

Spatio-temporal analysis of climatic variables in the western part of Bangladesh

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Abstract Monitoring and detecting trends of climatic variables like rainfall and temperature are essential for agricultural developments in the context of climate change. The present study has detected trends in annual and cropping seasonal rainfall and temperature data for the period of 1961–2011 using Mann–Kendall (MK) test, Spearman’s rho (SR) test and modified Mann–Kendall test that has been applied to the significant lag-1 serial correlated time series data, and slope has been estimated using Sen’s Slope estimator for twelve meteorological stations located in the western part of Bangladesh covering about 41 % of the country. Almost 71 % trends explored by MK test in annual rainfall are

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statistically insignificant, and SR test also complies it. The spatial distribution of rainfall trend shows insignificant positive trends in major part of the area. Significant positive trends both by MK test and by SR test at 95 % confidence levels are observed at rates of 8.56, 11.15 and 13.66 mm/year at Dinajpur, Rangpur and Khepupara stations, respectively, and the *Kharif* season rainfall of these stations also shows significant increasing trends except Dinajpur. On the other hand, significant decreasing trends in annual rainfall are found at Bhola (−11.67 mm/year) and Rajshahi (−5.951 mm/year) stations and decreasing trends in rainfall dominated the *Pre-Kharif* season over the area. But, 83.33 % of the stations show rising trends in annual mean temperature with significant positive trends (as observed by both MK test and SR test) at Rangpur, Bogra, Faridpur, Jessore and Bhola stations where the rate of changes vary from 0.013 °C/year at Faridpur to 0.08 °C/year at Bhola. Most of the trends in *Rabi* and *Pre-Kharif* seasons of mean temperatures are not statistically significant. However, all stations except Barisal show significant rising trends in temperature in *Kharif* season. To cope with this changing pattern of rainfall and temperature, effective adaptation strategies should be taken to keep up the agricultural production that is related to livelihood of the most people and to ensure the country's food security.

Keywords Climate variability and trend · Cropping seasons · Mann–Kendall test · Modified Mann–Kendall test · Spearman's rho test · Western part of Bangladesh

1 Introduction

Climate change is a global phenomenon, but its impact is comparatively higher in developing countries due to the lack of adequate resources to adapt with the changing environment. Many researchers found warming trends in surface temperature over the world, but the magnitude of changes is not uniform (e.g., Jones and Moberg 2003; Solomon et al. 2007a, b; Kerr 2009; Lorentzen 2014). Recently, the Intergovernmental Panel on Climate Change (IPCC 2014) report has also mentioned that significant trends in temperature and precipitation exist around the world. In Gyau-Boakye and Tumbulto (2000) found decline in rainfall that results in the lowering of the stream flow in Volta River Basin in Ghana. A recent study by Touch et al. (2016) found that changes in rainfall pattern and consequent drought cause reduction in crop production in northwest Cambodia. Study indicates that investigating trends in climatic parameters like rainfall is essential for a region whose economy and food security rely on water availability (Gajbhiya et al. 2016) such as India and Bangladesh. IPCC (2007) stated that Bangladesh is the showcase of climate change. Geographical settings with high spatial and temporal climatic variability, extreme weather events, high population density, high incidence of poverty and social inequity, poor institutional capacity, inadequate financial resources and poor infrastructure of the country have made it vulnerable to disaster (Ahmed 2004).

Some studies on rainfall variability and trends in Bangladesh have been conducted, and their results showed that rainfall as well as temperature of the country subjected to climate change. Shahid and Khairulmaini (2009) studied on spatial and temporal variability of rainfall in Bangladesh for the period 1969–2003 using Mann–Kendall (MK) test and Sen's Slope estimator and revealed the general insignificant positive trends in annual, monsoon and pre-monsoon rainfall with a negative trend in winter over the country. Ahasan et al.

(2010) also studied rainfall variability and trend by linear regression and found both positive and negative trends in annual and seasonal rainfall over Bangladesh. Rahman and Begum (2013) applied MK test for trend detection in rainfall of Bhola for the period 1966–2011 and found insignificant trends in the area from January to December. Kamruzzaman et al. (2015) studied adapting cropping pattern of NW Bangladesh and found a decreasing trend in annual and seasonal rainfall for the period 1971–2011 in some parts of NW Bangladesh. Jahan et al. (2015) and Rahman et al. (2016a, b) also found decreasing trends in rainfall at Rajshahi in NW Bangladesh. Hence, the changing pattern of rainfall and temperature at local scale is necessary to know for better understanding of the future state because local and regional climatic variations do not match with global scale and the assessment of climate variability and change on a smaller scale are key issues (Rahman and Lateh 2015). It will be helpful for proper planning and practices in agriculture, environment and water sectors.

But, studies on the rainfall and temperature trend analysis over Bangladesh have not considered cropping seasonal impacts, although the economy of Bangladesh is mainly dependent on this sector that contributes about 20.24 % to the total gross domestic product (GDP) and accommodates around 48.1 % of labor force (BBS 2012). In Bangladesh, agricultural crop is highly influenced by climatic variables like rainfall and temperature. The main cereal crop of Bangladesh is rice, *Aman* (paddy) and *Aus* (paddy) production depends on rainfall during these cropping seasons, and winter vegetables production also depends on cool temperature of this season. Agriculture sector is vulnerable to unfavorable extreme weather events and climatic conditions. In spite of advances in improved crop varieties and irrigation systems, weather and climate play vital role in agricultural productivity. In Bangladesh, climate change could have profound effect in agricultural sector as it is developing country in South Asia (BARC 1991). Therefore, the aim of this study is to detect the trends in annual and cropping seasonal rainfall and temperature and their spatial distribution in the western part of Bangladesh.

2 Study area

The study area, the western part of Bangladesh, extends in between 21°36' and 26°38' north latitudes and in between 88°19' and 91°01' east longitudes. The study area covers approximately 60,165 km² that is almost 41 % of Bangladesh. The total population live in the area about 61.5 million with a density 931/km². The location map of the study area along with location of meteorological stations is shown in Fig. 1. Bangladesh has a humid, warm and tropical climate which is influenced primarily by monsoon and partly by pre-monsoon and post-monsoon circulations. The southwest monsoon originates over the Indian Ocean and carries warm, moist and unstable air. According to Banglapedia (2003), there are three climatic seasons in Bangladesh like winter (November–February): dry and cool; pre-monsoon (March–May): hot summer; and rainy (June–October): rainy and hot. Agricultural calendar of Bangladesh is directly related to climatic seasons with slight deviation. Annual rainfall in Bangladesh varies from 1329 mm in the northwest to 4338 mm in the northeast, and the western part of Bangladesh receives comparatively lower amount of rainfall (Shahid and Khairulmaini 2009). The study area experiences the two extremities as during the summer season some hottest days experience temperatures above 45 °C, but in the winter the temperature falls to 5 °C in some places (Banglapedia 2003). There are three cropping

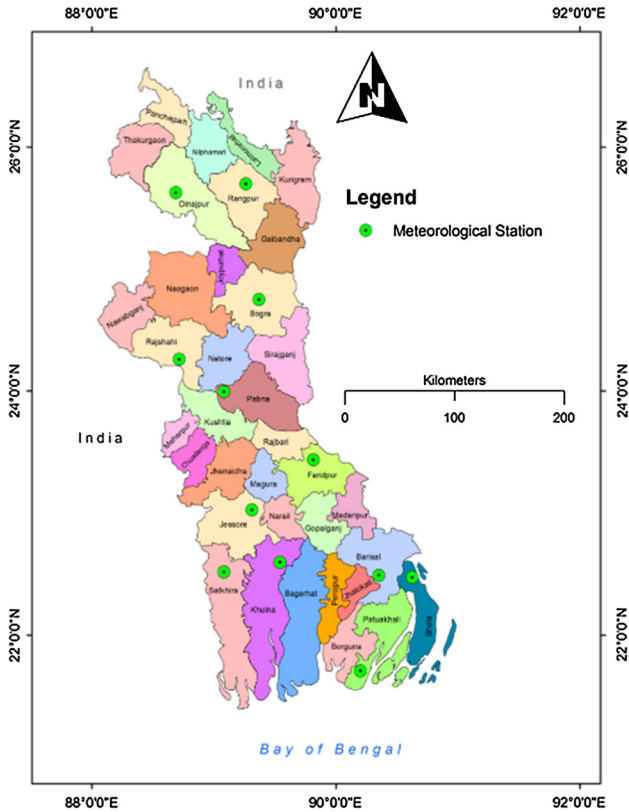


Fig. 1 Study area map with location of meteorological stations

seasons in the country as *Rabi*, *Pre-Kharif* and *Kharif* (Banglapedia 2003). *Rabi* season starts in November and ends in February, and it is the climatically dry season and the main crops during this season are *Boro* (paddy), wheat and a large varieties of winter vegetables like potatoes and cauliflower. *Pre-Kharif* season begins in March and continues up to June, and *Aus* is the main paddy during this season; *Kharif* season starts in July and ends in October. Rain-fed *Aman* rice is main crop. Above 63 % of the people in the area depend on agricultural practices. The study area has been suffering from extreme temperature, flood, drought and cyclone which make it more vulnerable to natural disasters due to the impact of climate change (IPCC 2007).

3 Data collection and sources

Data used in the present study have been collected from Bangladesh Meteorological Department (BMD). Fifty-one year (1960–2011) daily rainfall and temperature data of 12 stations in the western part of Bangladesh have been used for analysis except Bhola (1966–2011) and Khepupara (1975–2011).

3.1 Missing data estimation

The collected data of each station contain several missing values. Studies have relied on a variety of techniques to estimate missing daily temperature data. Missing data estimation methods can be organized into three basic categories: (1) within station; (2) between station; and (3) regression based (Allen and DeGaetano 2001). To estimate the missing daily temperature data up to three days, the study used within-station method, and if the temperature data are missing for one to three days, then we estimated the data for this particular day by average of the data before and after the particular day or average of the days before and after the particular days (Oliver 1973). When more than three-day data are missed, then data from neighboring stations are used performing regression-based approach. When monthly data are missed, then regression-based approach is also performed as this method is applied for both monthly and daily data (Eischeid et al. 1995, cited in Allen and DeGaetano 2001). To fill up the missing rainfall data, multiple imputation method is used for both daily (Recha et al. 2012) and monthly (Ingsrisawang and Potawee 2012) data because it appropriately adjusts the standard error for missing data (Enders 2010).

3.2 Rainfall and temperature trend analysis

In recent years, lot of studies have been conducted around the world for historical trend analysis in climatic parameters like temperature (e.g., El Kenawy et al. 2011; Tabari et al. 2012; Del et al. 2011; Croitoru et al. 2012; Shifteh Some'e et al. 2012) and rainfall (e.g., Kampata et al. 2008; Zhang et al. 2008). In Bangladesh, few previous studies have obtained good results in identifying trends of climatic data such as temperature (Azad et al. 2012) and rainfall (Shahid and Khairulmaini 2009). In the present study, Mann–Kendall (MK) test (Mann 1945; Kendall 1975) and Spearman's rho (SR) test for trend analysis have been used and before applying the MK test lag-1 serial correlation has been checked, and if lag-1 serial correlation is significant at 5 % level, then modified Mann–Kendall (MMK) test applied (Hamed and Rao 1998). *P* values of lag-1 autocorrelation of rainfall and temperature time series are given in Tables 1 and 2, respectively.

3.3 Mann–Kendall (MK) test

For time series with fewer than 10 data points, the *S* test is used; for time series with 10 or more data points, the *Z* test is used.

MK is based on the test statistics *S*, which is given as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (1)$$

$$\text{sgn}(x_j - x_k) = \begin{cases} +1 & \text{if } (x_j - x_k) > 0 \\ 0 & \text{if } (x_j - x_k) = 0 \\ -1 & \text{if } (x_j - x_k) < 0 \end{cases} \quad (2)$$

Here *S* value indicates the direction of trend. A positive value of *S* indicates increasing trend and vice versa. The MK test has documented that when data size is ≥ 10 , the test statistics *S* is approximately normally distributed and variance is as follows:

Table 1 Lag-1 autocorrelation of rainfall time series

Stations	Annual rainfall			Kharif rainfall			Pre-Kharif rainfall			Rabi rainfall		
	AC lag-1	DW statistic	P value	AC lag-1	DW statistic	P value	AC lag-1	DW statistic	P value	AC lag-1	DW statistic	P value
Bhola	-0.21	2.38	0.24	0.00	1.99	0.85	0.09	1.80	0.42	-0.07	2.12	0.78
Bogra	-0.15	2.28	0.35	-0.26	2.52	0.06	0.01	1.95	0.69	0.05	1.86	0.48
Barisal	-0.16	2.14	0.70	-0.16	2.14	0.70	-0.16	2.14	0.70	-0.16	2.14	0.70
Dinajpur	0.02	1.94	0.71	0.04	1.93	0.66	-0.03	2.05	0.95	-0.07	2.11	0.79
Faridpur	-0.12	2.23	0.55	-0.13	2.23	0.42	0.14	1.70	0.19	-0.06	2.11	0.79
Ishwardi	0.05	1.87	0.55	0.03	1.92	0.64	0.16	1.66	0.16	-0.08	2.13	0.81
Jessore	0.01	1.96	0.79	0.19	1.59	0.13	0.01	1.98	0.83	-0.04	2.07	0.92
Khepupara	0.04	1.91	0.63	0.22	1.52	0.10	0.24*	1.45	0.05	-0.09	2.15	0.83
Khulna	-0.16	2.31	0.31	-0.01	2.00	0.91	-0.02	2.03	0.94	0.19	1.62	0.14
Rajshahi	-0.12	2.23	0.47	-0.01	2.02	0.93	-0.05	2.08	0.87	0.28*	1.43	0.03
Rangpur	0.17	1.63	0.12	0.01	1.97	0.84	0.11	1.74	0.27	-0.07	2.13	0.75
Satkhira	-0.24	2.43	0.14	-0.07	2.12	0.77	-0.01	1.97	0.78	0.07	1.86	0.47

* Significant at 5 %

Table 2 Lag-1 autocorrelation of temperature time series

Stations	Annual temperature			Kharif temperature			Pre-Kharif temperature			Rabi temperature		
	AC lag-1	DW statistic	P value	AC lag-1	DW statistic	P value	AC lag-1	DW statistic	P value	AC lag-1	DW statistic	P value
	Bhola	0.19	1.57	0.08	0.14	1.70	0.20	0.01	1.92	0.69	0.11	1.72
Bogra	0.02	1.87	0.57	0.48*	1.00	0.00	0.12	1.72	0.25	-0.10	2.11	0.82
Barisal	0.52*	0.96	0.00	0.34*	1.32	0.01	0.21	1.53	0.07	0.49*	1.02	0.00
Dinajpur	0.35*	1.30	0.01	0.17	1.63	0.11	-0.09	2.18	0.53	0.56*	0.84	0.00
Faridpur	0.06	1.87	0.43	0.01	1.97	0.49	0.03	1.93	0.67	0.34*	1.25	0.00
Ishwardi	0.19	1.53	0.06	0.03	1.93	0.65	0.00	1.98	0.84	0.22*	1.37	0.01
Jessore	0.13	1.71	0.24	0.13	1.73	0.29	-0.06	2.10	0.86	0.16	1.64	0.15
Khepupara	0.10	1.78	0.44	-0.21	2.42	0.22	0.01	1.96	0.77	0.18	1.64	0.20
Khulna	0.28*	1.44	0.02	0.10	1.79	0.33	0.20	1.60	0.10	0.21*	1.58	0.05
Rajshahi	0.55*	0.87	0.00	0.42*	1.16	0.00	0.29*	1.41	0.02	0.47*	1.01	0.00
Rangpur	0.43*	1.12	0.01	0.41*	1.17	0.01	0.47*	1.01	0.00	0.30*	1.36	0.01
Satkhira	0.70*	0.59	0.00	0.45*	1.11	0.00	0.43*	1.11	0.00	0.67*	0.63	0.00

* Significant at 5 %

$$\text{Var}(S) = \frac{[(n(n-1)(2n+5)] - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18} \quad (3)$$

where m is the number of tied groups and t_i is the size of the i th tie group. The test statistic Z is computed as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}}, & \text{for } S > 0 \\ 0, & \text{for } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}}, & \text{for } S < 0 \end{cases} \quad (4)$$

The null hypothesis, H_0 , that there is no trend in the records is either accepted or rejected depending on whether the computed Z statistic is less or more than the critical value of Z statistic. In the present study, significant levels $\alpha = 0.01, 0.05$ and 0.1 corresponding to 99, 95 and 90 % confidence levels, respectively, have been applied.

3.4 Modified Mann–Kendall (MMK) test

In the present study, MMK test has been applied to the temperature time series with significant lag-1 autocorrelation, but it has not been applied to the rainfall time series as almost all rainfall time series exhibit insignificant lag-1 autocorrelation (Table 1).

The MMK test (Hamed and Rao 1998) has been applied to the significant lag-1 autocorrelation time series data. The modified variance of the test statistic S is calculated as (Hamed and Rao 1998):

$$\text{VAR}(S) = \left(\frac{n(n-1)(2n+5)}{18} \right) \cdot \left(\frac{n}{n_e^*} \right) \quad (5)$$

The correction factor $\left(\frac{n}{n_e^*} \right)$ is adjusted to the autocorrelation data and is given as:

$$\frac{n}{n_e^*} = 1 + \left(\frac{2}{n^3 - 3n^2 + 2n} \right) \sum_{f=1}^{n-1} (n-f)(n-f-1)(n-f-2)\rho_e(f) \quad (6)$$

The autocorrelation function between the ranks of the observations is represented by $\rho_e(f)$ and estimated using the inverse of equation (Kendall 1975; Hamed and Rao 1998) as:

$$\rho(f) = 2\sin\left(\frac{\pi}{6}\rho_e(f)\right) \quad (7)$$

3.5 Spearman's rho (SR) test

SR test is also a nonparametric test and can be applied to test the absence of trends (Yue et al. 2002; Tonkaz et al. 2007; Shadmani et al. 2012). The test statistic D and standardized test statistic Z_{SR} are given as:

$$D = 1 - \frac{6 \sum_{i=1}^n [R(X_i) - 1]^2}{n(n^2 - 1)} \quad (8)$$

$$Z_{SR} = D \sqrt{\frac{(n - 2)}{(1 - D^2)}} \tag{9}$$

where R is the rank of i th observation X_i in the time series and n is the sample size. The positive values of Z_{SR} indicate increasing trends and vice versa.

The probability values p for the MK, MMK and SR tests are estimated as:

$$p = 0.5 - \phi(|Z|), \quad (Z = \text{MK, MMK and SR}) \tag{10}$$

$$\left(\phi(|Z|) = \frac{1}{\sqrt{2\pi}} \int_0^{|Z|} e^{-t^2} dt \right) \tag{11}$$

The trend is significant or insignificant depending on the p value.

3.6 Sen’s Slope estimator

In this research, Sen’s Slope (Sen 1968) nonparametric approach is used to estimate the true slope of an existing trend (as change per unit time) where it is assumed to be linear. The estimation of slope of N pairs of data involves the following procedures.

$$Q_i = \frac{x_i - x_k}{j - k} \tag{12}$$

where $j > k$ and x_j and x_k are data values at times j and k , respectively.

The Sen’s Slope estimator is given by the median slope as:

$$Q_{\text{med}} = Q_{[(N+1)/2]} \tag{13}$$

where N is odd, or

$$Q_{\text{med}} = \frac{1}{2} (Q_{(N/2)} + Q_{[(N+2)/2]}) \tag{14}$$

where N is even.

Finally, Q_{med} is estimated by the nonparametric method based on the normal distribution and tested with a $100(1 - \alpha)$ two-sided confidence interval. In the present study, confidence intervals are obtained at different confidence levels. The computing procedures are as follows:

$$C_\alpha = Z_{1-\alpha/2} \sqrt{\text{VAR}(S)} \tag{15}$$

where $\text{VAR}(S)$ is computed by Eq. (3) and $Z_{1-\alpha/2}$ is obtained from the standard normal distribution. Further, $M_1 = (N - C_\alpha)/2$ and $M_2 = (N + C_\alpha)/2$ are calculated. The lower limit (Q_{min}) and upper limit (Q_{max}) of the confidence interval are the M_1^{th} largest and $(M_2 + 1)^{\text{th}}$ largest of the N -ordered slope estimates Q_i . If M_1 is not a whole number, the lower limit is interpolated. Correspondingly, if M_2 is not a whole number, the upper limit is interpolated (Salmi et al. 2002).

Software ‘R’ developed by the ‘R’ Core Development Team has been used for statistical analysis by programming. Spatial distribution maps have been prepared in ArcGIS version 9.3 using ordinary kriging method.

4 Results and discussion

4.1 Exploratory statistics of rainfall and temperature

The long-term average annual rainfall in the study area varies from 1492 to 2766 mm (Fig. 2a) with average value of 1925 mm. The southern part of the study area along the coast of the Bay of Bengal receives the highest amount of rainfall. Rainfall in the southern and northern of the area is much higher than that of the central part. The percentage of annual rainfall received in each season is shown in Fig. 3. The cropping season, *Kharif*, is the wettest season when almost 62 % of rainfall occurs, while *Rabi* is the driest season receiving only 3.23 % of total annual rainfall. The rest 35.20 % of annual rainfall occurs during the Pre-*Kharif* cropping season.

The long-term average annual temperature in the study area ranges from 24.18 to 26.17 °C with an average value of 25.44 °C. From northern part, i.e., close to the Himalayas, toward southern part, i.e., close to the Bay of Bengal, mean annual temperature rises (Fig. 2b). Average annual temperature is the lower in the northeastern part (24.18–24.43 °C). It increases toward the southern part, reaching in the extreme southwestern part along the coast of the Bay of Bengal (25.92–26.17 °C).

4.2 Spatio-temporal analysis of annual rainfall

Both positive and negative trends in annual rainfall time series are found in the study area. The positive slopes indicate increasing trends of annual rainfall, while negative slopes indicate decreasing trends. However, most of them (70.83 %) are statistically

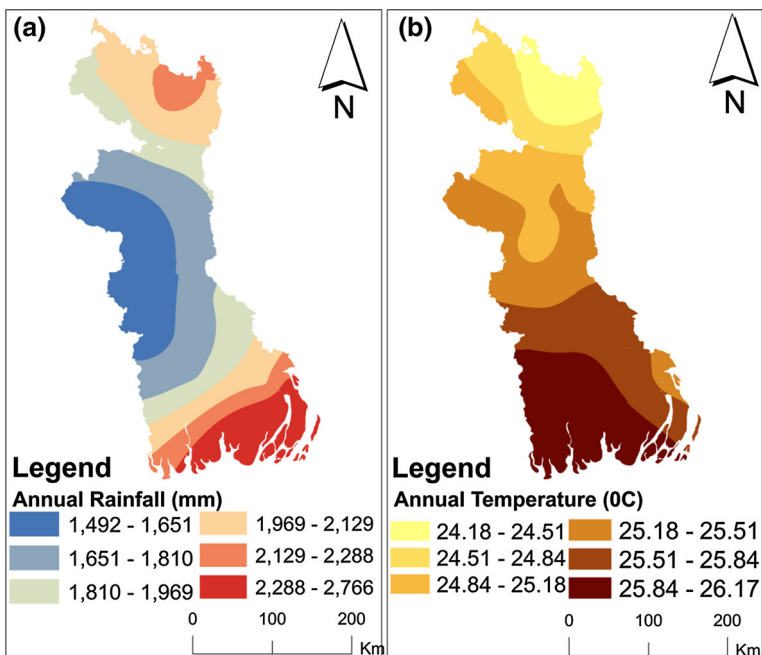
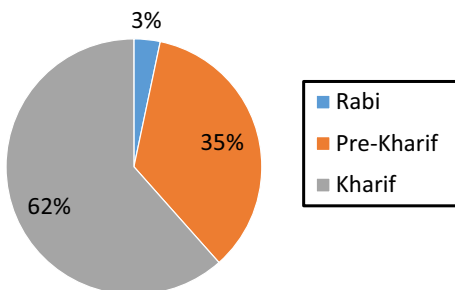


Fig. 2 Spatial distribution of **a** annual rainfall, **b** annual average temperature in the study area

Fig. 3 Percentage of annual rainfall occurs during the cropping seasons



insignificant at 90 and 95 % confidence levels. Increasing and decreasing trends in annual rainfall are observed in 58.3 and 41.67 % of the stations, respectively, with the MK test, and the results obtained from SR test are almost identical with MK test (Table 3) except Rajshahi station rainfall time series that shows insignificant negative trend with MK test but significant with SR test. The strongest significant positive trends at 95 % confidence levels are observed at the rates of 8.56, 11.15 and 13.66 mm/year at Dinajpur, Rangpur and Khepupara stations, respectively. The graphs of time series with linear trends of annual rainfall are presented in Fig. 4. The rainfall data of Khulna station also show an increasing trend at 90 % confidence level where the magnitude of change is 5.19 mm/year. On the other hand, the two significant decreasing trends at 95 and 90 % confidence levels are found at Bhola and Rajshahi stations at rates of -11.667 and -5.951 mm/year, respectively. Spatial distribution of MK test statistic (Z) of annual rainfall time series is shown in Fig. 5a. The significant increasing trend at 95 % confidence level is found in the northern part of the area where Z values range from 1.96 to 2.596. Major part of the area from north to south show insignificant positive trend at 90 and 95 % confidence interval except some parts of Rajshahi and Barisal region where trends are negative and insignificant. Shahid and Khairulmaini (2009); Ahasan et al. (2010) also found both positive and negative trends over the country with general dominating positive insignificant trends. Kamruzzaman et al. (2015) and Rahman et al. (2016a, b) found negative trends in annual rainfall in Rajshahi and Bogra stations for the period 1971–2011. Siddik and Rahman (2014) found both positive and negative trends in annual, seasonal and monthly rainfall in Bangladesh.

4.3 Spatio-temporal analysis of cropping seasonal rainfall

4.3.1 Rabi rainfall

The *Rabi* season rainfall series shows a rising trend (58.33 %) and a falling trend (33.33 %) of the stations. The calculated Z statistic and P value of MK test and SR test indicate that only two stations out of 12 like Khulna and Satkhira show statistically significant trends at 95 and 90 % confidence levels, respectively (Table 3). The magnitudes of changes assessed by Sen's Slope analysis of rainfall data of these two stations are 1.07 and 0.78 mm/year, respectively. Spatial distribution of MK test statistic (Z) of *Rabi* season rainfall time series (Fig. 5b) shows that values of Z statistic over the area vary from -1.194 to 2.3. Major part of the study area shows insignificant rainfall trend dominating except small part located in the southwestern part.

Table 3 P values of rainfall of Mann–Kendall (MK) test, Spearman’s rho (SR) test and Sen’s Slope

Stations	P values of rainfall MK				P values of rainfall of SR				Sen’s Slope						
	Annual		Pre-Kharif		Annual		Pre-Kharif		Annual		Pre-Kharif		Rabi		
	Kharif	Rabi	Kharif	Rabi	Annual	Kharif	Pre-Kharif	Rabi	Annual	Kharif	Pre-Kharif	Rabi	Annual	Kharif	
Bhola	0.07	0.32	0.24	0.31	0.09	0.32	0.40	0.34	-11.67	-3.96	-3.67	-0.83	4.09	1.41	2.23
Bogra	0.29	0.58	0.25	0.48	0.31	0.73	0.22	0.48	-3.15	0.62	-0.97	-0.27	8.60	3.17	4.10
Barisal	0.45	0.76	0.60	0.71	0.46	0.75	0.70	0.74	-1.59	0.00	-1.97	0.25	-1.75	0.24	-2.60
Dinajpur	0.04*	0.17	0.02*	0.37	0.06	0.22	0.02*	0.42	4.74	3.44	1.16	0.17	13.66	12.73	-1.33
Faridpur	0.64	0.99	0.33	0.48	0.67	0.99	0.38	0.53	5.19	6.16	-1.45	1.07	-5.95	-2.06	-1.20
Ishwardi	0.53	0.95	0.16	0.62	0.52	0.84	0.18	0.61	11.15	7.41	3.11	0.07	-1.75	0.24	-2.60
Jessore	0.11	0.26	0.44	0.65	0.08	0.24	0.36	0.74	3.60	2.02	2.28	0.78	4.74	3.44	1.16
Khepupara	0.03*	0.03*	0.88	0.65	0.03*	0.03*	0.95	0.63	13.66	12.73	-1.33	0.02	13.66	12.73	-1.33
Khulna	0.10	0.01*	0.41	0.02*	0.08	0.01*	0.33	0.03*	5.19	6.16	-1.45	1.07	-5.95	-2.06	-1.20
Rajshahi	0.21	0.36	0.44	0.65	0.03*	0.03*	0.95	0.63	11.15	7.41	3.11	0.07	-1.75	0.24	-2.60
Rangpur	0.01*	0.03*	0.09	0.81	0.01*	0.05*	0.07	0.74	3.60	2.02	2.28	0.78	4.74	3.44	1.16
Satkhira	0.23	0.44	0.25	0.06	0.31	0.55	0.32	0.08							

* Significant at 5 %

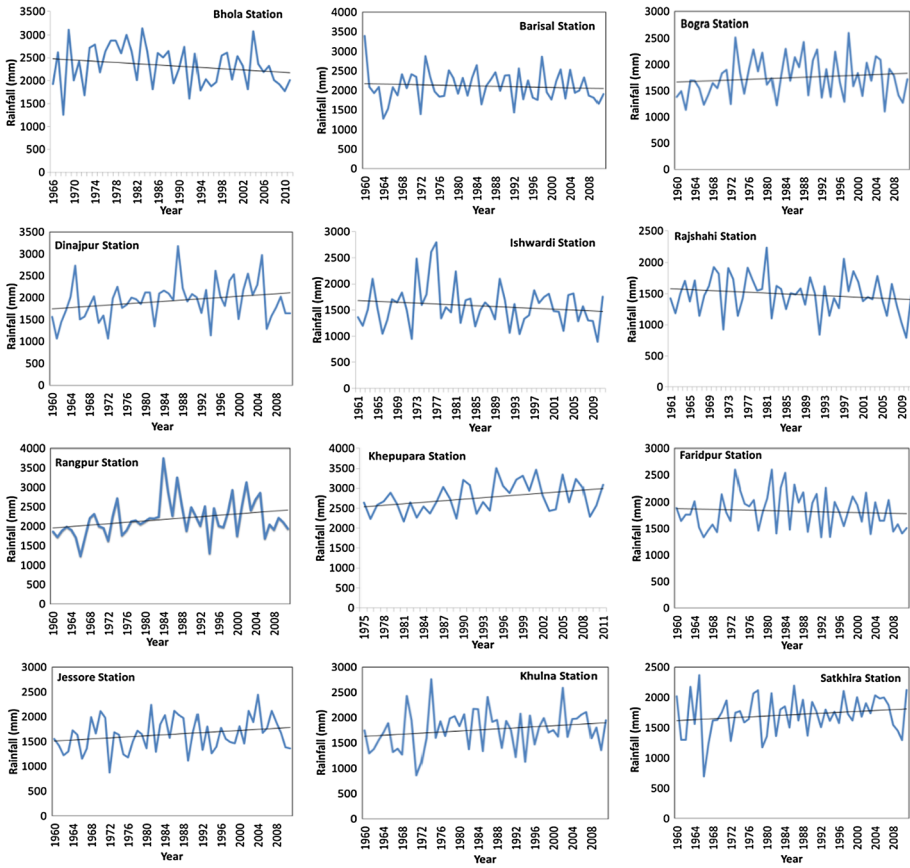


Fig. 4 Linear trends in annual rainfall

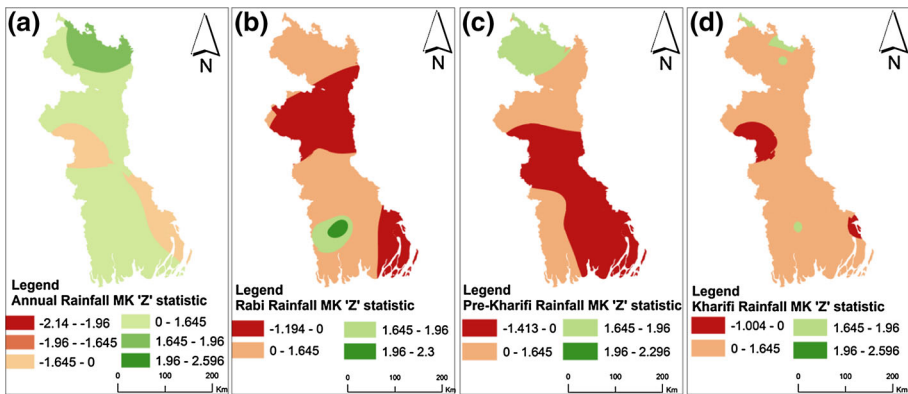


Fig. 5 Spatial distribution of MK 'Z' statistic of a annual, b Rabi, c Pre-Kharif and d Kharif rainfall

4.3.2 Pre-Kharif rainfall

Increasing and decreasing trends in Pre-Kharif rainfall are observed by MK test in 41.67 and 58.33 % of the stations, respectively, but most of them are not statistically significant (83.34 %) at 90 and 95 % confidence levels. The strong significant increasing trends at 95 and 90 % confidence levels in Pre-Kharif season rainfall are observed at the rates of 4.104 and 3.114 mm/year at Dinajpur and Rangpur stations, respectively, both by MK test and by SR test. The MK test statistic (Z) of Pre-Kharif season rainfall varies from -1.413 to 2.296 (Fig. 5c). Amount of rainfall during this season shows significant increasing trend at 90 and 95 % confidence interval in the northern part of the area. Southwestern part and some areas in northern part show insignificant positive trend in rainfall data during this season, whereas the central part and southeastern part of the area show insignificant negative trend.

4.3.3 Kharif rainfall

The Kharif season rainfall series shows a rising trend at 75 % of stations and a falling trend at 25 % of stations. Three stations like Rangpur, Khulna and Khepupara (25 % of stations) by both the tests (MK and SR) show statistically significant trends at 95 % confidence interval, and magnitude of changes assessed by Sen's Slope analysis is 7.407, 6.157 and 12.733 mm/year, respectively. Spatial distribution of the MK test statistic (Z) of Kharif season rainfall data is shown in Fig. 5d. The values of Z statistic over the area vary from -1.004 to 2.596 . The spatial map of Z statistic indicates that rainfall in all over the area except Rajshahi increases (Fig. 5d), but the trend is not significant at 90 and 95 % confidence levels. One pocket in Khulna and some portion of north show significant positive trend at 95 % confidence interval, whereas Rajshahi and some areas in Barisal show insignificant negative trend.

4.4 Spatio-temporal analysis of annual mean temperature

In the study area, 83.33 % of stations show rising and 16.67 % falling trends in annual mean temperature, respectively, with MK test and SR test results also show almost identical results. The strongest significant positive trends in annual mean temperature at 95 % confidence interval are observed at Rangpur, Bogra, Faridpur, Jessore and Bhola stations both by MK and by SR tests (Table 4) at rates of 0.015, 0.007, 0.013, 0.009 and 0.08 °C/year, respectively (Fig. 6). The mean annual temperature time series of five stations (Ishwardi, Rajshahi, Khulna, Satkhira and Barisal) also show rising trends, but the trends are not statistically significant with MK and SR tests. Two out of 12 stations (Dinajpur and Khepupara) temperature time series show falling trends where the trend of Dinajpur station is not significant at 90 or 95 % confidence intervals, but annual temperature of Khepupara station shows significant decreasing trend with both the tests. The rates of changes (°C/year) assessed by Sen's Slope analysis for these stations are -0.005 and -0.014 °C/year, respectively. Spatial distribution of MK test statistic (Z) of annual mean temperature time series (Fig. 7a) shows that the values of Z statistic over the area vary from -3.042 to 3.993 . The spatial map indicates that rising trends of annual mean temperature are significant at 90 and 95 % confidence levels in the northeastern part and rest of the part except small area in south indicate insignificant rising trends. Moreover, insignificant (at 90 and 95 % confidence level) rising trends in mean annual temperature are also found in the northwestern part of the area. Studies conducted to detect the trends in

Table 4 P values of temperature of Mann–Kendall (MK) test, modified Mann–Kendall (MMK) test, Spearman’s rho (SR) test and Sen’s Slope

Stations	P values of temperature MK				P values of temperature MMK				P values of temperature of SR				Sen’s Slope			
	Annual	Kharif	Pre-Kharif	Rabi	Annual	Kharif	Pre-Kharif	Rabi	Annual	Kharif	Pre-Kharif	Rabi	Annual	Kharif	Pre-Kharif	Rabi
Bhola	0.01*	0.00*	0.01*	0.77	NA	NA	NA	NA	0.01*	0.00*	0.02*	0.87	0.008	0.013	0.014	0.002
Bogra	0.01*	0.00*	0.92	0.47	NA	0.00*	NA	NA	0.01*	0.00*	0.95	0.14	0.007	0.016	-0.001	0.010
Barisal	0.48	0.26	0.98	0.15	0.65	0.46	NA	0.47	0.81	0.53	0.81	0.43	0.002	0.004	0.000	-0.002
Dinajpur	0.18	0.01*	0.00*	0.93	0.18	NA	NA	0.95	0.06	0.01*	0.00*	0.91	-0.005	0.009	-0.029	0.004
Faridpur	0.00*	0.00*	0.68	0.00*	NA	NA	NA	0.81	0.00*	0.00*	0.81	0.00*	0.013	0.014	0.004	0.018
Ishwardi	0.25	0.00*	0.93	0.97	NA	NA	NA	NA	0.27	0.00*	0.96	0.95	0.004	0.011	0.001	-0.002
Jessore	0.00*	0.00*	0.28	0.90	NA	NA	NA	NA	0.00*	0.00*	0.31	0.97	0.009	0.015	0.007	0.001
Khepupara	0.00*	0.12	0.88	0.00*	NA	NA	NA	NA	0.00*	0.13	0.90	0.00*	-0.014	0.006	-0.001	-0.043
Khulna	0.16	0.00*	0.66	0.69	0.16	NA	NA	0.70	0.26	0.00*	0.42	0.42	0.005	0.016	-0.003	-0.003
Rajshahi	0.62	0.02*	0.54	0.14	0.73	0.04*	0.62	0.35	0.69	0.01*	0.38	0.26	0.002	0.008	-0.005	-0.013
Rangpur	0.00*	0.00*	0.11	0.01*	0.00*	0.00*	0.19	0.01*	0.00*	0.00*	0.10	0.01*	0.015	0.012	0.012	0.020
Satkhira	0.14	0.01*	0.36	0.81	0.16	0.00*	0.44	0.70	0.13	0.00*	0.33	0.77	0.009	0.011	0.007	0.000

* Significant at 5 %

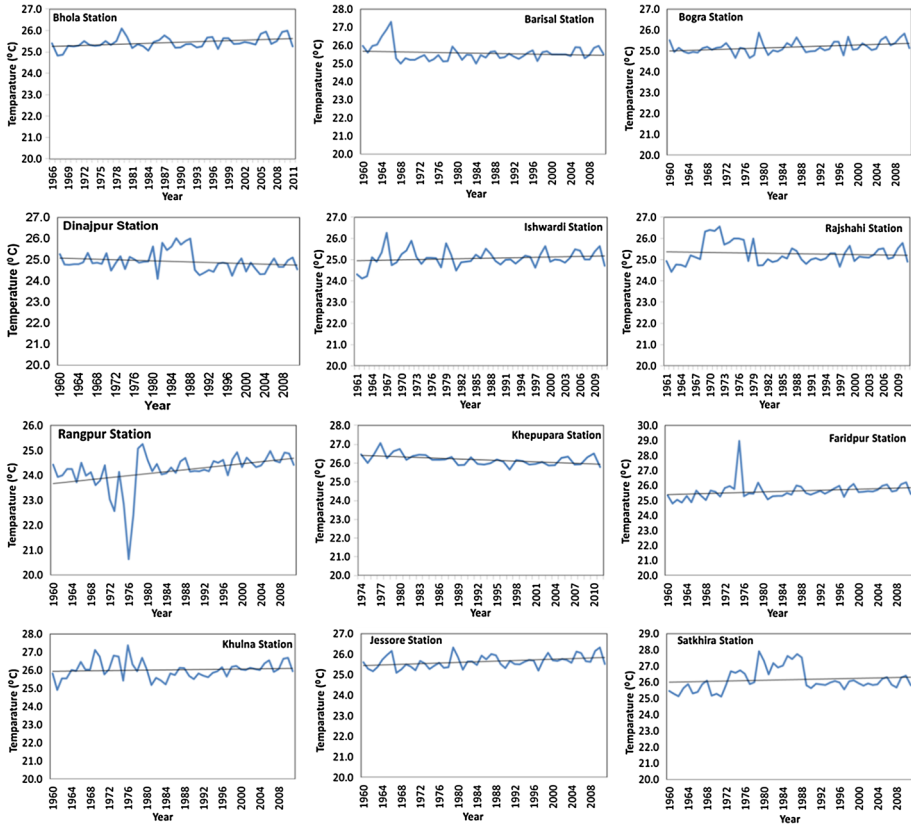


Fig. 6 Linear trends in annual mean temperature

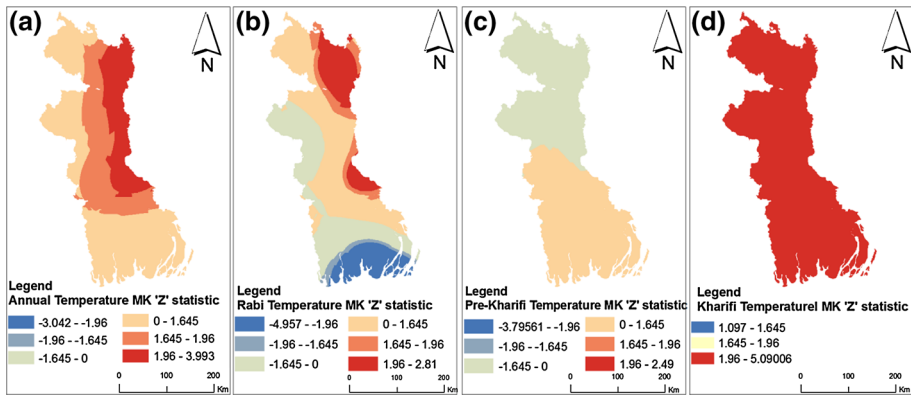


Fig. 7 Spatial distributions of Z statistic of mean temperature for **a** annual, **b** Rabi, **c** Pre-Kharif and **d** Kharif

temperature found more rising trends than that of falling trends, and trends for the recent period (1990–2010) show more warming trends (Hasan and Rahman 2013; Siddik and Rahman 2014; Rahman et al. 2015).

4.5 Seasonal mean temperature analysis

4.5.1 *Rabi* temperature

Increasing and decreasing trends in *Rabi* season mean temperature series are observed by MK test in 75 and 25 % of the stations, respectively, but most of them (about 75 %) are not statistically significant (Table 4). The strongest significant positive trends with nonparametric tests (MK, MMK and SR) at 95 % confidence intervals in mean temperature of *Rabi* season are observed at the rates of 0.020 and 0.018 °C/year at Rangpur and Faridpur stations, respectively. *Rabi* season temperature of Bogra station also shows increasing trend with MK test at 90 % confidence interval at a rate of 0.01 °C/year. The significant decreasing trend with both MK and SR tests at 95 % confidence level is observed at the rate of -0.043 °C/year at Khepupara station. Figure 7b shows the spatial distribution of MK test statistic (Z) of *Rabi* season mean temperature time series. The values of Z statistic of *Rabi* season mean temperature series over the area range from -4.957 to 2.810 (Fig. 7b).

The spatial map of Z statistic reveals that rising trends of *Rabi* season mean temperature are significant at 90 and 95 % confidence levels in the northeastern part of the area. The southern part of the area shows significant negative trend at 90 and 95 % confidence levels. The southwestern part shows the insignificant negative trend. Northwestern to southeastern part of the area shows insignificant positive change. Warming winter temperature is responsible for reduction of wheat, potato and other temperate crops grown during this season (Hasan and Rahman 2013).

4.5.2 *Pre-Kharif* temperature

In the present study area, 58.53 % of stations show rising trend in *Pre-Kharif* (summer season) mean temperature, while 41.67 % of stations show falling trend, but most of them (83.33 %) are not statistically significant at 90 % and 95 % confidence levels. Only two (16.67 %) out of 12 stations show significant trends where Bhola shows positive trend at rate of 0.014 °C/year with significant at 95 % confidence level with MK, MMK and SR tests; on the other hand, Dinajpur shows negative trend at 95 % confidence level with changing at the rate of -0.029 °C/year.

Further, six stations (Rangpur, Ishwardi, Faridpur, Jessore, Satkhira and Barisal) show rising mean temperature trends, but the trends are not statistically significant at 90 % and 95 % confidence levels with MK, MMK and SR tests. The rate of changes (°C/year) assessed by Sen's Slope analysis of all stations range from 0.0001 at Barisal station to 0.012 at Rangpur station. However, four stations (Bogra, Rajshahi, Khulna and Khepupara) show insignificant negative trends. Figure 7c shows the spatial distribution of MK test statistic (Z) of *Pre-Kharif* season mean temperature time series. The values of Z statistic in the area range from -3.796 to 2.49 . Spatial distribution map of Z statistic indicates both negative and positive trends over the area, but these are not significant and northern part of the area shows insignificant negative trend that extends up to the middle part and southern part to the middle shows insignificant positive trends, though station-wise estimation indicates significant trends.

4.5.3 *Kharif* temperature

All stations show a rising trend in *Kharif* season (rainy season) mean temperature except Barisal with MK, MMK and SR tests (Table 4). Sen's Slope analysis indicates that the magnitude of change ranges from 0.004 to 0.016 °C/year with an average value of 0.011 °C/year. Among all cropping seasons, this season shows the highest rate of change and almost all trends are significant at 90 or 95 % confidence levels. The strongest significant increasing trends at 95 % confidence levels in *Kharif* season mean temperature are observed at the rates 0.009, 0.012, 0.016, 0.011, 0.008, 0.014, 0.015, 0.016, 0.011, 0.013 and 0.007 °C/year at Dinajpur, Rangpur, Bogra, Ishwardi, Rajshahi, Faridpur, Jessore, Khulna, Satkhira, Bhola and Khepupara stations, respectively. Spatial distribution of MK test statistic (*Z*) of *Kharif* season mean temperature time series (Fig. 7d) indicates that all over the area, there is dominant significant rising trend.

5 Conclusions

The annual average rainfall is 1925 mm in the study area. The driest and wettest parts are Rajshahi and Khepupara areas, respectively. Rainfall is much higher in southern and northern parts than the central part of the study area. Annual average temperature is about 25.44 °C. The lowest mean annual temperature is in the northeast and increases toward the south, reaching the extreme in southwest along the coast of Bay of Bengal.

Both positive and negative trends are found in annual and seasonal rainfall time series data, though the trends vary spatially. The significant positive trends at 95 % confidence level in annual rainfall are found at Dinajpur, Rangpur and Khepupara stations, and *Kharif* season rainfall of these stations also shows significant increasing trends. As the *Kharif* season rainfall shows positive trends, the possibility of occurring frequent flood event is high that is potential to cause more loss of *Aman* rice. On the other hand, two significant decreasing trends in rainfall data are found at Bhola (−11.67 mm/year) and Rajshahi (−5.95 mm/year) stations, respectively. Major portion of the study area shows insignificant trends in rainfall in the northwest part during *Rabi* and Pre-*Kharif* seasons.

83.33 and 16.67 % of meteorological stations show rising and falling trends in annual mean temperature, respectively. Significant rising trends in the annual mean temperature are found in northeastern and insignificant in northwestern part of the study area. Increasing and decreasing trends both in *Rabi* and in Pre-*Kharif* seasons mean temperature are found, but most are insignificant. However, in *Kharif* season, all stations except Barisal show significant rising trends in temperature. The Sen's Slope analysis indicates that the rate of changes range from 0.004 to 0.016 °C/year with an average 0.011 °C/year during this season. Hence, effective adaptation strategies should be taken to keep up agricultural production that related to livelihood of the most people and ensure the country's food security to minimize the effect of climate change.

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