and conclusions

Climate change is likely to affect all facets of life. Decreasing rainfall, as expected, will result in decreased water availability (Gosain *et al*., 2006). For India, the affects on agriculture will be crucial. On the basis of the experimentation at New Delhi, Aggarwal (2007) has reported that a 1 °C rise in temperature throughout the growing period will reduce the wheat production by 5 million tons. Kalra *et al*. (2008) found that the yield of wheat, mustard, barley, and chickpea show sign of stagnation or decrease following a rise in temperature in four northern states of India. Of course, the extent of decrease was different for crops as well as their locations. Bandyopadhyay *et al*. (2009) found a significant decreasing trend in grass reference evapotranspiration all over India during 1971–2002; Jhajharia *et al*. (2011) also reported decreasing trends in reference ET over NE India.

An understanding of the spatial and temporal distribution and changing patterns in rainfall and temperature is

Table IV. Sen's estimator of slope (°C/year) for monthly temperature for northeast India.

S. No.	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1901–2003													
1	Max. temperature	**0.005**	**0.015**	0.006	**0.010**	0.005	**0.007**	**0.005**	**0.011**	**0.006**	**0.013**	**0.019**	**0.017**
2	Min. temperature	0.000	**0.007**	0.002	0.000	0.000	−0.002	**-0.003**	0.000	**-0.006**	0.000	**0.010**	**0.011**
3	Mean temperature	0.002	**0.011**	0.004	0.005	0.002	0.003	0.001	**0.005**	0.000	**0.007**	**0.015**	**0.014**
4	Temperature range	**0.007**	**0.007**	0.005	**0.009**	**0.005**	**0.010**	**0.007**	**0.011**	**0.013**	**0.011**	**0.007**	**0.007**
1901–1950													
1	Max. temperature	**0.019**	0.011	0.015	0.018	0.007	0.005	0.000	**0.008**	0.005	0.002	**0.017**	**0.029**
2	Min. temperature	0.007	0.005	0.014	0.008	**0.011**	**0.008**	0.000	0.000	0.004	0.004	0.000	**0.019**
3	Mean temperature	0.013	0.008	0.013	0.011	0.007	0.006	0.000	0.005	**0.005**	0.003	0.010	**0.022**
4	Temperature range	0.011	0.006	0.003	0.007	−0.005	0.000	0.000	**0.007**	0.003	0.000	**0.021**	**0.013**
1951–2003													
1	Max. temperature	−0.002	0.000	−0.011	−0.005	−0.008	0.006	0.010	**0.011**	0.003	**0.014**	**0.029**	**0.014**
2	Min. temperature	−0.005	0.006	−0.004	−0.009	−0.009	−0.005	0.000	0.000	−0.008	0.000	**0.024**	0.009
3	Mean temperature	−0.006	0.002	−0.008	−0.008	−0.010	0.000	0.006	0.007	−0.003	0.008	**0.027**	0.011
4	Temperature range	0.000	−0.009	−0.003	0.000	0.002	0.008	0.008	**0.010**	**0.012**	**0.018**	0.000	0.009

Bold values indicate statistical significance at 95% confidence level as per the Mann–Kendall test (+ for increasing and − for decreasing).

Table V. Sen's estimator of slope (°C/year) for annual and seasonal temperatures.

S. No.	Variable	Annual	Pre-monsoon	Monsoon	Post-monsoon	Winter
1901–2003						
1	Max. temperature	**0.005**	**0.007**	**0.007**	**0.019**	**0.015**
2	Min. temperature	0.000	0.002	0.000	**0.011**	0.000
3	Mean temperature	0.003	**0.004**	**0.005**	**0.015**	**0.007**
4	Temperature range	0.004	0.003	0.006	**0.008**	**0.015**
1901–1950						
1	Max. temperature	0.005	0.011	0.004	**0.017**	0.008
2	Min. temperature	0.005	0.014	0.004	**0.019**	0.007
3	Mean temperature	0.007	0.011	0.006	**0.017**	0.008
4	Temperature range	0.000	−0.004	0.000	0.000	0.011
1951–2003						
1	Max. temperature	−0.006	−0.004	0.006	**0.029**	0.000
2	Min. temperature	0.000	−0.004	0.000	0.009	−0.005
3	Mean temperature	−0.004	−0.006	0.002	**0.018**	−0.006
4	Temperature range	0.000	0.005	0.009	0.020	−0.005

Bold values indicate statistical significance at 95% confidence level as per the Mann–Kendall test (+ for increasing and − for decreasing).

a basic and important requirement for the planning and management of water resources. This study has examined trends in monthly, seasonal, and annual rainfall and temperature on the subdivision and regional scale for the NER. Although there was large variability in magnitude and direction of trend of rainfall data from one meteorological subdivision to another, overall, no clear pattern has emerged, either spatially or temporally. Trend analysis of temperature data showed that all the four temperature variables (maximum, minimum, and mean temperatures and temperature range) had rising trend.

Despite numerous international negotiations, emission of green house gases is continuously rising and land use–land cover changes are showing no signs of stabilizing. Hence, the future trends and variabilities may be much larger than what has been observed so far and the rise in temperature may be more pronounced. While

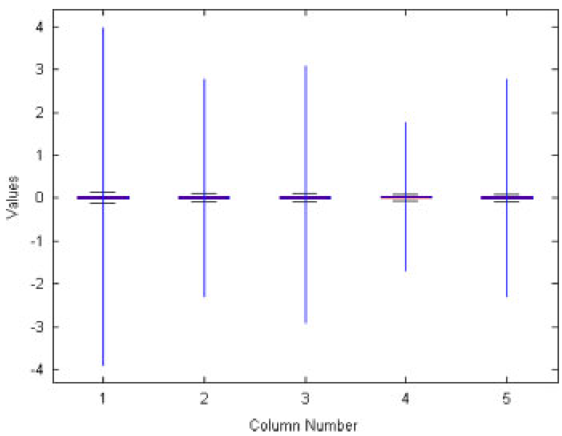

Figure 5. Box–Whisker plot of Sen's slopes of seasonal and annual maximum temperature. Columns 1–5 refer to winter, pre-monsoon, monsoon, post-monsoon, and annual, respectively. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

interpreting the results of trend analysis, it will be worthwhile to keep in mind the observations of Cohn and Lins (2005): 'that reported trends are real yet insignificant indicates a worrisome possibility: natural climatic excursions may be much larger than we imagine. So large, perhaps, that they render insignificant the changes, human-induced or otherwise, observed during the past century'.

References

Aggarwal PK. 2007. Climate change: implications for Indian agriculture. *Hydrology Review*, **22**: 37–46.

Arora M, Goel NK, Singh P. 2005. Evaluation of temperature trends over India. *Hydrological Sciences Journal* **50**(1): 81–93.

Bayazit M, Onoz B. 2007. To prewhiten or not to prewhiten in trend analysis? *Hydrological Sciences Journal* **52**: 611–624.

Bandyopadhyay A, Bhadra A, Raghuwanshi NS, Singh R. 2009. Temporal trends in estimates of reference evapotranspiration over India. *Journal of Hydrologic Engineering (ASCE)*, **14**: 508–515.

Burn DH, Cunderlik JM, Pietroniro A. 2004. Hydrological trends and variability in the Liard river basin. *Hydrological Sciences Journal* **49**: 53–67.

Chaudhary A, Abhyankar VP. 1979. Does precipitation pattern foretell Gujarat climate becoming arid. *Mausam* **30**: 85–90.

Cohn TA, Lins HF. 2005. Nature's style: naturally trendy. *Geophysical Research Letters*, **32**: L23402, DOI: 10.1029/2005GL024476.

Dash SK, Jenamani RK, Kalsi SR, Panda SK. 2007. Some evidence of climate change in twentieth-century India. *Climatic Change* **85**: 299–321.

Dore MHI. 2005. Climate change and changes in global precipitation patterns: what do we know? *Environmental International* **31**: 1167–1181.

Douglas EM, Vogel RM, Knoll CN. 2000. Trends in flood and low flows in the United States: impact of spatial correlation. *Journal of Hydrology* **240**: 90–105.

Gosain AK, Rao S, Basuray D. 2006. Climate change impact assessment on hydrology of Indian river basins. *Current Science* **90**: 346–353.

Goswami BN, Venugopal V, Sengupta D, Madhusoodanam MS, Xavier PK. 2006. Increasing trends of extreme rain events over India in a warming environment. *Science* **314**: 1442–1445.

Helsel DR, Hirsch RM. 1992. *Statistical Methods in Water Resources*. Elsevier: New York.

Hirsch RM, Helsel DR, Cohn TA, Gilroy EJ. 1993. Statistical treatment of hydrologic data. In *Handbook of Hydrology*, Maidment DR (ed). McGraw-Hill: New York, 17.1–17.52.

IPCC. 2007. Summary for policymakers. In *Climate Change 2007: The Physical Science Basis*, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Intergovernmental Panel on Climate Change, Cambridge University Press: UK.

Jagannathan P, Parthasarathy B. 1973. Trends and periodicities of rainfall over India. *Monthly Weather Review* **101**: 371–375.

Jhajharia D, Dinpashoh Y, Kahya E, Singh VP, Fakheri-Fard A. 2011. Trends in reference evapotranspiration in the humid region of northeast India. *Hydrological Processes*. DOI: 10.1002/hyp.8140.

Jhajharia D, Shrivastava SK, Sarkar D, Sarkar S. 2009. Temporal characteristics of pan evaporation trends under the humid conditions of northeast India. *Agricultural Forest Meteorology* **149**: 763–770.

Jhajharia D, Singh VP. 2010. Trends in temperature, diurnal temperature range and sunshine duration in northeast India. *International Journal of Climatology*. DOI: 10.1002/joc.2164.

Kalra N, Chakraborty D, Sharma A, Rai HK, Jolly M, Chander S, Kumar PR, Bhadraray S, Barman D, Mittal RB, Lal M, Sehgal M. 2008. Effect of increasing temperature on yield of some winter crops in northwest India. *Current Science* **94**(1): 82–88.

Kendall MG. 1975. *Rank Correlation Methods*. Charles Griffin: London, UK.

Khan TMA, Singh OP, Sazedur Rahman MD. 2000. Recent sea level and sea surface temperature trends along the Bangladesh coast in relation to the frequency of intense cyclones. *Marine Geodesy* **23**: 103–116.

Koteswaram P, Alvi SMA. 1969. Secular trends and periodicities in rainfall at west coast stations in India. *Current Science* **38**: 229–231.

Kothawale DR, Rupa Kumar K. 2005. On the recent changes in surface temperature trends over India. *Geophysical Research Letters* **32**: L18714, DOI: 10.1029/2005GL023528.

Kumar V, Jain SK. 2010. Trends in seasonal and annual rainfall and rainy days in Kashmir valley in the last century. *Quaternary International* **212**: 64–69.

Kumar V, Jain SK. 2011. Trends in rainfall amount and number of rainy days in river basins of India (1951–2004). *Hydrology Research* **42**(4): 290–306, DOI: 10.2166/nh.2011.067.

Kumar V, Jain SK, Singh Y. 2010. Analysis of long-term rainfall trends in India. *Hydrological Sciences Journal* **55**(4): 484–496.

Kumar V, Singh P, Jain SK. 2005. Rainfall trends over Himachal Pradesh, Western Himalaya, India. In: *Development of Hydro Power Projects – A Prospective Challenge.* Conference, Shimla, 20–22 April, 2005.

Lal M. 2001. Climatic change – implications for India's water resources. *Journal of Indian Water Resource Society* **21**: 101–119.

Lal M. 2003. Global climate change: India's monsoon and its variability. *Journal of Environmental Studies & Policy* **6**: 1–34.

Lettenmaier DP, Wood EF, Wallis JR. 1994. Hydro-climato-logical trends in the continental United States, 1948–88. *Journal of Climate* **7**: 586–607.

Mann HB. 1945. Nonparametric tests against trend. *Econometrica* **13**: 245–259.

Min SK, Kwon WT, Park EH, Choi Y. 2003. Spatial and temporal comparisons of droughts over Korea with East Asia. *International Journal of Climatology* **23**: 223–233.

Mirza MQ. 2002. Global warming and changes in the probability of occurrence of floods in Bangladesh and implications. *Global Environmental Change* **12**: 127–138.

Mooley DA, Parthasarthy B. 1984. Fluctuations of all India summer monsoon rainfall during 1871–1978. *Climatic Change* **6**: 287–301.

Pant GB, Kumar KR. 1997. *Climates of South Asia*. Wiley: Chichester, UK.

Partal T, Kahya E. 2006. Trend analysis in Turkish precipitation data. *Hydrological Processes* **20**: 2011–2026.

Parthasarathy B, Munot AA, Kothawale DR. 1995. Monthly and seasonal rainfall series for all-India homogenous regions and meteorological subdivisions of India for period 1871 – 1984. Research Report No. RR-065, Indian Institute of Tropical Meteorology, Pune.

Parthasarathy B, Sontakke NA, Munot AA, Kothawale DR. 1987. Droughts/floods in the summer monsoon season over different meteorological subdivisions of India for period 1871–1984. *Journal of Climatology* **7**: 57–70.

Procter J, Haridasan K, Smith GW. 1998. How far does lowland tropical rainforests go? *Global Ecology and Biogeography Letters* **7**: 141–146.

Raghavendra VK. 1974. Trends and periodicities of rainfall in subdivisions of Maharashtra state. *Indian Journal of Meteorology and Geophysics* **25**: 197–210.

Rao YP. 1981. The climate of the Indian subcontinent. In: *World Survey of Climatology*, vol. 9, Takahasi K, Arakawa H (eds). Elsevier: Amsterdam, 67–182.

Rupa Kumar K, Krishna Kumar K, Pant GB. 1994. Diurnal asymmetry of surface temperature trends over India. *Geophysical Research Letters* **21**(8): 677–680.

Salas JD. 1993. Analysis and modeling of hydrologic time series. In *Handbook of Hydrology*, Maidment DR (ed). McGraw-Hill: New York, 19.1–19.72.

Shrestha AB, Wake CP, Dibb JE, Mayewski PA. 2000. Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters. *International Journal of Climatology* **20**: 317–327.

Sen PK. 1968. Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association* **63**: 1379–1389.

Singh P, Kumar V, Thomas T, Arora M. 2008a. Changes in rainfall and relative humidity in different river basins in the northwest and central India. *Hydrological Processes* **22**: 2982–2992.

Singh P, Kumar V, Thomas T, Arora M. 2008b. Basin-wise assessment of temperature variability and trends in the northwest and central India. *Hydrological Sciences Journal* **53**: 421–433.

Srivastava HN, Dewan BN, Dikshit SK, Rao PGS, Singh SS, Rao KR. 1992. Decadal trends in climate over India. *Mausam* **43**: 7–20.

Thapliyal V, Kulshrestha SM. 1991. Decadal changes and trends over India. *Mausam* **42**: 333–338.

Vinnikov K, Graisman PY, Lugina KM. 1990. Empirical data on contemporary global climatic changes (temperature and precipitation). *Journal of Climate* **3**: 662–677.

Winstanley D. 1973. Recent rainfall trends in Africa, the Middle East and India. *Nature* **243**: 464–465.

Yue S, Hashino M. 2003. Temperature trends in Japan: 1900–1990. *Theoretical and Applied Climatology* **75**: 15–27.

Yue S, Pilon P, Phinney B. 2003. Canadian streamflow trend detection: impacts of serial and cross-correlation. *Hydrological Sciences Journal* **48**: 51–63.

