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Characterization of climate change in southwestern Bangladesh: trend analyses of temperature, humidity, heat index, and rainfall

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ABSTRACT: Recent studies have identified Bangladesh as one of the most vulnerable countries in the world with respect to climate change. The objective of this study was to determine the long-term trends in annual, seasonal, and monthly air temperature, relative humidity, heat index, and rainfall in the south-western region of Bangladesh. The non-parametric Mann-Kendall trend test and Sen's slope methods were applied to quality-controlled time series data at 7 meteorological stations distributed across the region to detect the significance and magnitude of the trends in the selected climatic variables during 1960–2010. Based on these analyses, (1) significant rising trends in daily maximum, minimum, and mean temperatures were detected at a majority of the stations within the area, with pronounced warming during summer months; (2) relative humidity showed a significant increasing trend at both annual and seasonal scales over the region; (3) analysis of the heat index, which indicates what the temperature feels like to the human body when relative humidity is factored in with temperature, displayed a distinct increase in level of discomfort, exposing the population of Bangladesh to heat-related health hazards; and (4) the distribution of monthly rainfall patterns in the region seems to be changing, with significant variation in rainfall trends within the monsoon season by 6–7 mm yr^{-1}. The findings of this study increase our understanding of regional climate patterns, which can simplify larger analyses such as water budgets and agricultural production that depend on these types of data inputs, especially for the south-western region of Bangladesh.

KEY WORDS: Climate change · Bangladesh · Trends · Significant · Magnitude

1. INTRODUCTION

Studies to detect climate change and its impact on agriculture, water scarcity, and decreases in river flows deserve special attention (IPCC 2007). Temperature, relative humidity, and rainfall variability appear to be dominant aspects of climate change, having consequences for extreme climatic events. Temperature plays a prominent and well-known role in evaporation and transpiration, and therefore significantly affects water requirements and the policies that are enacted to ensure its availability (Chattopadhyay & Edwards 2016). On the other hand, rainfall is the most important natural factor that influences flood and drought conditions, and directly influences regional water resources and agricultural production (Jain et al. 2013), and we do not yet possess sufficient understanding to project the timing, magnitude, and consequences of many of these effects.

The last decades of the 20th century were globally the hottest since worldwide temperature measurement began in the 19th century (Frich et al. 2002, Jones et al. 2006). Annual trends in daily minimum and maximum temperatures in the latter half of the 20th century increased at many locations throughout the world (Jones 1999, Alexander et al. 2006). IPCC

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(2007) predicts global warming ranging between 1.4–5.8°C by the end of the 21st century. A change in the global mean temperature has been found to be significantly associated with the median intensity of extreme precipitation changes (Westra et al. 2013). Dai (2006) reported increases in relative humidity (0.5–2.0% decade^{-1}) over the United States, India, and China during the later parts of the 20th century. Despite a number of studies on climate change detection and forecast, the global picture of changes in climate extremes typically shows large areas with sparse data coverage (Frich et al. 2002). Such areas include parts of central and south Asia, including Bangladesh.

The Intergovernmental Panel on Climate Change (IPCC) designated Bangladesh as one of the most vulnerable countries in the world with respect to climate change (IPCC 2007). Hydrological changes are the most significant impacts of climate change in Bangladesh (Shahid 2010). A study on climate change vulnerability ranked water resources as the greatest concern for Bangladesh due to climate change (Agrawala et al. 2003). It has been predicted that climate change will cause a steady increase in temperature and rainfall across Bangladesh (IPCC 2007). In addition, due to its location in a sub-tropical region, inhabitants of Bangladesh are highly vulnerable to heat-related mortality. Recent studies have concluded that the trends and magnitudes of climate change over Bangladesh are broadly consistent with global trends and magnitudes (Ali 1999, Shahid 2010, Shahid 2011, Ferdous & Baten 2012, Mondal et al. 2013). Rajib et al. (2012) predicted increases in minimum and maximum temperatures by 1.1–2.7° and 1.2–1.8°C, respectively, over the north-western part of Bangladesh by the end of 21st century. Using simulated precipitation-related climate change indicators, Rahman et al. (2012) forecast an irregular distribution of rainfall over the country. Analyses of temperature indices by Rakib & Abedin (2012) and Rakib (2013) indicated warming of both daily minimum and maximum temperatures in the monsoon and premonsoon seasons over Bangladesh in recent times. The heat index (i.e. apparent temperature) in the south-western region of the country seems to be increasing the most (Rakib 2013). Mondal et al. (2013) observed increasing relative humidity trends in the winter, post-monsoon, and pre-monsoon seasons in south-western parts of Bangladesh. As such, more attention should be given to establish the precise relationship between climate change and human health in this region. The study of rainfall and temperature variability and the trends of extreme climate events are therefore important for a better understanding of floods, droughts, long-term water resource planning, agricultural development, and disaster management in Bangladesh in context of future climate scenarios. However, this region is not well studied.

In the present study, a trend analysis of the pattern of temporal change along with spatial variations of climate variables were analyzed for the south-western region of Bangladesh. The variables of interest include minimum, maximum, and mean temperatures, relative humidity, heat index, and rainfall. Mann-Kendall trend analysis and Sen's slope were used to detect the presence of significant change and the magnitude of change respectively.

2. MATERIALS AND METHODS

2.1. Study area and data set description

Geographically, Bangladesh stands on the northern shoreline of the Bay of Bengal, extending between 20° 34′–26° 38′ N latitude and 88° 01′–92° 41′ E longitude. The area has a tropical monsoon climate characterized by heavy seasonal rainfall, high temperatures, and high humidity. In general, maximum summer temperatures range between 38–41°C; May is the hottest month in most parts of the country. January is the coolest month, when the average temperature over most parts of the country is 16–20°C. Total annual rainfall varies from 1400 mm in the west to more than 4300 mm in the east. The monsoon months of June and July typically receive the most rainfall; 470 and 525 mm on average respectively. Average annual relative humidity ranges from 70.5 to 78.1% across the country, with values exceeding 80% from June through September. The plain land lies almost at sea level along the southern part of the country, with elevations of <10 m (Shahid 2010, Rajib et al. 2012). The majority of land in the south-west region of the country is used for agriculture and agro-based human settlement, and it is home to the world's largest coastal mangrove forest, the Sundarbans.

In this study, a trend analysis of patterns of temporal change and spatial variations of climate variables were analyzed for the south-western region of Bangladesh. Hydro-meteorological data were obtained from the Bangladesh Meteorological Department (BMD). To maintain data quality, the following criteria were applied to the climate variables: (1) a month was considered as having complete data if there were ≤5 d missing; (2) a year was considered complete if all months were complete according to item (1); and (3) a station series was considered complete if it had ≥65 % complete years according to item (2) in different periods (Rajib et al. 2012). Following these criteria, records from 7 meteorological stations distributed over the south-western region of Bangladesh were selected for inclusion in the analysis. Fig. 1 shows the spatial distribution of the selected stations, and Table 1 contains information on their geographic location. The statistical properties of the selected climate variables, which include daily maximum, minimum, and mean temperatures, relative humidity, and rainfall, averaged over the south-western region of Bangladesh are compiled in Table 2.

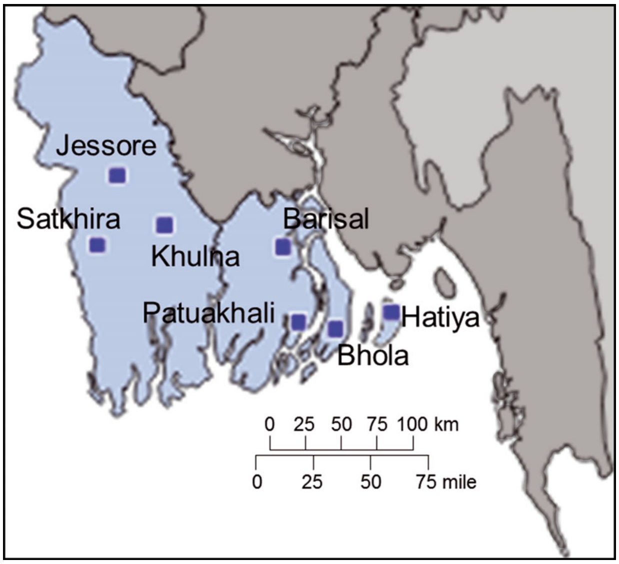

Fig. 1. Selected meteorological stations over the south-western region of Bangladesh used in the analyses

Table 1. Geographic location of selected stations over south-western Bangladesh

Station name	°N	°E
Barisal	22.701	90.353
Bhola	22.178	90.710
Hatiya	22.282	91.097
Jessore	23.163	89.218
Khulna	22.845	89.540
Patuakhali	22.225	90.455
Satkhira	22.723	89.075

2.2. Pre-processing of data

The 50 yr of daily data (1960–2010) were reduced to annual series of climate variables. These series were subsequently tested for the presence of break points, and to determine whether pre-whitening (discussed below, this subsection) was necessary. Detection of break points was tested in this study following the method described by Longobardi & Villani (2010), in which the time series must pass a *t*-test to be included in subsequent analyses. This approach has also been adopted in other relevant studies, such as Alamgir et al. (2015) and Chattopadhyay & Edwards (2016). The purpose of the *t*-test is to determine whether the mean, μ_1, of the series subset consisting of the first n_1 values should be considered as different from the mean, μ_2, of the remaining n_2 values of the series. The *t*-test statistic, $t_{n1,n2}$, which has a Student's distribution, is calculated as:

$$t_{n_1,n_2} = \frac{X_{1,\mathrm{mean}} - X_{2,\mathrm{mean}}}{S}\sqrt{\frac{n_1 n_2}{n_1 + n_2}} \qquad (1)$$

where $X_{1,\mathrm{mean}}$ and $X_{2,\mathrm{mean}}$ are the sample mean of n_1 and n_2 sample sizes from the time series, and the weighted sample variance, S, is given by:

$$S = \sqrt{\frac{n_1 S_1^2 + n_2 S_2^2}{n_1 + n_2 - 2}} \qquad (2)$$

where S_1 and S_2 are the variance of n_1 and n_2 values of the time series.

The *t*-statistics are calculated for all possible values of n_1 and compared to $t_{\nu,1-\alpha/2}$, where α is taken as 0.05, and the degrees of freedom, ν, are calculated from:

$$\nu = \frac{\left(S_1^2 / n_1 + S_2^2 / n_2\right)^2}{\frac{\left(S_1^2 / n_1\right)^2}{n_1 - 1} + \frac{\left(S_2^2 / n_2\right)^2}{n_2 - 1}} \qquad (3)$$

If $t_{n1,n2} > t_{\nu,1-\alpha/2}$ for any value of n_1, then the null hypothesis H_0: $\mu_1 = \mu_2$ is rejected, and the alternate

Table 2. Statistical properties of climate variables over south-western Bangladesh, 1980–2010, annual scale

	Maximum temperature (°C)	Minimum temperature (°C)	Mean temperature (°C)	Relative humidity (%)	Total rainfall (mm)
Mean	30.81	21.56	25.78	81.08	1870.1
Median	30.77	21.53	25.72	81.83	1851.3
Standard deviation	0.38	0.25	0.22	1.95	150.9

hypothesis H_a: $\mu_1 \neq \mu_2$ is accepted. The series was consequently considered to contain a break point, as it failed the *t*-test, and was excluded from subsequent analysis. The *t*-test was applied in this study, supposing that each year of the monitored period could represent a potential changing point, by breaking the sample series into 2 subset series and calculating whether the differences between the subset series were significant or not for the given confidence level (Longobardi & Villani 2010). The differences between the subset series may occur due to changes in the probability distribution through time. The purpose of the statistical test was to identify any such break point in the metadata for data consistency classification. There can be instances where the metadata indicate a break point, but statistical methods do not (or vice versa) (Longobardi & Villani 2010). In this study, time series that passed both the preliminary graphical inspection and statistical test were considered for trend analysis.

Other relevant studies have highlighted the need to test and correct for serial correlation in time series data prior to a trend analysis (Gocic & Trajkovic 2013, Chattopadhyay & Edwards 2016). The time series data passing the *t*-test was examined next for the presence of significant serial correlation as described by Gocic & Trajkovic (2013), to determine whether pre-whitening was required. Prewhitening is the process of eliminating or reducing short-term stochastic persistence to enable detection of deterministic changes in the time series analysis of hydroclimatic variables used in this study. It prevents the false detection of a non-existing trend by removing the autocorrelation in the time series (Bayazit & Önöz 2007). The serial correlation coefficient, r_1, is calculated as:

$$r_1 = \frac{\frac{1}{n-1}\sum_{i=1}^{n-1}(x_i - X_{\text{mean}})(x_{i+1} - X_{\text{mean}})}{\frac{1}{n}\sum_{i=1}^{n}(x_i - X_{\text{mean}})^2} \quad (4)$$

where n is the sample size and X_{mean} is the mean of the time series. No significant serial correlation is said to be present if the value of r_1 falls inside the bounds given by:

$$\frac{-1-1.645\sqrt{n-2}}{n-1} \le r_1 \le \frac{-1+1.645\sqrt{n-2}}{n-1} \quad (5)$$

If, however, significant serial correlation is detected, then a pre-whitened series, x^* (with one fewer data point than the original), is created for subsequent analysis:

$$x_i^* = x_{i+1} - r_1 x_i \quad (6)$$

2.3. Trend detection and characterization

A trend is a significant change over time exhibited by a random variable, detectable by statistical parametric and non-parametric procedures (Longobardi & Villani 2010). For trend detection in the climatic variables time series, non-parametric statistical procedures were applied in this study. In some cases, time series were divided into partially overlapping periods to detect whether trends appeared particularly severe during any time interval of the study period. The magnitude of the trend in a time series was determined using a non-parametric method known as Sen's estimator (Sen 1968), and the statistical significance of the trend was analyzed using the Mann-Kendall (MK) test (Mann 1945, Kendall 1975).

The MK test compares the relative magnitudes of the data rather than the data values themselves (Gilbert 1987). The benefit of this test is that the data does not need to conform to any statistical distribution. In this test, each data value in the time series is compared with all subsequent values. The MK statistic, S, of series x is given by:

$$S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} sgn\left(x_j - x_i\right) \quad (7)$$

where sgn is the signum function. The variance associated with S is calculated from:

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{m} t_k(t_k-1)(2t_k+5)}{18} \quad (8)$$

where m is the number of tied groups and t_k is the number of data points in group k. In cases where the sample size $n > 10$, the test statistic $Z(S)$ is calculated from:

$$Z(S) = \begin{cases} \frac{S-1}{\sqrt{V(S)}}, & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{V(S)}}, & \text{if } S < 0 \end{cases} \quad (9)$$

Positive values of $Z(S)$ indicate increasing trends, while negative $Z(S)$ values reflect decreasing trends. Trends are considered significant if values of $|Z(S)|$ are greater than the standard normal deviate $Z_{1-\alpha/2}$ for the desired value of α.

The Sen's approach was used in this study to quantify the significant linear trends in the time series. Widely used for determining the magnitude of trends in hydro-meteorological time series (Shahid 2010, Jain et al. 2013, Chattopadhyay & Edwards 2016), Sen's slope has the advantage over the regression slope in the sense that it is not affected by gross data errors and outliers. The slope, Q, between any 2 values of a time series x can be estimated from:

$$Q = \frac{x_k - x_j}{k - j}, \quad k \neq j \tag{10}$$

For a time series x having n observations, there are a possible $N = n(n - 1)/2$ values of Q that can be calculated. According to Sen's method, the overall estimator of the slope is the median of these N values of Q. The overall slope estimator Q^* is given by:

$$Q^* = \begin{cases} Q_{(N+1)/2}, & N \text{ is odd} \\ \dfrac{Q_{N/2} + Q_{(N+2)/2}}{2}, & N \text{ is even} \end{cases} \tag{11}$$

The confidence interval of the slope is calculated from the same array of ordered slopes Q_i using indexes M_1 and M_2. The lower and upper limits of the confidence interval, $Q_{\min}$ and $Q_{\max}$, are the M_1th largest and the $(M_2 + 1)$th largest of the N ordered slope estimates, Q_i.

$$Q_{\text{Lower}} = Q_{M_1} \tag{12}$$

$$Q_{\text{Upper}} = Q_{M_2+1} \tag{13}$$

where

$$M_1 = (N - C_\propto)/2 \tag{14}$$

$$M_2 = (N - C_\propto)/2 \tag{15}$$

and

$$C_\propto = Z_{1-\propto/2} * \sqrt{Var(S)} \tag{16}$$

where S is the MK test statistic, and $C_\propto$ is the confidence interval. Using tabulated Z-values for a cumulative normal distribution, the 95% confidence interval is calculated using $Z_{1-0.05/2} = 1.96$.

3. RESULTS AND DISCUSSION

3.1. Temperature trends

The mean annual temperature ranged from a low of 25.47°C for Bhola station to a high of 26.30°C for Satkhira station, with a regional mean of 25.78°C during 1980–2010. The minimum, maximum, and mean temperature time series at all stations passed the t-test for detection of break point. Pre-whitening was necessary for 2 of the stations and did not affect the detection of a significant trend.

For the trend analysis of average annual temperatures, 2 timeframes were examined: 1960–2010 and 1980–2010. Fig. 2 provides a detailed depiction of the average annual maximum, minimum, and mean temperature data, along with the calculated trend slope and 95% confidence limits of the slope for the south-

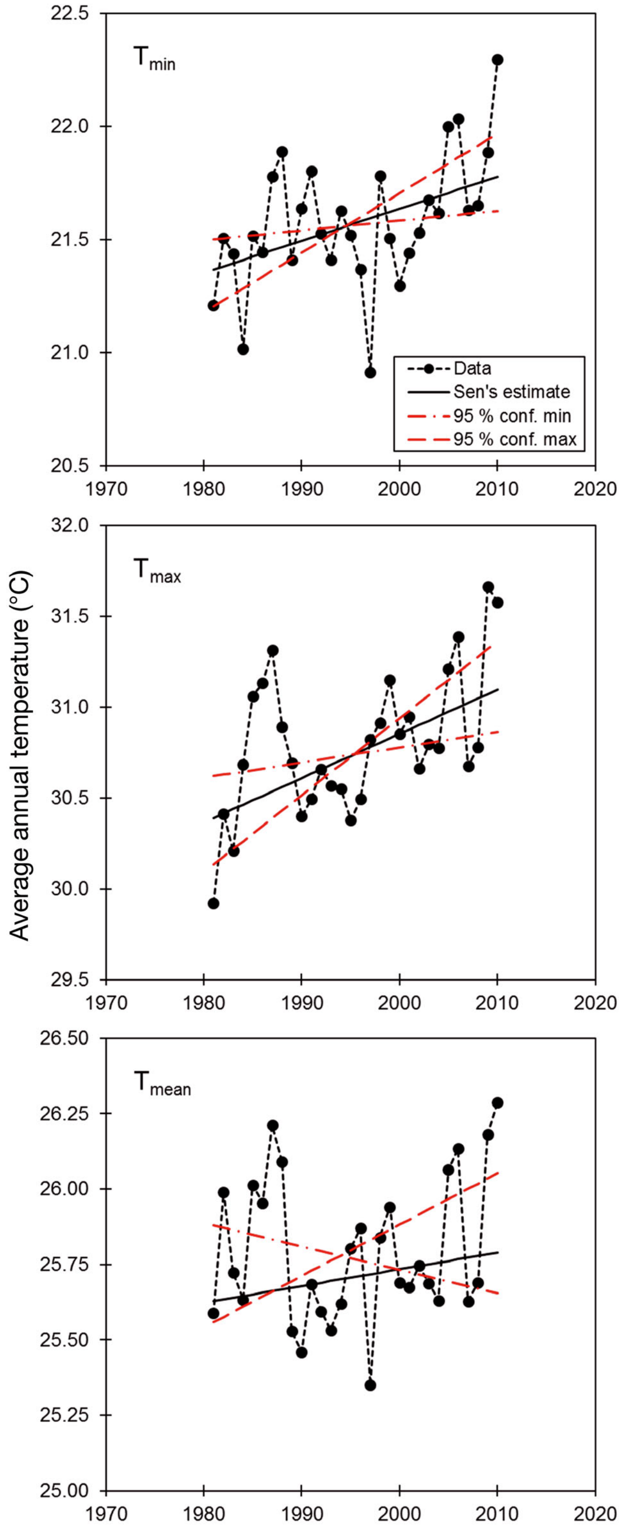

Fig. 2. Time series of annual minimum temperature (top), maximum temperature (middle), and mean temperature (bottom), averaged over the south-western region of Bangladesh during 1980–2010. Black straight lines: linear trend; red straight lines: 95% confidence limits estimated with Sen's slope estimator

western region during 1980–2010. The magnitude and statistical significance of the trend in the above time series over the region are shown in Table 3. A negative slope sign on the trend line indicates decline, while a positive sign indicates rise. The rate of temperature increases for 1980–2010 was higher than the 1960–2010 period.

The average annual maximum temperature change in the south-west region during 1980–2010 indicates significant variation, increasing at a rate of 0.24 ± 0.17°C decade^{-1} ($p < 0.01$). The analysis shows rising maximum temperature trends at all stations except for Satkhira. The trend is statistically significant at Barisal, Hatiya, Jessore, Khulna, and Patuakhali. Results of the MK trend test shows that the average annual minimum temperature over the study area has increased, and is statistically significant at $p < 0.01$. Minimum temperature also shows rising trends at all stations, except for Hatiya and Patuakhali. The trend is statistically significant at Barisal, Bhola, Khulna, and Satkhira. Overall, the minimum temperatures have been increasing at a rate of 0.14 ± 0.11°C decade^{-1}. Over the study area, there is an increasing trend in annual mean temperature as well. Except for Patuakhali and Satkhira, positive trends were observed at all stations, 4 of which were statistically significant.

On a seasonal basis, Rakib (2013) previously reported average maximum and minimum temperatures of 27.7 and 15.6°C during the dry season (November to February), 33.2 and 23.3°C during the pre-monsoon season (March to May), and 31.7 and 25.5°C during the monsoon season (June to October) for the south-western region of Bangladesh. In the present study, trend analysis was performed for the monthly time series of minimum, maximum, and mean temperatures averaged over the region. The magnitude and statistical significance of these trends are tabulated in Table 4. Except January, minimum and maximum temperatures in all months showed positive trends, 5 of which

Table 3. Station-wise temperature trend detection and characterization for the south-western region of Bangladesh during 1980–2010. Mann-Kendall (MK) analysis detects the presence of significant change and Sen's slope method quantifies the magnitude of change; Sen's slope estimates are °C yr^{-1}. ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$; (+) $p < 0.1$. SWR: south-west region

Station	Maximum temperature			Minimum temperature			Mean temperature		
	MK test Z	Sen's Q	Signif.	MK test Z	Sen's Q	Signif.	MK test Z	Sen's Q	Signif.
Barisal	2.96	0.026	**	3.28	0.028	**	2.39	0.013	*
Bhola	0.54	0.007		2.96	0.017	**	2.64	0.015	**
Hatiya	1.74	0.026	+	−0.17	−0.001		1.33	0.006	
Jessore	4.46	0.031	***	1.25	0.007		2.28	0.010	*
Khulna	2.48	0.027	*	4.39	0.046	***	4.39	0.036	***
Patuakhali	4.42	0.051	***	−0.54	−0.002		−1.00	−0.010	
Satkhira	−0.89	−0.012		2.53	0.020	*	−1.71	−0.024	+
SWR	2.75	0.024	**	2.68	0.014	**	1.07	0.006	

Table 4. Monthly temperature trend detection and characterization over the south-western region of Bangladesh during 1980–2010. Mann-Kendall (MK) analysis detects the presence of significant change and Sen's slope method quantifies the magnitude of change; Sen's slope estimates are °C yr^{-1}. ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$; (+) $p < 0.1$

Month	Maximum temperature			Minimum temperature			Mean temperature		
	MK test Z	Sen's Q	Signif.	MK test Z	Sen's Q	Signif.	MK test Z	Sen's Q	Signif.
January	−0.11	−0.005		−1.43	−0.027		−2.64	−0.043	**
February	1.68	0.035	+	0.18	0.005		0.11	0.005	
March	0.46	0.012		0.61	0.021		0.21	0.004	
April	1.46	0.028		2.00	0.036	*	1.21	0.023	
May	2.32	0.046	*	1.28	0.018		1.75	0.022	+
June	1.57	0.033		0.57	0.006		0.96	0.011	
July	3.21	0.032	**	2.43	0.016	*	2.60	0.020	**
August	3.43	0.033	***	2.07	0.012	*	1.39	0.012	
September	2.57	0.026	*	1.86	0.011	+	1.21	0.012	
October	1.03	0.012		1.07	0.019		−0.50	−0.008	
November	0.89	0.013		1.75	0.028	+	0.29	0.004	
December	0.21	0.003		1.11	0.019		−0.96	−0.013	

are statistically significant. For mean temperature, 9 months exhibited positive trends, 2 of which are statistically significant. Months from April to September display a higher magnitude of change, meaning that the summer period is becoming hotter relative to the other periods. This finding was further strengthened by the trend analysis of the number of days in a year with maximum temperature >35°C. On an average, 59 days in a year exhibit maximum temperature >35°C at Jessore, Khulna, and Satkhira stations. Results of the MK trend test show that the average number of days in a year with maximum temperature >35°C has increased over the study area, and the positive trend is statistically significant at $p < 0.01$.

3.2. Relative humidity trends

Relative humidity depends on the temperature and pressure of the atmosphere. A preliminary graphical inspection of relative humidity over the south-western region of Bangladesh indicated a progression from relatively moist patterns during 1950–1970 to relatively dry patterns during 1970–1985, and then back to the moist patterns from 1985–2010. This multi-decadal variability showing an increasing, decreasing, and again increasing pattern could be related to the frequency of depressions/cyclonic storms that form over the Bay of Bengal and move towards Bangladesh (Ali 1996, Dasgupta et al. 2014). The mean annual relative humidity ranged from a low of 77.6% for Satkhira station to a high of 83.9% for Bhola station, with a mean of 80.4% over all stations during 1970–2010. Time series data at all stations for this period passed the *t*-test for the detection of a break point, and pre-whitening was necessary for Hatiya station only.

Fig. 3 shows the average annual relative humidity for the south-western region during 1970–2010, along with the calculated trend slope and 95% confidence limits on the slope. Station-wise magnitude of the change in relative humidity and statistical significance of the trends are shown in Table 5. Over the region, relative humidity has been rising at a rate of 1.15 ± 0.36% decade^{-1}. Relative humidity at all stations shows an increasing trend, and the overall positive trend over the south-western region is statistically significant at $p < 0.001$. Trends at Jessore, Patuakhali, and Satkhira are also statistically significant at $p < 0.001$, while those at Barisal and Hatiya are statistically significant at $p < 0.1$. In context, considering 1950–2010 timeframe, the magnitude of the trend over the region is 0.55 ± 0.23% decade^{-1}, statistically significant at $p < 0.001$. For the recent period 1970–2010, the magnitude of the trend of relative humidity rise is nearly twice the rate of the 1950–2010 timeframe. The analysis elucidates that the increase in relative humidity in recent decades has been greater.

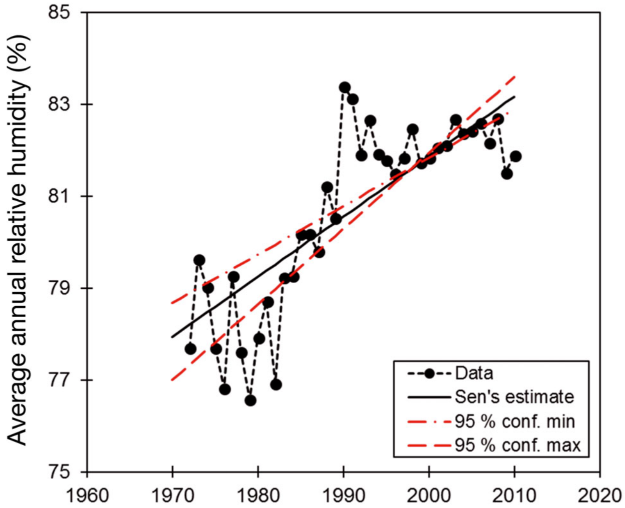

Fig. 3. Time series of annual relative humidity data averaged over the south-western region of Bangladesh during 1970–2010. Black straight line: linear trend; red straight lines: 95% confidence limits estimated with Sen's slope estimator

Table 5. Relative humidity trend detection and characterization at the south-western stations of Bangladesh during 1970–2010. Mann-Kendall (MK) analysis detects the presence of significant change and Sen's slope method quantifies the magnitude of change; Sen's slope estimates are % yr^{-1}. ***$p < 0.001$; *$p < 0.05$; (+) $p < 0.1$. SWR: south-west region

Station	MK test Z	Sen's Q	Signif.	Q_{min95}	Q_{max95}
Barisal	2.44	0.054	*	0.010	0.098
Bhola	0.97	0.016		−0.017	0.059
Hatiya	1.89	0.091	+	−0.004	0.152
Jessore	5.09	0.159	***	0.119	0.208
Khulna	0.97	0.026		−0.027	0.126
Patuakhali	4.75	0.246	***	0.125	0.339
Satkhira	3.33	0.176	***	0.077	0.270
SWR	4.35	0.115	***	0.081	0.153

In terms of seasonal variation, the average relative humidity in the south-western region of Bangladesh during dry, pre-monsoon, and monsoon seasons was 73.6, 78.0, and 88.2% respectively. Trend analysis of the seasonal time series over the region reveals that the relative humidity has increased during all seasons, of which the trends during pre-monsoon and monsoon are statistically significant at $p < 0.01$ and $p < 0.05$, respectively.

3.3. Heat index trends

As seen from analysis, the temperature and relative humidity over the study area has shown a rising trends, both spatially and temporally. Relative humidity has important considerations for the comfort of the human body. When the body gets too hot, it begins to perspire or sweat to cool itself off. However, when the relative humidity is high, the rate of evaporation from the body decreases. Thus, heat is removed from the human body at a lower rate, causing the experienced temperature to be more uncomfortable. On the other hand, when the relative humidity is low, the apparent temperature can be lower than the air temperature. Combining the effects of elevated temperature and humidity, Steadman (1979) presented an approach that allows us to compute a relevant heat wave index to assess the severity of heat-related events. Based on multiple regression analysis, the following heat index equation was attained (Rothfusz 1990):

$$HI = \frac{5}{9}\Big[\big\{-42.379 + 2.04901523\ (1.8T+32) + 10.14333127\ R - 0.22475541\ (1.8T+32)R - 6.83783\times10^{-3}\ (1.8T+32)^2 - 5.481717\times10^{-2}\ R^2 + 1.22874\times10^{-3}(1.8T+32)^2 R + 8.5282\times10^{-4}(1.8T+32)R^2 - 1.99\times10^{-6}(1.8T+32)^2 R^2\big\} - 32\Big] \quad (17)$$

where HI = heat index (°C), T = ambient dry bulb temperature (°C), and R = relative humidity. Because this equation is obtained by multiple regression analysis (Steadman 1979), the HI value has an error of ±0.72°C. The formula is valid only when air temperature and relative humidity are higher than 27°C and 40% respectively. Temperature and relative humidity time series data at stations that passed the t-test for the detection of break points were used to calculate HI. Pre-whitened data was used for the analysis.

Based on values calculated at different stations, the mean annual heat index ranged from a low of 29.5°C for Hatiya station to a high of 30.9°C for Satkhira station, with a mean of 30.2°C for all stations during 1980–2010. Comparing with the heat index table (Rakib 2013), these values can be classified as 'very warm'; fatigue is possible with prolonged exposure, and continuing activity could result in heat cramps.

Although the heat index approach uses dry bulb temperature for computation, a modification was applied in this study by using the daily maximum temperature to calculate a 'modified' heat index. As the relative humidity in the south-western region of Bangladesh varies little over the day, a heat index calculated by combining the relative humidity with the daily maximum temperature provides a more realistic picture of the heat hazard conditions during the daytime.

The modified heat index ranged from a low of 37.9°C for Hatiya station to a high of 44.2°C for Jessore station, with a mean of 42.1°C for the region. The mean modified heat index at Khulna and Satkhira were also >43°C. Based on the heat index chart, heat hazard conditions at all stations except Hatiya were categorized as 'very hot'. This scenario is considered dangerous, as heat cramps and heat exhaustion are very likely, and heat stroke is probable with continued activity or exposure.

Fig. 4 provides a detailed depiction of the heat indices calculated with dry bulb temperature and

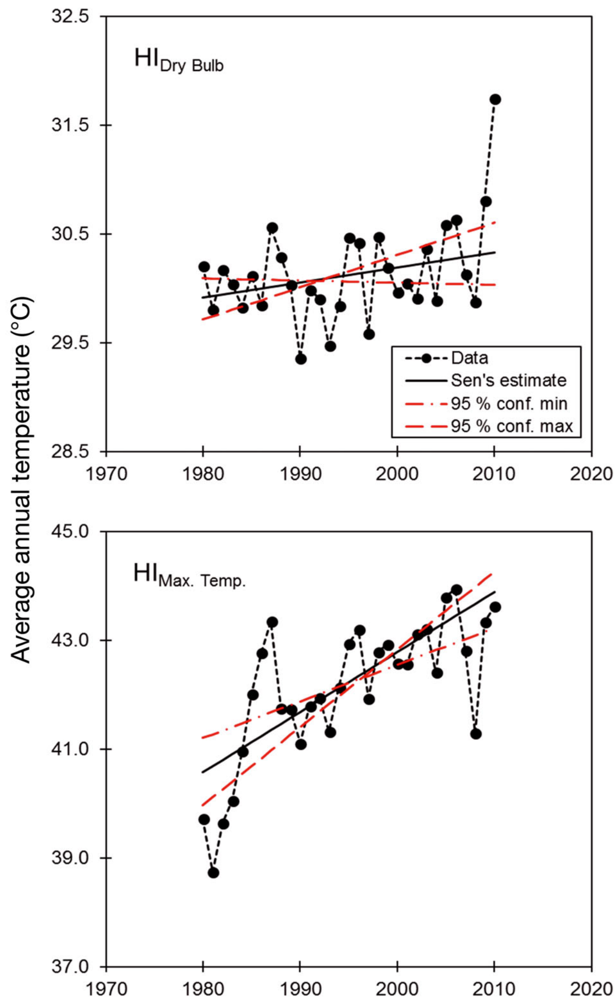

Fig. 4. Time series of annual heat index calculated with dry bulb temperature (top) and daily maximum temperature (bottom), averaged over the south-western region of Bangladesh during 1980–2010. Black straight lines: linear trend; red straight lines: 95% confidence limits estimated with Sen's slope estimator

maximum temperature, along with the calculated trend slopes and 95% confidence limits on the slopes for the south-western region during 1980–2010. Magnitudes and statistical significance of the trends in the above time series over the region are tabulated in Table 6 by station. The MK trend test showed that the average annual heat index over the study area has increased at a rate of 0.014 ± 0.016°C yr^{-1}, which is significant at $p < 0.1$. All stations except Satkhira showed an increasing trend, with statistically significant trends evident at Bhola, Hatiya, Jessore, and Khulna. The average annual modified heat index, calculated with maximum temperatures, indicates a significant trend over the region with a magnitude of 0.11 ± 0.038°C yr^{-1}. Apart from Bhola, trends at all stations were statistically significant at $p < 0.1$. Overall, the level of discomfort due to heat hazard conditions appears to be increasing with time.

On seasonal scale, Rakib (2013) previously reported mean heat index temperatures (dry bulb) of 24.9, 27.9, and 34.8°C during the dry (November to February), pre-monsoon (March to May), and monsoon season (June to October) respectively for the south-western region of Bangladesh. As per these values, heat hazard conditions over the region can be categorized as 'very warm' during dry and pre-monsoon months, and as 'hot' during monsoon months. Elevated temperatures and relative humidity during the monsoon results in higher discomfort levels. Trend analysis results of the seasonal heat index in this study indicate that the apparent temperature over the region is increasing at a rate of 0.046, 0.093, and 0.057°C yr^{-1} in the dry, pre-monsoon, and monsoon seasons; these trends are statistically significant at $p < 0.05$.

Table 6. Heat index trend detection and characterization at the south-western stations of Bangladesh during 1980–2010. Mann-Kendall (MK) analysis detects the presence of significant change and Sen's slope method quantifies the magnitude of change; Sen's slope estimates are °C yr^{-1}. ***$p < 0.001$; *$p < 0.05$. SWR: south-west region

Station	With dry bulb temperature			With maximum temperature		
	MK test Z	Sen's Q	Signif.	MK test Z	Sen's Q	Signif.
Barisal	1.63	0.023		3.67	0.105	***
Bhola	2.14	0.017	*	1.32	0.038	
Hatiya	1.77	0.019	+	2.04	0.085	*
Jessore	1.73	0.023	+	6.15	0.182	***
Khulna	3.84	0.055	***	1.86	0.066	+
Patuakhali	1.16	0.013		5.98	0.261	***
Satkhira	−1.80	−0.029	+	2.07	0.073	*
SWR	1.77	0.014	+	4.32	0.110	***

3.4. Rainfall trends

Annual total rainfall across the south-western region varied from the west (with average low of 1644 mm at Jessore station) to the east (with a high of 2133 mm at Barisal station). The annual rainfall averaged over the stations during 1960–2010 was 1835 mm. The time series at 3 stations failed the t-test and were excluded from further analysis. Pre-whitening was not required for the remaining stations and therefore did not affect the detection of significant trends.

Annual total rainfall at Khulna, Jessore, Barisal, and Satkhira during the 1960–2010 timeframe increased at a rate of 5.5 ± 6.9, 8.9 ± 6.8, 0.03 ± 7.8, and 4.7 ± 7.3 mm yr^{-1} respectively. Over this period, the annual total rainfall increase rate was 4.5 ± 3.8 mm yr^{-1} for the south-western region. This is consistent with the findings from Kripalani et al. (1996), who found an increasing trend in rainfall over Bangladesh after 1960. However, for the 1980–2010 timeframe, the annual rainfall trends at Khulna, Jessore, Barisal and Satkhira were −2.2 ± 17.2, 5.1 ± 18.0, −2.9 ± 16.9, and 7.9 ± 12.6 mm yr^{-1} respectively, although none of these trends were statistically significant. This, however, hints that the rainfall in some areas of south-west Bangladesh may have decreased in recent decades.

Examining the rainfall trends on a monthly scale revealed the severity of the situation. The magnitude and statistical significance of the trends in monthly rainfall over the region are presented in Table 7. Averaged over all stations, the monthly rainfall totals show a decreasing trend for 6 months during the 1960–2010 period, and 9 months during 1980–2010, although annual rainfall seems to have increased. June, which has traditionally been the month with maximum rainfall, showed an insignificant negative trend at a magnitude of 0.3–1.5 mm yr^{-1}. Rainfall decreased at a rate of 1.0–2.9 mm yr^{-1} in August, with the trend being significant for the 1980–2010 timeframe. Other months with a statistically significant negative trend in rainfall were April and December. On the other hand, July and September saw a statistically significant rise in rainfall amounts, at a rate of 1.6–4.4 and 1.4–4.7 mm yr^{-1} respectively. The trend analysis suggests that the monthly distribution of rainfall patterns in south-west Bangladesh may be shifting from June to July and from August to September by 5.8 ± 4.3 and 7.4 ± 2.9 mm yr^{-1}, respectively, making the monsoon rainfall more variable. Fig. 5 provides an illustration of the

Table 7. Monthly rainfall trend detection and characterization over the south-western region of Bangladesh. Mann-Kendall (MK) analysis detects the presence of significant change and Sen's slope method quantifies the magnitude of change; Sen's slope estimates are mm yr^{-1}. $^{**}p < 0.01$; $^{*}p < 0.05$; (+) $p < 0.1$

Month	1960–2010 timeframe			1980–2010 timeframe		
	MK test Z	Sen's Q	Signif.	MK test Z	Sen's Q	Signif.
January	0.88	0.011		−0.19	0.000	
February	0.22	0.000		−1.47	−0.790	
March	−0.06	−0.021		−0.09	−0.100	
April	−0.03	−0.010		−2.31	−2.391	*
May	1.33	0.985		−1.46	−1.414	
June	−0.27	−0.290		−0.47	−1.463	
July	1.78	1.557	+	2.42	4.350	*
August	−1.28	−1.017		−2.10	−2.901	*
September	1.70	1.358	+	2.72	4.469	**
October	−0.15	−0.161		1.97	3.587	*
November	0.18	0.034		−0.58	−0.158	
December	−1.99	−0.031	*	−2.55	−0.125	*
Annual	2.34	0.377	*	0.73	0.185	

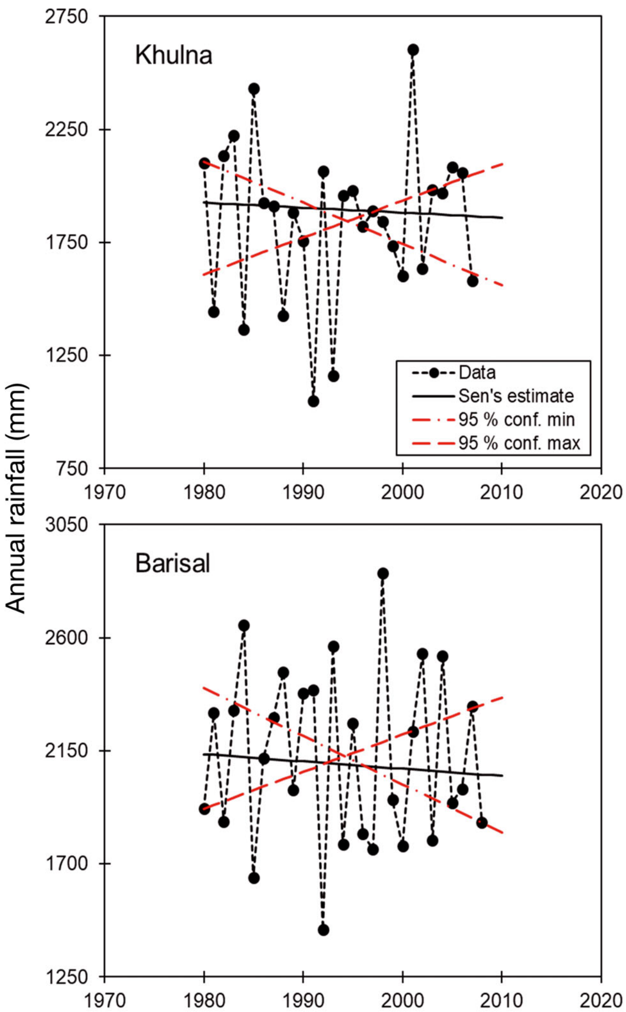

Fig. 5. Time series of annual rainfall at Khulna (top) and Barisal (bottom) stations in the south-western region of Bangladesh during 1980–2010. Black straight lines: linear trend; red straight lines: 95% confidence limits estimated with Sen's slope estimator

annual rainfall at Khulna and Barisal stations, along with the calculated trend slope and 95% confidence limits on the slope during the period from 1980–2010.

4. CONCLUSIONS

An understanding of the spatial and temporal distribution and changing patterns in climatic variables is an important requirement for planning and management of water resources. This study examined trends in annual, monthly, and seasonal temperature, relative humidity, heat index, and rainfall on a regional scale for the south-western region of Bangladesh. The results obtained agree well with the findings from other relevant studies for the focus area.

Trend analysis of the temperature data showed that all 3 temperature variables (maximum, minimum, and mean) exhibited a rising trend at a majority of the stations within the study area. Summer months are becoming hotter, with a significant increase in the number of days in a year with maximum temperature >35°C. The increasing temperature, rising at a rate of 0.14–0.24°C decade^{-1}, has the potential to reduce rice and wheat production by one-quarter in the region (Kalra et al. 2008, Sarker et al. 2012). Higher temperatures will likely reduce livestock production as well during the summer season. Based on the magnitudes of the significant positive trends obtained from this study, the minimum and maximum temperatures over the south-western region of Bangladesh are expected to rise by 1.26 and 2.16°C by the end of the 21st century. In comparison, Rajib et al. (2012) predicted a 1.64 and 1.59°C increase in minimum and maximum temperatures by the year 2100 over the north-western region of the country based on regional climate model results. The magnitudes of the temperature increases over south-west Bangladesh are comparable to the trends reported for neighboring areas, such as 0.21, 0.17, and 0.14°C decade^{-1} over the southern, central, and western regions of India (Jain & Kumar 2012, Sonali

& Kumar 2013). Consistent with these studies, monsoon season warming has been found to be greater for south-west Bangladesh. The temperature increases observed over the region also align with global warming of 1.4–5.8°C by the end of the 21st century as predicted by IPCC (2007).

The spatial analysis of rainfall variability revealed decreasing trends in parts of south-western Bangladesh in recent times, although annual rainfall averaged over the entire region seems to be increasing. However, the trends were not significant. The overall increasing trend in annual total rainfall in the region is consistent with previous studies (Kripalani et al. 1996, Shahid 2010). More importantly, the analysis suggests that the temporal distribution of monthly rainfall patterns in the province has shifted within the monsoon season in recent decades. As monsoon rainfall becomes more variable, local crops will begin to experience failure, and systemic changes in agricultural resource allocation and planning will need to be considered. The rainfall trends of the surrounding regions are comparable to the magnitude of the trends obtained in this study, such as –3.01 mm yr^{-1} over north-east India (Jain et al. 2013), –1.83 to –2.41 mm yr^{-1} over west India (Jain & Kumar 2012), and –6.3 mm yr^{-1} over Nepal (Panthi et al. 2015).

Trend analysis of relative humidity over the region confirms an increasing pattern at both annual and seasonal scales. The apparent temperature, represented by a heat index obtained by combining air temperature and relative humidity, also showed an upward shift through time over south-western Bangladesh. The level of discomfort has increased markedly in recent decades. With worsening temperature scenarios, the population is expected to face a wide range of heat-related health hazards.

As the consequences of climate change are not distributed uniformly within communities, individual and social factors will lead to differential vulnerability and capacity to adapt to the effects of the change. The findings of this study can simplify, or at least not complicate, larger analyses that depend on this type of data input, especially for the south-western portions of the country.

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