Rainfall variability and the trends of wet and dry periods in Bangladesh

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ABSTRACT: Spatial patterns of annual and seasonal rainfall trends of Bangladesh over the time period 1958–2007 has been assessed using rainfall data recorded at 17 stations distributed over the country. Mann–Kendall trend test and the Sen’s slope method are used to detect the significance and the magnitude of rainfall change, respectively. Historical dry and wet months are identified by using standardised precipitation index method and their trends are analysed to assess the possible change in wet and dry events in Bangladesh. The result shows a significant increase in the average annual and pre-monsoon rainfall of Bangladesh. The number of wet months is found to increase and the dry months to decrease in most parts of the country. Seasonal analysis of wet and dry months shows a significant decrease of dry months in monsoon and pre-monsoon. Copyright © 2009 Royal Meteorological Society

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1. Introduction

Bangladesh is an agriculture-based country where about 80% of its 145 million people are directly or indirectly engaged in a wide range of agricultural activities (Banglapedia, 2003). Rainfall is the most important natural factor that determines the agricultural production in Bangladesh. The variability of rainfall and the pattern of extreme high or low precipitation are very important for the agriculture as well as the economy of the country. It is well established that the rainfall is changing on both the global (Hulme et al., 1998; Lambert et al., 2003; Dore, 2005) and the regional scales (Rodriguez-Puebla et al., 1998; Gemmer et al., 2004; Kayano and Sansigolo, 2008) due to global warming. The implications of these changes are particularly significant for Bangladesh where hydrological disasters of one kind or another is a common phenomenon (Shahid and Behrawan, 2008). Bangladesh is one of the most flood-prone countries in the world due to its geographic position (Banglapedia, 2003). Drought in northwestern part of the country is also a common phenomenon (Shahid, 2008; Shahid and Behrawan, 2008). The country experienced a number of extreme dry and wet periods in past 50 years. Heavy rainfall in the monsoon of 2007 together with the onset of flooding by Himalayan-fed rivers resulted in severe flood in Bangladesh which affected more than 9 million people in more than half of the districts of the country. On the other hand, drought due to low precipitation in 1994–1995 led to a decrease in rice and wheat production by $3.5 \times 10^6$ MT (Rahman and Biswas, 1995).

The Intergovernmental Panel on Climate Change termed Bangladesh as one of the most vulnerable countries in the world due to climate change (Intergovernmental Panel on Climate Change, 2007). Hydrological changes are the most significant impacts of climate change in Bangladesh. A study on climate change vulnerability based on certainty of impact, timing, severity of impacts and importance of the sector, ranked water resources as the greatest concern due to climate change in Bangladesh (Organization for Economic Co-operation and Development, 2003). It has been predicted that due to climate change, there will be a steady increase in temperature and rainfall of Bangladesh (Intergovernmental Panel on Climate Change, 2007). Small changes in the mean and standard deviation values can produce relatively large changes in the probability of occurrence of extreme events (Groisman et al., 1999; Rodrigo, 2002; Chiew, 2006; Su et al., 2006). Studies in different parts of the world indicate that global warming has altered the precipitation patterns and resulted in frequent extreme weather events, such as floods, droughts and rainstorms (WMO 2003; Schmild and Frei, 2005; Zhang et al., 2008, 2009; Briffa et al., 2009). The study of rainfall variability and the trends of wet and dry events are therefore important for long-term water resources planning, agricultural development and disaster management in Bangladesh in the context of global climatic change.

Although a number of studies have been carried out on rainfall patterns (Ahmed and Karmakar, 1993; Hussain and Sultana, 1996; Kripalini et al., 1996; Rahman et al., 1998;...
1997; Ahmed and Kim, 2003; Shahid et al., 2005; Islam and Uyeda, 2008; Shahid, 2008), only very few works have been found on rainfall trends and extremes in Bangladesh. Rahman et al. (1997) used trend analysis to study the changes in monsoon rainfall of Bangladesh and found no significant change. Ahmed (1989) estimated the probabilistic rainfall extremes in Bangladesh during the pre-monsoon season. Karmakar and Khatun (1995) repeated a similar study on rainfall extremes during the southwest monsoon season. However, both the studies were focussed only on the maximum rainfall events for a limited period. May (2004) reported that the frequency of wet days has noticeably increased over the tropical Indian Ocean. He predicted that intensity of heavy rainfall events in Bangladesh will be increased in the future. Immerzeel (2007) predicted accelerated seasonal increases in precipitation in the 21st century with strongest increase in monsoon in the Brahmaputra basin.

A study has been carried out in this article to assess the changes in rainfall and extreme events in Bangladesh through the analysis of the spatial patterns of the trends of long-term annual and seasonal rainfall as well as the number of wet and dry months in different seasons. Standardised precipitation index (SPI) method (Mckee et al., 1993) is used to identify the wet and dry months from rainfall time series. Mann–Kendall trend analysis (Mann, 1945; Kendall, 1975) and the Sen’s slope (Sen, 1968) method are used to detect the presence of significant change and the magnitude of change, respectively. Geographical Information System (GIS) is used to show the spatial variation of trends over the country.

2. Climate of Bangladesh

Bangladesh is primarily a low-lying plain of about 144,000 km², situated on deltas of large rivers flowing from the Himalayas. Geographically, it extends from 20°34’N to 26°38’N latitude and from 88°01’E to 92°41’E longitude. Bangladesh has a sub-tropical humid climate characterised by wide seasonal variations in rainfall, moderately warm temperatures and high humidity (Rashid, 1991). Four distinct seasons can be recognised in Bangladesh from the climatic point of view: (1) the dry winter season from December to February, (2) the pre-monsoon hot summer season from March to May, (3) the rainy monsoon season from June to September and (4) the post-monsoon autumn season which lasts from October to November. Rainfall variability in space and time is one of the most relevant characteristics of the climate of Bangladesh. Spatial distribution of rainfall in Bangladesh is shown in Figure 1(a). Rainfall in Bangladesh varies from 1400 mm in the west to more than 4300 mm in the east of the country. Higher rainfall in the northeast is caused by the additional uplifting effect of the Meghalaya plateau. Rainfall in Bangladesh mostly occurs in monsoon, caused by weak tropical depressions that are brought from the Bay of Bengal into Bangladesh by the wet monsoon winds. Monthly distribution of rainfall over Bangladesh is shown in Figure 1(b). More than 75% rainfall in Bangladesh occurs in monsoon. The average temperature of the country ranges from 17 to 20.6 °C during winter and 26.9 to 31.1 °C during summer. The average relative humidity for the whole year ranges from 70.5% to 78.1% in Bangladesh (Banglapedia, 2003).

The topography of Bangladesh is extremely flat (Figure 2(a)) with some upland in the northeast and the southeast. The plain land lies almost at sea level along the southern part of the country and rises gradually towards north. Land elevation in the plain varies from 1 to 60 m above the sea level from south to north. The hilly areas are located in the southeastern and northeastern regions, and the terrace land can be found in the northwestern and central regions of the country. Land use map of Bangladesh (United Nations Environment Program, 1994) is shown in Figure 2(b). Agriculture, being the main economic mainstay of the country, covers almost all cultivable land of Bangladesh. About 68% land of the country is used for agriculture and village settlement. Rivers and standing water bodies covers almost 13% of the area. About 14% area is covered by mangrove and upland forests. Urban area covers about 5% of the land and the rest is used for other purposes.

3. Data and methodology

Monthly rainfall records of 17 stations of Bangladesh for fifty years (1958–2007) are collected from Bangladesh Meteorological Department for the study. Location of rainfall recording stations in Bangladesh is shown in Figure 3. Out of the 17 stations, a complete set of data was available in 12 stations. Rate of missing data in rest of the stations was less than 2%. If data for one monsoon or pre-monsoon month of a year is found missing then that year is discarded from the trend analysis.

The homogeneity of the rainfall records are analysed by calculating the von Neumann ratio (Von Neumann, 1941), standard normal homogeneity test (Alexandersson, 1986) and the range test (Buishand, 1982). The data sets of all the stations are found homogeneous. Mann–Kendall test is applied to detect the trend in rainfall time series. Confidence levels of 90%, 95% and 99% are taken as thresholds to classify the significance of positive and negative trends. The methods used in the present study are discussed below.

3.1. Mann–Kendall trend test

In the Mann–Kendall test (Mann, 1945; Kendall, 1975) the data are evaluated as an ordered time series. Each data are compared to all subsequent data. The initial value of the Mann–Kendall statistic, S, is assumed to be 0 (e.g. no trend). If data from a later time period is higher than data from an earlier time period, S is incremented by 1. On the other hand, if the data from a later time period is lower than data sampled earlier, S is decremented by 1. The net result of all such increments and decrements yields the final value of S. If \( x_1, x_2, x_3, \ldots, x_i \) represent
n data points where \( x_j \) represents the data point at time \( j \), then \( S \) is given by:

\[
S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sign}(x_j - x_k)
\]

where:

\[
\text{sign}(x_j - x_k) = \begin{cases} 
1 & \text{if } (x_j - x_k) > 0 \\
0 & \text{if } (x_j - x_k) = 0 \\
-1 & \text{if } (x_j - x_k) < 0 
\end{cases}
\]

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

\[
Z = \begin{cases} 
\frac{S - 1}{\sqrt{\text{VAR}(S)}} & \text{if } S > 0 \\
0 & \text{if } S = 0 \\
\frac{S - 1}{\sqrt{\text{VAR}(S)}} & \text{if } S < 0 
\end{cases}
\]

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 90% significance level, the null hypothesis of no trend is rejected if \( |Z| > 1.645 \). More details of the Mann–Kendall test can be found in Sneyers (1990).

3.2. Sen’s slope estimator

Some trends may not be evaluated to be statistically significant while they might be of practical interest (Yue...
and Hashino, 2003; Basistha et al., 2007). Even if climate change component is present, it may not be detected by statistical tests at a satisfactory significance level (Radziejewski and Kundzewicz, 2004). Therefore, in the present study, linear trend analysis is also carried out and the magnitude of the trend is estimated by the Sen’s slope method (Sen, 1968). The Sen’s slope method gives a robust estimation of the trend (Yue et al., 2002). The method requires a time series of equally spaced data. The method proceeds by calculating the slope as a change in measurement per change in time:

\[ Q' = \frac{x_t - x_{t'}}{t - t'} \]  

(3)

where, \( Q' = \) slope between data points \( x_t \) and \( x_{t'} \), \( x_t = \) data measurement at time \( t \), \( x_{t'} = \) data measurement at time \( t' \).

Sen’s estimator of slope is simply given by the median slope:

\[ Q = Q'_{(N+1)/2} \quad \text{if } N \text{ is odd} \]

\[ = (Q'_{N/2} + Q'_{(N+2)/2})/2 \quad \text{if } N \text{ is even} \]

(4)

where \( N \) is the number of calculated slopes.

3.3 Standardised precipitation index

SPI (Mckee et al., 1993) is a widely used drought index based on the probability of precipitation for multiple timescales, e.g. 1-, 3-, 6-, 9-, 12-, 18- and 20-month.
It provides a comparison of the precipitation over a specific period with the precipitation totals from the same period for all the years included in the historical record. Consequently, it facilitates the temporal analysis of wet and dry phenomena.

To compute SPI, historic rainfall data of each station are fitted to a gamma probability distribution function:

\[ g(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \quad \text{for } x > 0 \]  

where \( \alpha > 0 \) is a shape parameter, \( \beta > 0 \) is a scale parameter, \( x > 0 \) is the amount of precipitation and \( \Gamma(\alpha) \) defines the gamma function.

The maximum likelihood solutions are used to optimally estimate the gamma distribution parameters \( \alpha \) and \( \beta \) for each station and for each timescale:

\[ \alpha = \frac{1}{4A} \left( 1 + \sqrt{1 + \frac{4A}{3}} \right) \]  
\[ \beta = \frac{\sum x}{\alpha} \]  

where \( A = \ln(T) - \left[ \sum \ln(x)/n \right] \), \( n \) = number of precipitation observations.

This allows the rainfall distribution at the station to be effectively represented by a mathematical cumulative probability function given by:

\[ G(x) = \int_0^x g(x) dx = \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^x x^{\alpha-1} e^{-x/\beta} dx \]  

As the gamma function is undefined for \( x = 0 \) and a precipitation distribution may contain zeros, the cumulative probability becomes:

\[ H(x) = q + (1 - q)G(x) \]  

where \( q \) is the probability of a zero. The cumulative probability \( H(x) \) is then transformed to the standard normal distribution to yield the SPI (McKee et al., 1993).

As the precipitation rate is fitted to a gamma distribution for different multiple timescales for each month of the year, the resulting function represents the cumulative probability of a rainfall event of a station for a given month of the data set and at different multiple timescales of interest. This allows establishing a classification value for SPI. McKee et al. (1993) classified wet and dry events according to SPI values as given in Table I. Details of the SPI algorithm can be found in McKee et al. (1993, 1995).

### 3.4. Spatial interpolation

For the mapping of spatial pattern of trends from point data, Kriging interpolation method is used. Geostatistical analysis tool of ArcMap 9.1 (ESRI, 2004) is used for this purpose. Kriging is a stochastic interpolation method (Journel and Huijbregts, 1981; Isaaks and Srivastava, 1989), which is widely recognised as the standard approach for surface interpolation based on scalar measurements at different points. Studies show that Kriging gives better global predictions than other methods (van Beers and Kleijnen, 2004). Kriging is an optimal surface interpolation method based on spatially dependent variance, which is generally expressed as a semivariogram. Surface interpolation using kriging depends on the selected semivariogram model and the semivariogram must be fitted with a mathematical function or model. Depending on the shape of semivariograms, different models are used in the present study for their fitting.

Rainfall is a dynamic phenomenon, which changes over time and space. Complete analysis of rainfall events requires a study of both its spatial and temporal extents. Hydrological investigation over a large area requires assimilation of information from many sites each with a unique geographic location (Shahid et al., 2000, Shahid and Nath, 2002). GIS maintains the spatial location of sampling points, and provides tools to relate the sampling data contained through a relational database. Therefore, it can be used effectively for the analysis of spatially distributed hydro-meteorological data and modelling. In the present article, GIS is used to show the spatial variation of rainfall trends.

### 4. Results and discussion

#### 4.1. Trends of annual rainfall

The annual rainfall data of 17 stations of Bangladesh are averaged to get the time series of annual average rainfall of Bangladesh for the period 1958–2007 which is shown in Figure 4(a). The mean annual rainfall over Bangladesh for this period is 2488 mm. The deviation of annual precipitation from the mean precipitation is found to vary from +413 to −571 mm. The trend analysis of annual average rainfall time series by Mann–Kendall test reveals the presence of a positive trend at the 90% level of confidence. Mann–Kendall normalised test statistic (Z) of 1.957 means the trend is very close to the 95% level of confidence. The analysis of annual rainfall by Sen’s slope method shows that the annual average rainfall is increasing at a rate of +5.525 mm/year in Bangladesh.

<table>
<thead>
<tr>
<th>SPI</th>
<th>Category</th>
<th>Probability of occurrence (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 and above</td>
<td>Extremely wet</td>
<td>2.3</td>
</tr>
<tr>
<td>1.50 to 1.99</td>
<td>Severely wet</td>
<td>4.4</td>
</tr>
<tr>
<td>1.00 to 1.49</td>
<td>Moderate wet</td>
<td>9.2</td>
</tr>
<tr>
<td>0.99 to −0.99</td>
<td>Near normal</td>
<td>34.1</td>
</tr>
<tr>
<td>−1.00 to −1.49</td>
<td>Moderate drought</td>
<td>9.2</td>
</tr>
<tr>
<td>−1.50 to −1.99</td>
<td>Severe drought</td>
<td>4.4</td>
</tr>
<tr>
<td>−2.00 and less</td>
<td>Extreme drought</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Table I. The wet and dry event categories based on the classification of SPI values.
Figure 4. (a) Trend of average annual rainfall of Bangladesh shows a significant increase during the time period 1958–2007 and (b) the spatial pattern of annual rainfall trends in Bangladesh. The numbers in white colour denote significant change.

The spatial presentation of the detected precipitation trends can be helpful for a better understanding of rainfall variations in Bangladesh. Therefore, annual rainfall trends at each of the 17 stations are calculated and interpolated to prepare the map of spatial pattern of annual rainfall trends of Bangladesh which is shown in Figure 4(b). The classes in the map are based on confidence levels. The numbers in the map show the magnitude of rainfall change in millimetre per year during the time period 1958–2007. The numbers in white colour indicate the trends are statistically significant. The map shows an increasing trend of annual rainfall in most of the stations of Bangladesh. A significant increase is observed in the western part of Bangladesh. The maximum increase of annual rainfall is noted in northern Bangladesh by 16.45 mm/year at the 99% level of confidence.

The monsoon of Bangladesh flows into two branches, one of which strikes western India and the other travels up the Bay of Bengal and over eastern India and Bangladesh. The monsoon from the Bay of Bengal crosses the plain to the north and northeast before being turned to the west and northwest by the foothills of the Himalayas. Simulated increases in sea surface temperature in general circulation model show that it alters wind patterns to the west of Bangladesh, leading to an accumulation of moisture in the region and greater rainfall during the summer monsoon season (Cash et al., 2007). Therefore, it can be remarked that the increase in rainfall in western part of Bangladesh might be an effect of global climate change.

Besides the western part of Bangladesh, rainfall is found to increase significantly in only one station located in the southeastern hill area at the 95% level of confidence. The shift of easterly anomalies in circulation leads the westerlies over India in July and the intensification of the winds and rainfall in the southeastern part of Bangladesh (Cash et al., 2007).
4.2. Trends of seasonal rainfall

The time series of average monsoon rainfall in Bangladesh for the time period 1958–2007 is shown in Figure 5(a). Mann–Kendall trend analysis of average monsoon rainfall shows no significant change ($Z = 1.02$) of monsoon rainfall over Bangladesh. The spatial pattern of monsoon rainfall trends is shown in Figure 5(b). The numbers in the map show the amount of rainfall change in millimetre per year. The map shows an increase in monsoon rainfall in most of the stations of Bangladesh. However, a significant increase is observed only in northwestern Bangladesh.

The time series of average pre-monsoon rainfall of Bangladesh over the time period 1958–2007 is shown in Figure 6(a). The average pre-monsoon rainfall in Bangladesh is 435.8 mm. Mann–Kendall trend test shows a significant increase ($Z = 2.24$) of pre-monsoon rainfall of Bangladesh at the 95% level of confidence. The Sen’s slope analysis shows that the pre-monsoon rainfall is increasing at a rate of 2.47 mm/year or approximately 0.55% per year. Spatial pattern of pre-monsoon rainfall trends in Bangladesh (Figure 6(b)) shows a significant increase of pre-monsoon rainfall in northwestern and southeastern parts of Bangladesh. The maximum increase is observed in north Bangladesh by 7.44 mm/year at the 99% level of confidence.

No significant change in post-monsoon rainfall of Bangladesh for the time period 1958–2007 (Figure 7(a)) is observed by the Mann–Kendall test ($Z = 1.04$). Spatial pattern of post-monsoon rainfall trends (Figure 7(b)) shows an increase of post-monsoon rainfall all over the country. However, a significant increase is observed in the central north part of Bangladesh at the 95% level of confidence. Besides that, post-monsoon rainfall is also
Figure 6. (a) Trend of average pre-monsoon rainfall of Bangladesh shows a significant increase during the time period 1958–2007 and (b) the spatial pattern of pre-monsoon rainfall trends in Bangladesh. The numbers in white colour denote significant change.

found to increase in Khulna situated in the southwestern part of the country at the 90% level of confidence.

No significant change ($Z = 0.78$) is also observed in the winter rainfall (Figure 8(a)) of Bangladesh. Spatial pattern of winter rainfall trends, as shown in Figure 8(b), shows a significant change in winter rainfall only in two stations, one in the south and the other in the north. Maximum increase of winter rainfall is observed at Dinajpur station by 0.5 mm/year at the 95% level of confidence.

Thunderstorms are the sources of pre-monsoon rainfall of Bangladesh (Sanderson and Ahmed, 1979). The thunderstorm begins in the northeastern and eastern parts of the country by the first week of March. The thunderstorm activity gradually moves westward, and becomes significant in the western part of the country before the advent of the summer monsoon in late May or early June. During the early part of the thunderstorm season, a zone of discontinuity crosses the country from the southwest to the northeast separating the hot dry air from the dry interior of India and the warm moist air from the Bay of Bengal (Sanderson and Ahmed, 1979). The activity of the thunderstorms during the pre-monsoon season depends on the supply of moist air from the Bay of Bengal. Stronger and more continuous winds from the Bay of Bengal during pre-monsoon months due to the increase of sea surface temperature may be the cause of increased pre-monsoon rainfall of Bangladesh.

Pre-monsoon rainfall is very important for agriculture in Bangladesh. Increase in pre-monsoon precipitation can reduce the groundwater irrigation demand in Boro rice field which shares almost 70% of the total rice production of Bangladesh. Therefore, it may help to decrease the pressure on groundwater resources in...
northwestern Bangladesh where declining groundwater level is a major problem due to the overexploitation of groundwater for irrigation.

4.3. Trends of wet and dry months

The SPI is designed to flexibly present the incremental rainfall excess or deficit at any timescale of interest (McKee et al., 1993). Therefore, SPI can be used as an indicator of drought or flood (Giddings et al., 2005). Shahid (2008) used SPI to study the spatial and temporal patterns of drought in the western part of Bangladesh. Seiler et al. (2002) used SPI to study the recurrent floods affecting the southern Cordoba Province in Argentina and found that SPI satisfactorily explains the development of conditions leading up to the three main flood events in the region. As the 1-month SPI (SPI-1) reflects relatively short-term conditions, it can be a good indicator of short-term soil moisture and crop stress as well as flood if properly interpreted (National Drought Mitigation Center, 2006). Therefore, in the present study, SPI-1 is calculated and analysed to assess the trends of rain-induced extreme events in Bangladesh.

SPI-1 time series for the period 1958–2007 is calculated at each of the 17 stations of Bangladesh. SPI-1 values for only non-winter months, i.e. from March to November, are considered for analysis in the present study. Rainfall during winter accounts for less than 2% of total rainfall of Bangladesh. If rainfall is normally low during a month, large negative or positive SPI-1s may result even though the departure from the mean is relatively small (National Drought Mitigation Center, 2006). Therefore, SPI-1s of winter months are not considered in trend analysis. The annual maximum and
minimum SPI-1 values of all the stations during non-winter months are averaged to get the maximum and minimum SPI-1 time series of Bangladesh over the time period 1958–2007, which are shown in Figures 9(a) and 10(a), respectively. The maximum SPI-1 means the wettest month and the minimum SPI-1 means the driest month in a year. Maximum and minimum SPI-1 values of Bangladesh are found to vary from 0.9 to 2.1 and from -0.6 to -2.05, respectively, during the time period 1958–2007. The trend analysis shows that the maximum SPI-1 is increasing significantly at the 95% level of confidence (Figure 9(a)). On the other hand, a non-significant decreasing trend is observed for minimum SPI-1 (Figure 10(a)).

Maximum and minimum SPI-1 trends at each of the 17 stations are also calculated and interpolated to prepare the maps of spatial pattern of maximum and minimum SPI-1 trends in Bangladesh which are shown in Figures 9(b) and 10(b), respectively. The classes in the maps are based on the confidence levels. The numbers in the maps are Z values which indicate the trend of annual maximum (minimum) SPI-1 over the time period 1958–2007. The map of maximum SPI-1 (Figure 9(b)) shows a significant increase of maximum SPI-1 in north and southeast Bangladesh. Isolated pockets of significant increase of maximum SPI-1 are also observed in northeast and southwest parts of Bangladesh. The strongest trend is observed in the north Bangladesh where the Z value is 3.09. Spatial pattern of minimum SPI-1 of Bangladesh (Figure 10(b)) shows that the major parts of the country are characterised by increasing trend of minimum SPI-1 i.e. decreasing of dry events. A decreasing trend of minimum SPI-1 is observed in the central-eastern part of the country. However, neither the increasing nor the decreasing trend is statistically significant.

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The study reveals that with the increase of rainfall in Bangladesh, the intensity of wet months has also increased. Most significant increase of maximum SPI-1 is observed in northern Bangladesh where highest increase of annual and monsoon rainfall is recorded. However, the spatial pattern of annual rainfall trend is not similar to that of maximum SPI-1. The SPI-1 (Figure 9(b)) is also found to increase in the areas where no significant increase of annual (Figure 4(b)) or monsoon (Figure 5(b)) rainfalls is observed. Concentration of rainfall in the particular months of a year can cause an increase of SPI-1. A positive trend in monthly precipitation concentration is observed in the areas where SPI-1 is increasing but at the same time annual or monsoon rainfall is not increasing significantly. Therefore, it may be remarked that increasing trend of SPI-1 in those areas may be due to the concentration of rainfall.

4.4. Seasonal trends of wet and dry months

The wet events during the monsoons are often responsible for floods and the dry events in pre-monsoon are responsible for crop stress and production loss in Bangladesh. Therefore, trends of wet and dry months during monsoon and pre-monsoon seasons are analysed to assess the change in extreme periods in Bangladesh. Wet and dry months during monsoon and pre-monsoon seasons for the past 50 years (1958–2007) are identified by using the SPI method and are classified into three categories (Table I)
according to their severity. As the number of dry or wet months of extreme category during monsoon and pre-monsoon seasons are very few, the trends of wet or dry months of this category are not analysed in the present study. The trends in the number of dry and wet months of severe and moderate categories in monsoon and pre-monsoon seasons are given in Table II. The result shows a significant increase in the number of moderate wet months during pre-monsoon at the 95% level of confidence. Number of monsoon wet months of different categories is also found to increase, although the increases are not statistically significant. On the other hand, a significant decrease of moderate and severe dry months during pre-monsoon and severe dry months during monsoon is observed in Bangladesh over the time period 1958–2007.

Spatial patterns of the trends of moderate and severe wet months in monsoon, and moderate and severe dry months during pre-monsoon are also prepared as those events are important for Bangladesh. Figure 11(a) and (b) shows the spatial patterns of the trends in the number of monsoon wet months of moderate and severe categories, respectively. The figure shows an increasing number of moderate and severe wet months during monsoon in most parts of Bangladesh. A significant increase of moderate monsoon wet months (Figure 11(a)) is observed in north Bangladesh as well as in MCort station situated

Figure 10. (a) Trend of monthly minimum SPI of Bangladesh for the timer period 1958–2007 and (b) the spatial pattern of minimum SPI trends for the same time period. The numbers in the figure are Z values.
Table II. Trends of SPI-1 values of different categories during monsoon and pre-monsoon seasons.

<table>
<thead>
<tr>
<th>Number of wet and dry months</th>
<th>Mann–Kendal Z value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-monsoon moderate wet</td>
<td>2.36</td>
</tr>
<tr>
<td>Pre-monsoon severe wet</td>
<td>1.39</td>
</tr>
<tr>
<td>Pre-monsoon moderate dry</td>
<td>-1.96</td>
</tr>
<tr>
<td>Pre-monsoon severe dry</td>
<td>-2.60</td>
</tr>
<tr>
<td>Monsoon moderate wet</td>
<td>0.67</td>
</tr>
<tr>
<td>Monsoon severe wet</td>
<td>0.35</td>
</tr>
<tr>
<td>Monsoon moderate dry</td>
<td>-0.67</td>
</tr>
<tr>
<td>Monsoon severe dry</td>
<td>-1.65</td>
</tr>
</tbody>
</table>

Bold numbers denote a significant change.

in southeast Bangladesh. On the other hand, a significant increase of severe monsoon wet months (Figure 11(b)) is observed in southeast Bangladesh as well as in a station situated in north Bangladesh. The strongest increasing trend of severe monsoon wet months is observed in Chittagong station situated in the southeast hill region of Bangladesh. The region experienced a number of landslides in the recent years. A significant increase of wet events may trigger more landslides in the region in future. No significant increase of monsoon wet months is observed in the flood-prone areas of Bangladesh. However, increasing trends of severe wet months in the upstream of the rivers (northern Bangladesh) might increase the possibility of floods in some parts of Bangladesh.

The spatial patterns of trends in the number of pre-monsoon dry months of moderate and severe categories are shown in Figure 12(a) and (b), respectively. The figure shows decrease of moderate and severe dry months in most of the stations in Bangladesh. However, the decreases are significant only in few stations. A significant decrease of moderate pre-monsoon dry months (Figure 12(a)) is observed in two stations located in southeast Bangladesh. On the other hand, a significant decrease of severe dry months (Figure 12(b)) at the 90% level of confidence is observed in two stations located in the southwestern part of Bangladesh.

Rainfall and the wet events in pre-monsoon are very important in northern and northwestern parts of Bangladesh as these events help to increase soil moisture contents and crop productivity in the region. Drought in north and northwest Bangladesh especially during pre-monsoon is a frequent phenomenon because of high rainfall variability (Shahid, 2008). No significant decrease of dry months is observed in this part of the country, and therefore it is not possible to conclude that the situation of crop water stress during pre-monsoon will be improved with the significant increase of pre-monsoon rainfall in the region.

5. Conclusion

A study has been carried out in this article to assess the spatial patterns of the trends of long-term annual and seasonal rainfall as well as the number of wet and
dry months to detect the changes in rainfall and rain-induced extreme events in Bangladesh. The trend analysis shows a significant increase of average annual rainfall of Bangladesh at a rate of 5.52 mm/year over the time period 1958–2007. Spatial pattern of average annual rainfall shows that rainfall is significantly increasing in the western part of Bangladesh. Increased sea surface temperature might have altered the wind patterns to the west of Bangladesh, leading to an accumulation of moisture and to an increase of rainfall in the region. The trend analysis of seasonal rainfall over Bangladesh shows no significant changes in monsoon, post-monsoon and winter rainfall of Bangladesh. However, a significant increase of pre-monsoon rainfall by 2.47 mm/year at the 95% level of confidence is noted. The trend analysis of wet and dry months in Bangladesh shows that the number of wet months is increasing and the number of dry months is decreasing both in monsoon and pre-monsoon in most parts of the country. Increased pre-monsoon precipitation can reduce the pressure on groundwater for irrigation in Bangladesh. However, it might not help to improve the crop water stress conditions in north and northwestern region during pre-monsoon as no significant decrease of pre-monsoon dry months is observed in this part of the country. Increasing annual rainfall and pre-monsoon rainfall, and decreasing number of dry months may help to reduce the drought vulnerability and increase crop productivity in some parts of Bangladesh. Increasing trends of moderate and severe wet months in the upstream of the river might increase the possibility of floods in some parts of the country. Increase of severe monsoon wet months and maximum SPI-1 in southeast hill region of Bangladesh may accelerate the landslide events in the area.

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