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Unidirectional trends in rainfall and temperature of Bangladesh

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Abstract To quantify the human-induced changes in precipitation and temperature, it is required to remove the natural climate variability from corresponding time series. Natural climate variability can be explained by the multi-scale variability of hydro-meteorological time series or the scaling effect, which denotes the invariance properties of a time series aggregated on different time scales. A number of studies have been carried out on rainfall and temperature trends in Bangladesh in recent years, but none of the studies considered the natural variability of climate that is present in time series in the form of auto-correlation that inflates the variance of the test statistics and changes the chance of significance. In the present paper the modified Mann-Kendall test, which can discriminate multi-scale variability from unidirectional trends, is used to analyse the trends in rainfall and temperature of Bangladesh over the period 1958–2007. The study shows that significant trends obtained in rainfall amount and extremes at many stations of Bangladesh by previous studies without considering the natural climate variability are due to the scaling effect. After removing the scaling effect, it was found that the annual rainfall only increased in north Bangladesh. Analysis of seasonal rainfall trends only shows a significant increase in pre-monsoon rainfall in Bangladesh. However, temperature was found to increase over the entire country, a similar trend to that suggested by other authors.

Key words unidirectional trends; modified Mann-Kendall test; climate variability; Bangladesh

INTRODUCTION

The implications of climate change are particularly significant for the regions already under stress, such as in Bangladesh where hydrological disasters are a common phenomena (Shahid & Behrawan, 2008; Shahid, 2010c). It has been predicted that, due to climate change, there will be a steady increase of temperature and change in rainfall pattern, which might have a number of implications for agriculture (Karim *et al.*, 1999), water resources (Shahid, 2011), public health (Shahid, 2010c) and the energy sector (Shahid, 2012) in Bangladesh.

A number of studies have been carried out on historical rainfall and temperature trends in Bangladesh to understand the changing pattern of rainfall and temperature (Jones, 1995; Rahman *et al.*, 1997; Singh, 2001; Shahid & Khairulmaini, 2009; Shahid, 2010a,b). Rahman *et al.* (1997) analysed the trend of monsoon rainfall patterns in Bangladesh and found that the southeast part of the country shows a changing pattern of rainfall. Singh (2001) reported that the monsoon rainfall over Bangladesh has increased during the period 1961–1991, with maximum increase in September followed by that in July. Jones (1995) analysed the monthly mean maximum and minimum temperatures of Bangladesh during 1949–1989 and found no significant change in annual mean minimum and maximum temperatures. Shahid & Khairulmaini (2009) and Shahid (2010a) reported a significant increase of rainfall in recent years in the west part of Bangladesh.

Most of the past studies on climate trend analysis of Bangladesh used a standard Mann-Kendall test over 30–50 years of climate data, considering that natural variability alters the climate pattern on time scales shorter than 30 years (WMO, 1996). Recent analysis of multi-centennial time series of observed or proxy hydro-climatic data reveals that wet or dry periods exceeding 50 years can exist (Beran, 1994; Sano *et al.*, 2009; Lacombe *et al.*, 2012). It has been reported that long-term persistence (LTP) or Hurst phenomenon (Hurst, 1951) can lead to a considerable reduction in significance of trends (Koutsoyiannis, 2003; Koutsoyiannis & Montanari, 2007; Hamed, 2008). As a result, some of these recent findings on the effect of LTP raise questions about using the results from past national and regional trends studies that did not include LTP/Hurst phenomenon. Recently, Hamed (2008) modified the Mann-Kendall test (Kendall, 1975) to account for the scaling effect, thus enhancing the ability of the test to discriminate multi-scale variability from unidirectional trends.

It becomes necessary to re-analyse the trends in the climate of Bangladesh by using a modified approach for estimating significance of climatic trends considering the scaling effect. In

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the present study, the Mann-Kendall test modified by Hamed (2008) is applied on temperature and precipitation data of Bangladesh over the period 1958–2007 to understand the unidirectional trends in the climate of Bangladesh by discriminating multi-scale variability.

CLIMATE OF BANGLADESH

Bangladesh has a tropical humid climate characterized by wide seasonal variations in rainfall, moderately warm temperatures, and high humidity (Shahid & Khairulmaini, 2009). Four distinct seasons can be recognized in Bangladesh from a climatic point of view: (i) the dry winter season from December to February, (ii) the pre-monsoon hot summer season from March to May, (iii) the rainy monsoon season from June to September, and (iv) the post-monsoon autumn season which lasts from October to November. Rainfall in Bangladesh varies from 1400 mm in the northwest to more than 4000 mm in the northeast. Higher rainfall in the northeast is caused by the additional uplifting effect of the Meghalaya plateau. More than 75% of rainfall in Bangladesh occurs during the monsoon, caused by weak tropical depressions that are brought from the Bay of Bengal into Bangladesh by the wet monsoon winds. The average temperature of the country ranges from 7.2°C to 12.8°C during winter and 23.9°C to 31.1°C during summer. January is the coldest month and May is the hottest month in Bangladesh. The mean temperature gradient in the pre-monsoon is oriented southwest to northeast with the warmer zone in the southwest and the cooler zone in the northeast. In winter the mean temperature gradient is oriented in a south to north direction where the southern part is 5°C warmer than the northern part of Bangladesh (Shahid, 2010a).

The Bangladesh Meteorological Department (BMD) has 27 stations for measuring daily rainfall and other weather parameters. Long-term (more than 50 years) daily temperature and rainfall records are available for only 17 out of the 27 stations. Fifty years (1958–2007) of rainfall and temperature records of those stations are used in the present study to assess the change in the climate of Bangladesh. Location of meteorological stations is shown in the trend maps given in Fig. 1. It can be seen from the figures that meteorological stations under study are distributed over the country. The topography of Bangladesh is extremely flat with some upland in the northeast and the southeast. Therefore, it can be considered that the meteorological stations under study represent the climate of the whole of Bangladesh.

The homogeneity of the rainfall records are analysed by calculating the von Neumann ratio, Standard Normal Homogeneity Test (SNHT), and the Range test. The data sets of all the stations were found to be homogeneous. The Mann-Kendall test (Kendall, 1975) and modified Mann-Kendall test (Hamed, 2008) are applied to detect the trends in rainfall and temperature time series. The methods used in the present study are discussed below.

Mann-Kendall (MK2) trend test

If x_1, x_2, x_3 ….. x_i represent n data points where x_i represents the data point at time i, then the Mann-Kendall statistic, S, is calculated as,

$$S = \sum_{k=1}^{n-1} \sum_{i=k+1}^{n} sign(x_i - x_k) \tag{1}$$

where, $sign(x_i - x_k) = \begin{cases} 1 & if(x_i - x_k) > 0 \\ 0 & if(x_i - x_k) = 0 \\ -1 & if(x_i - x_k) < 0 \end{cases}$

The probability associated with S and the sample size, n, are then computed to statistically quantify the significance of the trend. Normalized test statistic Z is computed as follows:

$$Z = \begin{cases} \dfrac{S - 1}{\sqrt{VAR(S)}} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \dfrac{S - 1}{\sqrt{VAR(S)}} & if \quad S < 0 \end{cases} \tag{2}$$

At the 99% significance level, the null hypothesis of no trend is rejected if $|Z| > 2.575$; at 95%

significance level, the null hypothesis of no trend is rejected if $|Z| > 1.96$; and at 95% significance level, the null hypothesis of no trend is rejected if $|Z| > 1.645$.

Magnitude of trends can be determined by using Sen's slope method (Sen, 1968). The method proceeds by calculating the slope (β) as a change in measurement per change in time:

$$\beta = median\left[\frac{x_j - x_i}{j - i}\right] \; for \; all \; i < j \tag{3}$$

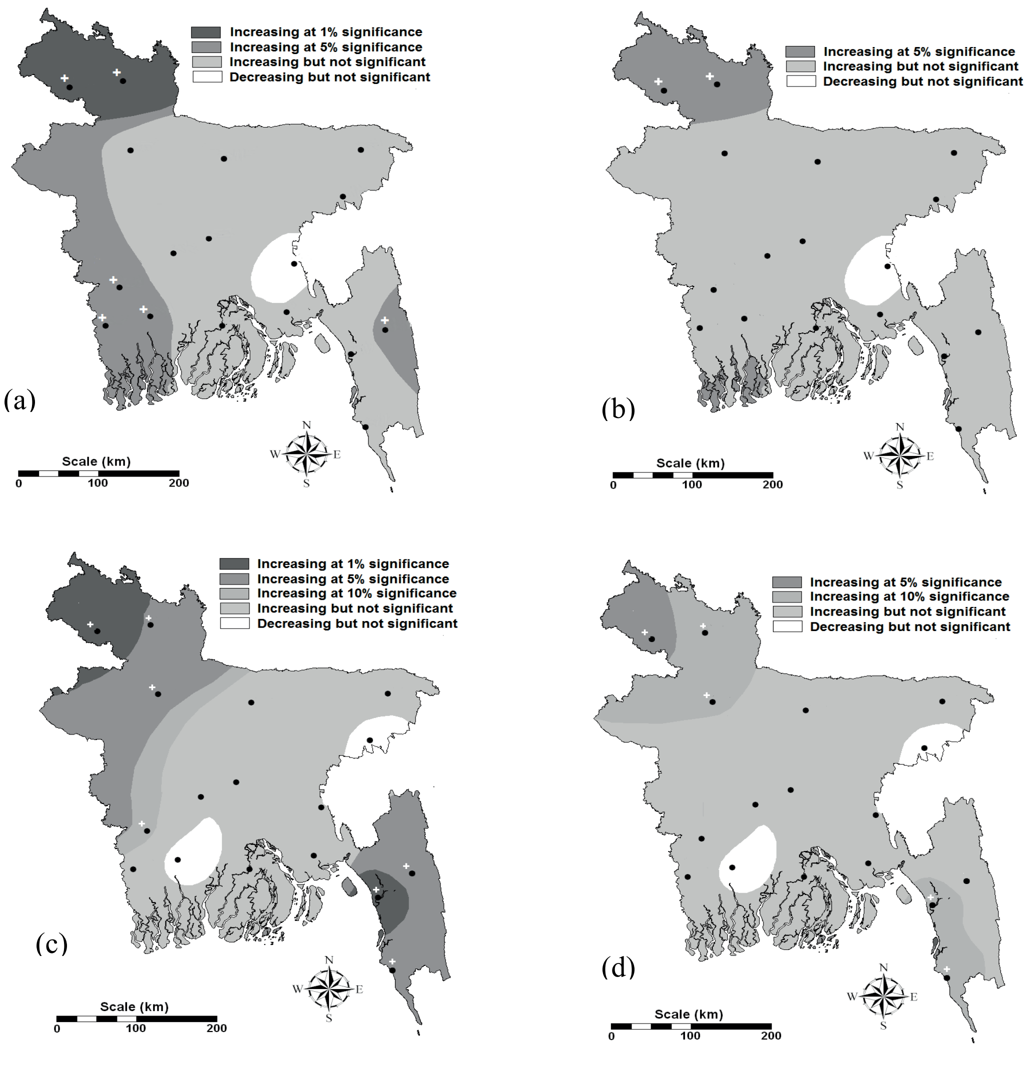

Fig. 1 Spatial pattern in annual rainfall trends obtained by using (a) MK1; (b) MK2; pre-monsoon rainfall trends obtained by using (c) MK1; (d) MK2

Modified Mann-Kendall (MK2) trend test

The modified Mann-Kendall test (MK2) is proposed by Hamed (2008) to account for the scaling effect. To assess trend by using MK2, non-parametric Sen's slope (β) is computed for the sample data by using equation (3) and the trend from the time series, x_i is removed to get the de-trended series by using the following equation:

$$x_i' = x_i - (\beta \times i) \; for \; i = 1{:}\, n \tag{4}$$

The equivalent normal variants of rank of the de-trended series are obtained by using following equation:

$$Z_i = \phi^{-1}\left(\frac{R_i}{n+1}\right) \quad for\ i = 1{:}n \tag{5}$$

where, R_i is the rank of the de-trended series $x_i^{/}$, n is the length of the time series, and ϕ^{-1} is the inverse standard normal distribution function (mean = 0, standard deviation = 1).

In the next step, the correlation matrix for a given Hurst coefficient is derived by using the following equation:

$$C_n(H) = \left[\rho_{|j-i|}\right], for\ i = 1{:}n, j = 1{:}n \tag{6}$$

$$\rho_l = \frac{1}{2}\left(|l+1|^{2H} - 2|l|^{2H} + |l-1|^{2H}\right) \tag{7}$$

where, ρ_l is the autocorrelation function of lag l for a given H, and is independent of the time scale of aggregation for the time series (Koutsoyiannis, 2003).

The value of H is obtained by maximizing the log likelihood function of H as given below:

$$LogL(H) = -\frac{1}{2}\log|C_n(H)| - \frac{Z^T[C_n(H)]^{-1}Z}{2\gamma_0} \tag{8}$$

where, $|C_n(H)|$ is the determinant of correlation matrix $[C_n(H)]$, Z^T is the transpose vector of equivalent normal variates Z, $[C_n(H)]^{-1}$ is the inverse matrix, and $\gamma_0$is the variance of z_i. Equation (8) can be solved numerically for a different value of H, and the value for which $LogL(H)$ is maximum is taken as the H value for the given time series x_i. In this study, the value of H is solved between 0.50 and 0.98 with an incremental step of 0.01.

A significance level of H is determined by using mean (μ_H) and standard deviation (σ_H) when $H = 0.5$ (normal distribution) as given by the following equations (Hamed, 2008):

$$\mu_H = 0.5 - 2.87n^{-0.9067}$$

$$\sigma_n = 0.7765n^{-0.5} - 0.0062$$

In the present study, 10% significance level is used for rainfall and 5% significance level is used for temperature for determining significant H. If H is found to be significant the variance of S is calculated by using the following equation for given H:

$$V(S)^{H'} = \sum_{i<j}\sum_{k<l}\frac{2}{\pi}sin^{-1}\left(\frac{\rho\,|j-i| - \rho\,|i-l| - \rho\,|j-k| + \rho\,|i-k|}{\sqrt{(2-2\rho\,|i-j|)(2-2\rho\,|k-l|)}}\right) \tag{9}$$

where, ρ_l is calculated by using equation (7) for given H and $V(S)^{H'}$ is the biased estimate. The unbiased estimate $V(S)^H$ is calculated by multiplying by a bias correctin factor B as below:

$$V(S)^H = V(S)^{H'} \times B \tag{10}$$

where, B is a function of H as below:

$$B = a_0 + a_1H + a_2H^2 + a_3H^3 + a_4H^4 \tag{11}$$

The coefficients a_0, a_1, a_2, a_3, a_4 in equation (11) are functions of the sample size n. These are found in Hamed (2008) and Kumar (2009). The significance of the Mann-Kendall test is computed by using $V(S)^H$ in place of $V(S)$ in equation (2).

RESULTS AND DISCUSSION

The trends in rainfall of Bangladesh are analysed by performing Mann–Kendall (MK1) and modified Mann-Kendall (MK2) tests on annual and seasonal rainfall. Trends at each of the 17 s are interpolated to show the spatial pattern of annual rainfall trends in Bangladesh. Figure 1(a) shows the spatial pattern in annual rainfall trend obtained by using MK1. The classes in the map are based on significance levels. A significant increase in rainfall is shown by a white coloured plus (+) sign at the station. Figure 1(a) shows MK1 detected a significant increase of rainfall at six of 17 stations in Bangladesh. The map shows a significant increase in annual rainfall in the western part of Bangladesh. The result is consistent with the findings of previous studies (Shahid & Khairulmaini, 2009; Shahid, 2010a). The spatial pattern of rainfall trends obtained using MK2 is shown in Fig. 1(b). The figure shows a reduction of significance level and number of stations showing significant trends. MK2 reveals a significant increase of rainfall at only two stations in Bangladesh located in the north at the Himalayan foothills. MK1 detected a significant increase at 1% significance level at two northern stations, but MK2 only shows the increase in significance at the 5% level.

Analysis of monsoon rainfall by the MK1 method shows a significant increase of monsoon rainfall at only three stations located in the north and northwest of Bangladesh. When analysed by using MK2, significant trends are only detected at two northern stations similar to the annual rainfall trend. The map is similar to Fig. 1(b) and therefore not presented here. It is reported in previous studies that changes in pre-monsoon rainfall of Bangladesh is most widespread (Shahid, 2010a,b). The spatial pattern of pre-monsoon rainfall obtained by using MK1 is shown in Fig. 1(c). The figure shows that rainfall is increasing at seven stations in Bangladesh. Pre-monsoon rainfall is detected to change at 5% level of significance at stations located in northwest and southeast of Bangladesh. However, when analysed by using MK2, reduction of significance level and number of stations showing significant trends are observed. Figure 1(d) shows the spatial pattern of pre-monsoon rainfall trends obtained by MK2. It can be seen from Fig. 1(d) that pre-monsoon rainfall is only increasing at a 5% level of significance at one station in north Bangladesh and at a 10% level of significance at five stations located in northwest and southeast Bangladesh. MK1 detected a significant trend at three stations for post-monsoon rainfall and two stations for winter rainfall. However, MK2 reveals that those trends are due to a scaling effect. No significant trend exists in post-monsoon and winter rainfall at any stations in Bangladesh.

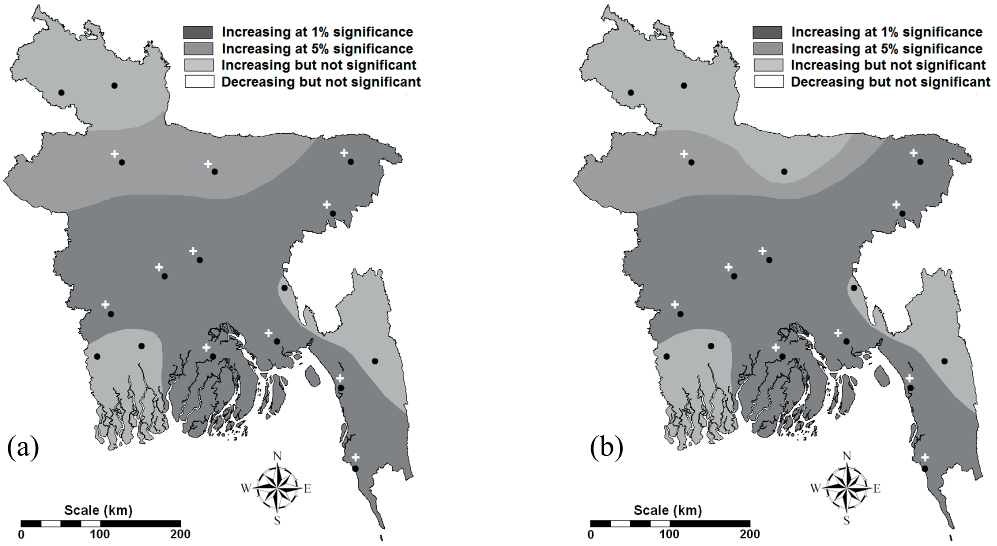

Fig. 2 Spatial pattern in mean temperature trends obtain by using (a) MK1; (b) MK2.

Three variables related to temperature namely, mean, mean maximum and mean minimum are considered for the analysis of temperature trends in Bangladesh. Analysis of temperature series by the MK1 method shows a significant increase of mean temperature at 10 stations, and mean minimum and mean maximum temperatures at nine stations out of 17 stations in Bangladesh. The MK2 method shows a similar pattern in temperature trend. A significant increase of mean temperature, minimum and maximum temperature is noted at nine stations by MK2. Spatial pattern of mean temperature trends by MK1 and MK2 methods are shown in Fig. 2(a) and (b), respectively. Both methods show a significant increase of mean temperature in the majority of the country, except in north Bangladesh, where annual and seasonal rainfalls are increasing significantly. Temperature trends are found to be consistent with the findings of previous studies (Shahid, 2010a).

CONCLUSION

All past studies on climatic trends in Bangladesh estimated a significant increase in annual rainfall in the western part of Bangladesh. Many climate change adaptations are proposed based on the analysis. The present study reveals that significant trends obtained at stations located in the west and southwest parts of Bangladesh are due to a scaling effect. Annual and monsoon rainfalls of Bangladesh are only increasing in the northern region located in the foothills of the Himalayas at a lower significant level. Only pre-monsoon rainfall in Bangladesh is found to increase in other parts of the country beyond north Bangladesh. Trends in temperature in Bangladesh are consistent with previous studies. The temperature in Bangladesh is increasing over the entire country, except in the north. It is expected that the findings of this study will help to streamline the policy adopted to combat climate variability and changes in Bangladesh.

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