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Historical trends and variability of temperature extremes in two climate vulnerable regions of Bangladesh

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Abstract

Research on temperature extremes deserves more importance because it reacts sensitively to climate change. As elsewhere across the world, Bangladesh has already become a victim of temperature extremes. Hence, this study was conducted to assess the trends and variability of 11 temperature-related extreme indices based on daily maximum (TX) and daily minimum (TN) temperature recorded at Rajshahi and Barisal over the period 1976–2015. The indices were calculated on annual basis and their average annual and decadal trends were evaluated by non-parametric Mann-Kendall test and Sen's slope estimate. Significant ($p \leq 0.01$) upward trend was observed in some of the hot extremes, such as SU35: number of days with TX > 35°C and TR25: number of days with TN > 25°C, indicating that the number of days and nights with extreme hot temperature are increasing in both sites. Significant decreasing rate (-0.308 day/year) of SU25: number of days with TX > 25°C and increasing rate (1.00 day/year) of SU35 demonstrate that moderate hot days are converting to extreme hot days at Rajshahi. All cold indices showed significant ($p \leq 0.05$) variations at Rajshahi implying that cold extremes are becoming severe in this area. Significant rising trend of diurnal temperature range (DTR) indicated the higher rate of increase in TX than in TN at Rajshahi. The increasing trend of all hot indices at Barisal, close to the coast, reveals more warming in hot extremes. However, no significant trends of cold indices were observed at Barisal. Significant average decadal variations of temperature indices were only observed for hot index TNx: annual maximum TN (0.372 °C/decade) and cold index CD25: number of days with TX < 25°C (4.70 days/decade) at Rajshahi and hot index SU35 (5.650 days/decade) at Barisal. So, the relatively dry western region of the country is vulnerable to both hot and cold extremes, whereas coastal area is susceptible to only hot extremes.

Introduction

Global warming has already manifested changes in climate extremes as well as changes in climate averages. Changes in climate extremes deserve more attention of scientific community because they react more sensitively to climate change than mean climate (Katz and Brown, 1992). Substantial changes in the frequency of temperature extremes may occur whereas one can observe relatively small changes in the mean temperature (Mearns *et al.*, 1984; Hansen *et al.*, 1988). Changes in frequency, intensity, spatial extent, duration and timing of extreme temperature events have already been observed over the planet (Meehl *et al.*, 2007). All these are resulting in unprecedented impacts on different parts of life.

Agriculture is very responsive to precipitation and temperature extremes. The effects of extreme temperature on mortality, comfort, ecology, agriculture and hydrology are already evident (Ciais *et al.*, 2005; Patz *et al.*, 2005). Higher temperature adversely affects plant growth, pollination and reproductive processes (Klein Tank *et al.*, 2006; Sacks and Kucharik, 2011). A short period of abnormally high or low temperatures can have a significant harmful effect on crop growth and final yield (Mearns *et al.*, 1984). As elsewhere across the world, most imminent impacts of climate change in Bangladesh are mainly attributed to the higher daily temperature and temperature-related extreme events (Shahid *et al.*, 2016). The effects of temperature extremes on agriculture (Sikder *et al.*, 2014) and other

sectors (Shahid *et al.*, 2016) have been observed in the country. The agricultural sector is most likely to face significant yield reduction in future due to temperature variability (Islam *et al.*, 2011). Substantial effects will be on rice production (MoEF, 2005; Yamin *et al.*, 2005). The overall rice production in Bangladesh is predicted to decrease by an average of 7.4% every year over the period of 2005–2050 (Sarker *et al.*, 2012) due to variation in temperature extremes.

Considering the consequences of temperature extremes, substantial efforts have been made to estimate not only changes in mean temperature series, but also changes in the frequency, intensity and duration of extreme temperature events (Easterling *et al.*, 2000; Jones *et al.*, 2001; Moberg and Jones, 2005; Alexander *et al.*, 2006). These studies have analyzed temperature extremes at different spatial scales, ranging from the regional to the global. Overall, a global significant decrease in cold temperature extremes and an increase in the frequency and intensity of hot extremes have been noted (Alexander *et al.*, 2006; Wu *et al.*, 2017). South Asian countries have been observing an increase in occurrence of extreme climate events in recent decades (Ghosh *et al.*, 2016). However, the characteristics of climate extremes are still poorly understood at regional scale. Therefore, monitoring the actual changes in climate extremes is needed for many regions, particularly in Africa, South America and parts of Asia (Alexander *et al.*, 2006).

Historical trends of daily temperature extremes

Several attempts have been made to detect the climate change and climate extremes in Bangladesh. Over the past few decades, a warmer winter with a prominent increase in the minimum temperature and more hot summer were experienced by the country (Nishat and Mukherjee, 2013). General increasing trends of monthly average temperature both in winter and summer seasons and yearly average temperature were observed at different agro-ecological zones (Mia, 2003). The increasing trend was observed for monthly maximum temperature, whereas the monthly minimum temperature showed both decreasing and increasing trends (Islam *et al.*, 2004). Similarly, yearly average maximum and minimum temperatures recorded at Rajshahi, Barisal and Mymensingh stations showed an increasing trend over a period spanning from 1961 to 2009; however, the incremental rate was higher in case of minimum temperature (Rahman *et al.*, 2017). An overall increasing trend for annual average temperature and decreasing trends for the annual highest maximum and lowest minimum temperatures (Nasher and Uddin, 2013) were found for Rajshahi station. All these studies have analyzed the trends of average temperature and temperature extremes, but the later only considered monthly and yearly maximum and minimum values as extremes. However, to better characterize the temperature extremes, the Expert Team on Climate Change Detection and Indices (ETCCDI) has defined 16 temperature extreme indices, which are widely used in climate change related studies in different parts of the world (Zhang *et al.*, 2011). International community has agreed to the ETCCDI indices aiming to monitor changes in extremes and to augment studies on climate extremes as these are statistically robust, and cover a wide range of climates (Keggenhoff *et al.*, 2014). The indices also have potential to obtain a broad and more reliable scenario of temperature behavior in the study area (El Kenawy *et al.*, 2011). Researchers from different regions or countries can calculate the indices the same way such that the results are comparable with analysis conducted elsewhere in the world and can fit perfectly into the global picture (Guan *et al.*, 2015). Very few studies in Bangladesh have so far incorporated some of these indices. Hasan *et al.* (2013) computed and analyzed six extreme temperature indices to focus on their seasonal changes by using finer resolution climatic change projections. Shahid *et al.* (2016) also analyzed the trends of six threshold temperature indices and their impacts on different sectors of Bangladesh. However, there is still enough scope to better characterize the temperature-related climate extremes in Bangladesh by incorporating a wide variety of ETCCDI extreme temperature indices. Moreover, it is necessary to compare country's climate change with global climate change as well as to assess how global warming might affect the country's future climate. Therefore, this study aims to calculate ETCCDI defined extreme temperature indices and analyze their average annual and decadal trends to check the reality of climate change in two climate-vulnerable (drought prone and coastal) areas of Bangladesh.

Materials and Methods

Study area

Barisal and Rajshahi were selected as the study area (Figure 1). These regions, respectively, represent the coastal and dry ecosystems, which are sensitive to climate change (Rahman *et al.*, 2017). Barisal is a coastal district of Bangladesh having a tropical monsoon-type climate, hot and rainy summer and dry winter. This area is subjected to cyclones originating over the Bay of Bengal. Mean annual maximum and minimum temperatures of Barisal are 35.1°C and 12.1°C, respectively. Annual average rainfall is about 1955 mm. Rajshahi, the relatively dry region of the country, is drought prone and often impacted by the late arrival or early withdrawal of the monsoon. The area is characterized with rainfall, generally below 1500 mm, summer humidity less than 50%, and summer maximum temperature over 35°C (Banglapedia, 2006). The average elevation of Rajshahi and Barisal is 16.8 m and 2.1 m, respectively.

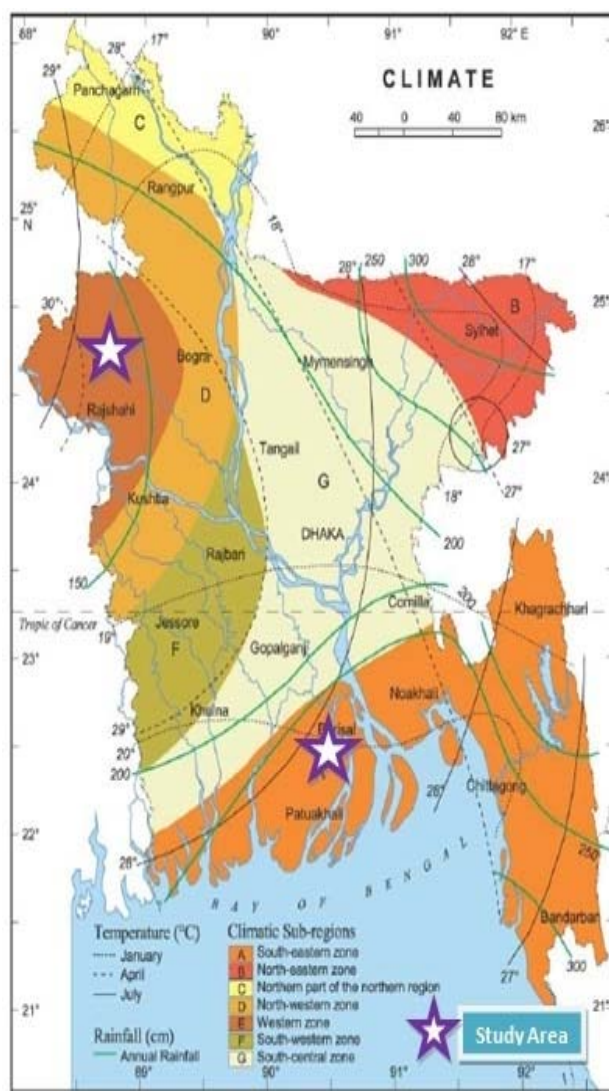


Fig 1. Locations of study areas in Bangladesh [adapted from Banglapedia (2014)].

Data collection and processing

Daily values of the maximum and minimum temperatures recorded at Rajshahi and Barisal meteorological stations were collected from Bangladesh Meteorological Department (BMD). There were some missing data in the collected temperature data series. The study was restricted to 40-year period of 1976–2015 to ensure the least number of missing data in temperature time series. Several data were still missing that were estimated by using nearby values. Any single missing data for a particular day in the time series was estimated by averaging the values of the previous and the following 3 days' data, whereas a series of consecutive missing values were estimated by averaging the data values of that date in the previous and the following 3 years' data (Mahmud, 2012). The collected data were subjected to several quality control checks to identify erroneous data resulting from archiving, transcription and digitizing processes (e.g. $T_{min} \geq T_{max}$, temperature values less than 2°C). Finally, a set of 11

extreme temperature indices were calculated on annual basis using Microsoft Excel spreadsheets.

Definition of extreme temperature indices

The Expert Team on Climate Change Detection and Indices, ETCCDI, has recommended a suite of 16 temperature indices that cover many relevant aspects of temperature extremes (Zhang *et al.*, 2011, <http://cccma.seos.uvic.ca/ETCCDI>). These indices have been utilized often to research temperature extremes throughout the last several years and in many countries (Klein Tank *et al.*, 2006; Li *et al.*, 2012; Guan *et al.*, 2015). These indices reflect different aspects in climate extremes, e.g., frequency, intensity and duration. Among the 16 ETCCDI-defined temperature indices, 7 indices (TXx, TNx, TXn, TNn, SU25, TR20 and DTR) were used for this study. In addition, based on the nature of meteorological data of Bangladesh, the authors defined 4 other threshold temperature indices, which are: SU35, TR25, CD25 and CN10. All these indices are described in the Table 1.

Table 1. Definition of extreme temperature indices

	Index	Description	Definition	Units
Hot Extremes	TXx ^a	Maximum TX ^c (Warmest TX)	Annual maximum value of TX	°C
	TNx ^a	Maximum TN ^d (Warmest TX)	Annual maximum value of TN	°C
	SU25 ^a	Summer days (Hot days)	Annual count of days where TX > 25 °C	days
	SU35 ^b	Summer days (Extreme hot days)	Annual count of days where TX > 35 °C	days
	TR20 ^a	Tropical nights (Hot nights)	Annual count of days where TN > 20 °C	days
	TR25 ^b	Tropical nights (Extreme hot nights)	Annual count of days where TN > 25 °C	days
Cold Extremes	TXn ^a	Minimum TX (Coldest TX)	Annual minimum value of TX	°C
	TNn ^a	Minimum TN (Coldest TN)	Annual minimum value of TN	°C
	CD25 ^b	Cold days	Annual count of days where TX < 25 °C	days
	CN10 ^b	Cold nights	Annual count of days where TN < 10 °C	days
Variability Extreme	DTR ^a	Diurnal temperature range	Annual mean difference between TX and TN	°C

^a ETCCDI defined index; ^b Authors' defined index; ^c TX = Daily maximum temperature; ^d TN = Daily minimum temperature

Methods for trend analysis

Trend analysis was done by using MAKESENS trend model. MAKESENS performs two types of statistical analyses. First, the presence of a monotonic increasing or decreasing trend is tested with the nonparametric Mann-Kendall test (Kendall, 1975) and, secondly, the slope of a linear trend is estimated with the nonparametric Sen's method (Gilbert, 1987). The Mann-Kendall statistic is a rank-based nonparametric test, which is advantageous compared to parametric tests because it is robust to outliers and does not assume an underlying probability distribution of the data series. That is why this statistic has been widely used in climatological and hydrological applications (Choi *et al.*, 2009). The Sen's method uses a linear model to estimate the slope of the trend and the variance of the residuals remains constant in time. Missing values are allowed, and the data need not conform to any distribution. Details of the Mann-Kendall test and Sen's Slope

estimation along with their theory of statistics are found in the MAKESENS manual (Salmi *et al.*, 2002).

Data analysis

Historical trends along with statistical significance of 11 temperature indices were calculated by using MAKESENS model in two steps. In step 1, 40-year annual time series of all temperature indices were entered into annual data worksheet of the model. The model was then run to calculate trend statistics, test Z ($n = 40$), and significance level of each index. In step 2, the inter-decadal change in the temperature indices was estimated. For that, 10-year averages for each extreme temperature index were calculated from their annual series. Hence, 4 consecutive decadal average values (past to recent) for each index were found and entered into MAKESENS annual data worksheet considering them as continuous annual data. The model was again run for test S ($n = 4$) and statistical significance was calculated.

Results and Discussion

Inter-annual variations

Hot extremes: General upward/increasing trends in most of the hot extremes such as TN_x (annual maximum TN), SU35 (number of days with TX > 35°C), TR20 (number of days with TN > 20°C), and TR25 (number of days with TN > 25°C) were observed for both Rajshahi and Barisal areas (Table 2). Two hot extremes, TX_x (annual maximum TX) and SU 25 (number of days with TX > 25°C), changed differently at the two study sites: upward trend at Barisal and downward trend at Rajshahi. However, both SU35 and TR25 showed highly significant ($p \leq 0.01$) upward trends at both sites at a rate of 1.00 day/year and 0.762 day/year, respectively at Rajshahi (Table 2, Fig 2), and 0.50 day/year and 1.435 day/year, respectively at Barisal (Table 2, Fig 3). The results indicate that extreme hot days and extreme hot nights were increasing in both areas. The increasing number of hot nights at Rajshahi was in line with the findings of Shahid *et al.* (2016) and Brammer (2016); however, the increasing number of hot days was only consistent with Shahid *et al.* (2016). The index TR20 was found to increase at both areas. But, the significant average annual rate of increase (0.276 day/year) was found at Barisal only (Fig 3). The trend of SU25 was

inconsistent with the changes of SU35 at Rajshahi. Though SU25 decreased at a rate of 0.308 day/year, a high increasing rate of SU35 (1.00 day/year) was observed, indicating that moderate hot days are converting to extreme hot days at Rajshahi (Table 2). Such change is more confined to summer as the city experienced some of the hottest days with a temperature of about 42°C or even more in this season (Shahid *et al.*, 2016). This result is also consistent with the findings of Dastagir (2015) who found that warm days were increasing in the northern Bangladesh during the period of 1970–2009. At Barisal, only SU35 increased significantly ($\alpha \leq 0.001$) (Table 2, Fig 3). In general, all the hot extreme indices revealed a general increasing trend at Barisal indicating that the area is becoming warmer day by day. This result is in support with the findings of more warming in hot extremes close to the coasts (EI Kenawy *et al.*, 2011). Nonetheless, the result comes in contrast to the other studies documenting less warming near the coasts compared to continental areas (IPCC, 2007). The general upward trends of hot extremes at both study areas are also consistent with the results obtained in other global temperature studies (Alexander *et al.*, 2006) as well as regional studies (Zhai and Pan, 2003; Guan *et al.*, 2015).

Table 2. Inter-annual variations of temperature extremes

Index	Rajshahi Station		Barisal Station		
	Mann-Kendall Test Z	Sen's slope (°C or days/year)	Mann-Kendall Test Z	Sen's slope (°C or days/year)	
Hot Extremes	TX _x	-0.4	-0.012	1.27	0.020
	TN _x	1.22	0.013	1.37	0.114
	SU25	-2.23	-0.308*	0.48	0.044
	SU35	3.24	1.00**	3.30	0.50***
	TR20	0.83	0.167	1.90	0.276 ⁺
	TR25	3.86	0.762***	3.37	1.435***
Cold Extremes	TX _n	-3.34	-0.12***	-1.91	-0.067 ⁺
	TN _n	-2.71	-0.044*	0.55	0.004
	CD25	2.94	0.506**	0.51	0.067
	CN10	2.45	0.333*	-0.06	0
Variability Extreme	DTR	1.71	0.013 ⁺	4	0

NB: ⁺ = 0.1 level of significance, * = 0.05 level of significance, ** = 0.01 level of significance, *** = 0.001 level of significance; negative sign indicates decreasing trends

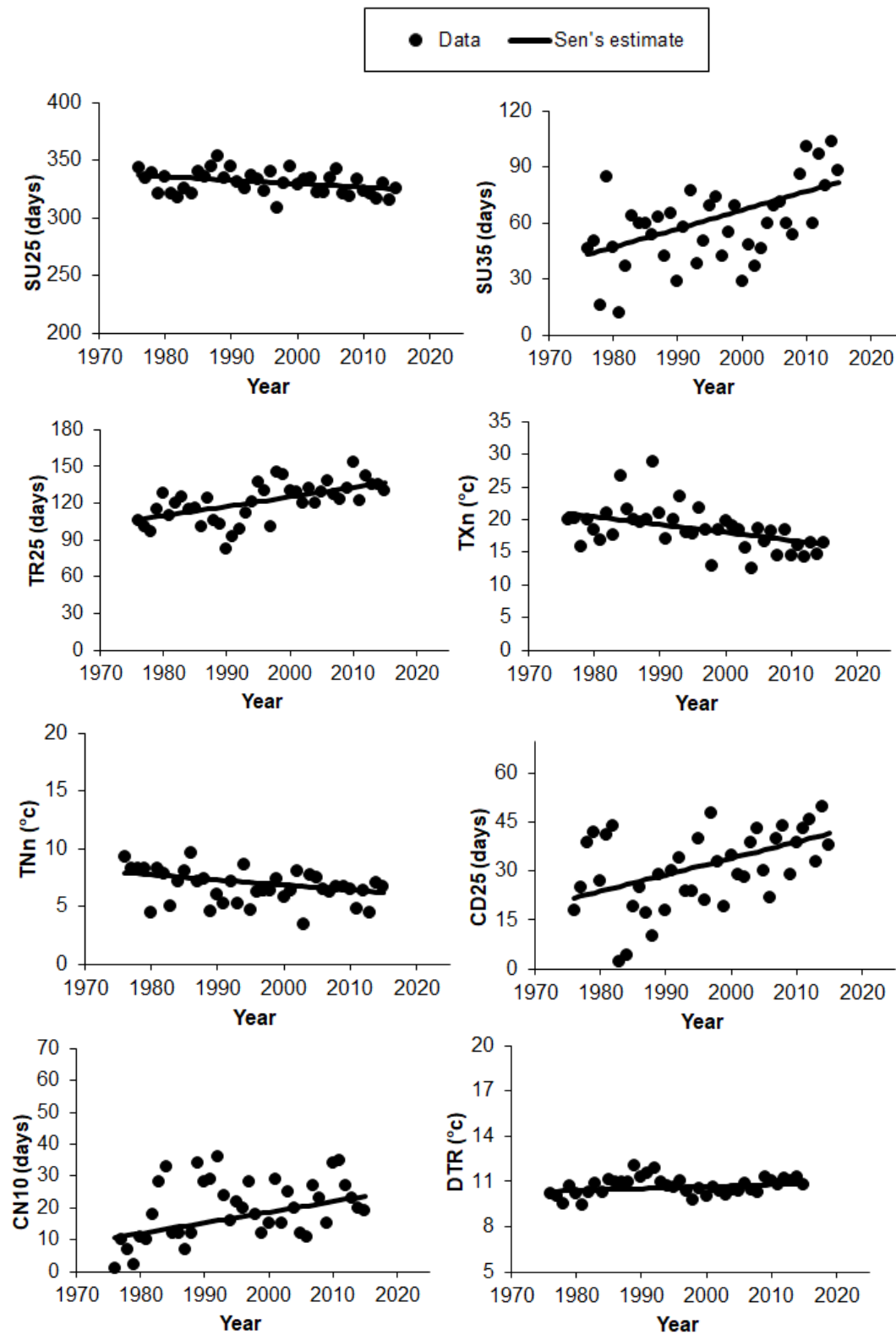


Fig. 2. Average annual trends of hot indices, i.e. SU25 (days with daily maximum temperature (TX) > 25 °C), SU35 (days with TX > 35 °C), TR25 (days with daily minimum temperature (TN) > 25 °C); cold indices i.e. TXn (annual minimum TX), TNn (annual minimum TN), CD25 (days with TX < 25 °C), CN10 (days with TN < 10 °C) and variability index DTR (diurnal temperature range) at Rajshahi

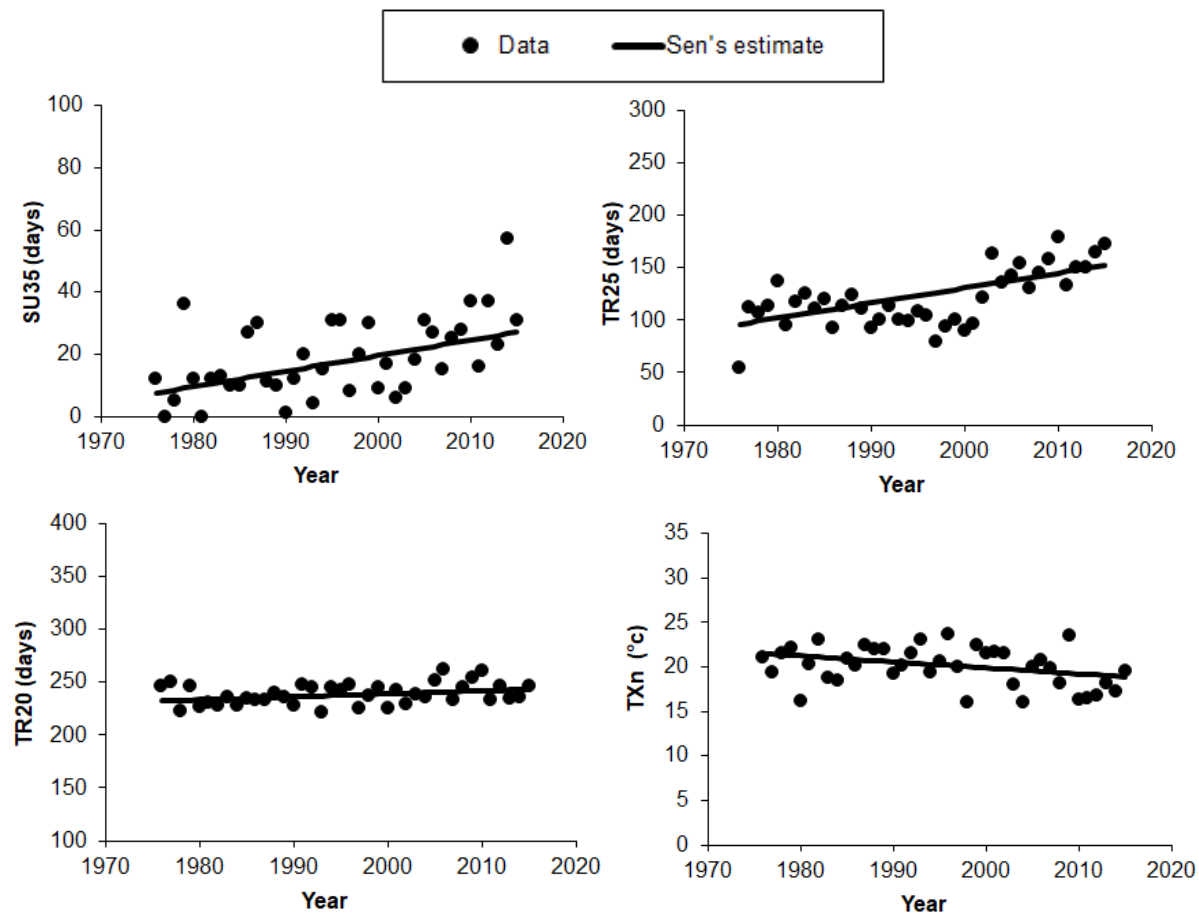


Fig. 3. Average annual trends of hot indices, i.e. SU35 (days with daily maximum temperature (TX) > 35 °C), TR25 (days with daily minimum temperature (TN) > 25 °C), TR20 (days with TN > 20 °C) and cold index TXn (annual minimum TX) at Barisal

Cold extremes: Among the cold extreme indices, TXn (annual minimum TX) showed significant downward trends at both study sites (Table 2, Figs 2 & 3). In contrast, TNn (annual minimum TN) showed significant downward trends at Rajshahi but insignificant upward trend at Barisal (Table 2). General downward trends of these indices, except TNn, designate that cold extremes are generally getting severe meaning that winter is getting colder. Two cold extreme indices, CD25 (number of days with TX < 25°C) and CN10 (number of days with TN < 10°C), showed rising trends at Rajshahi (Fig 2), signifying that number of cold days and cold nights increased over the study period at a rate of 0.506 day/year and 0.333 day/year, respectively. Such cold extremes are particularly skewed to January when the temperature falls to about 5°C or even less. Similar results were also found for a study period of 1958–2012 at the same place (Shahid *et al.*, 2016). Such findings are, however, not sufficient to conclude the increasing trends of cold extremes at Rajshahi because the area also experienced with reduction in the number of cold nights (Dastagir, 2015). Increasing changing pattern of cold days (CD25 = 0.067 day/year) was found at Barisal but it was not statistically significant. In general, changes in cold extremes for both study areas are not too prominent like hot extremes. Similar findings, confirmed in other

studies worldwide, showed little changes in cold extremes and lower variance in cold tail of temperature distribution (EI Kenawy *et al.*, 2011).

Variability extreme: Variability index DTR (annual mean difference between daily maximum and minimum temperatures) of Rajshahi showed significant increasing trend (0.013 °C/year) at 10% level of significance (Table 2, Fig 2). The change of the diurnal temperature range (DTR) is related to the asymmetric evolution of both maximum and minimum temperature. The increasing trend of DTR at Rajshahi is linked to the higher increasing rate in maximum temperature than in minimum temperature. Similar evidence was found not only at Rajshahi, but also at Chittagong and Sylhet (Shahid *et al.*, 2016). The result, however, contradicts with several studies (Dai *et al.*, 1997; Easterling *et al.*, 2000), showing that the globe has experienced a general downward trend in DTR that is mainly due to the rapid increase in minimum temperatures rather than maximum temperatures. Significant increasing trend of DTR confirms that Rajshahi experienced a more warming environment during the last four decades.

Inter-decadal variations

Inter-decadal variations of temperature extremes were almost consistent with the average inter-annual variations with few exceptions at Barisal where downward inter-decadal trends of two cold extremes, CD25 and CN10 (Table 3), were observed that contradicts with their upward average annual and no annual trend (Table 2). This is due to the inconsistent variation of decadal averages and lowest number of data values ($n = 4$) for decadal trend analysis. One hot extreme (TNx) and one cold extreme (CD25) at Rajshahi respectively showed significant upward trends of 0.372 °C/decade and 4.70 days/decade (Fig 4) at 10% level of significance. Similarly, one hot index, SU35 (TX > 35°C), showed significant upward trend meaning that summer days significantly increased ($p < 0.1$) at a rate of 5.650 days/decade during the study period at Barisal (Fig 5). Inter-decadal variation of DTR showed insignificant increasing trends at both Rajshahi and Barisal (Table 3). Significant increasing decadal changes

of warm indices at Rajshahi (TNx) and Barisal (SU35) are in line with several previous studies done in Bangladesh (Dastagir, 2015; Shahid *et al.*, 2016) and worldwide (Guan *et al.*, 2015; EI Kenawy *et al.*, 2011). However, increasing trend of CD25 at Rajshahi was not in line with the previous studies, perhaps, due to use of higher threshold value (25°C) compared to other studies. For instance, number of cold days (TX < 18°C) was found to decrease at a rate of 0.08 days/decade (Shahid *et al.*, 2016), noting that extreme cold days were converting to moderate cold days in north-western Bangladesh. Results from decadal trend analysis reconfirm that hot temperature extremes are undoubtedly becoming rigorous in both study regions that will likely to have diverse impacts on different sectors of those areas. For instance, substantial effects of climate change on rice water demand, rice physiology and phenology, and soil-water balances are already evident in the northwest Bangladesh (Shahid, 2011).

Table 3. Inter-decadal variations of temperature extremes

Index	Rajshahi Station		Barisal Station		
	Mann-Kendall Test Z	Sen'sslope (°C or days/decade)	Mann-Kendall Test Z	Sen'sslope (°C or days/decade)	
Hot Extremes	TXx	2	-0.240	2	0.126
	TNx	6	0.372 ⁺	2	0.114
	SU25	-4	-3.483	0	-4.167
	SU35	4	8.800	6	5.650 ⁺
	TR20	2	1.483	2	2.817
	TR25	4	7.050	4	11.067
Cold Extremes	TXn	-4	-1.427	-4	-0.732
	TNn	-4	-0.430	4	0.053
	CD25	6	4.700 ⁺	0	-0.433
	CN10	4	3.250	0	-0.075
Variability Extreme	DTR	2	0.134	4	0.024

NB: ⁺ = 0.1 level of significance, * = 0.05 level of significance, ** = 0.01 level of significance, *** = 0.001 level of significance; negative sign indicates decreasing trends

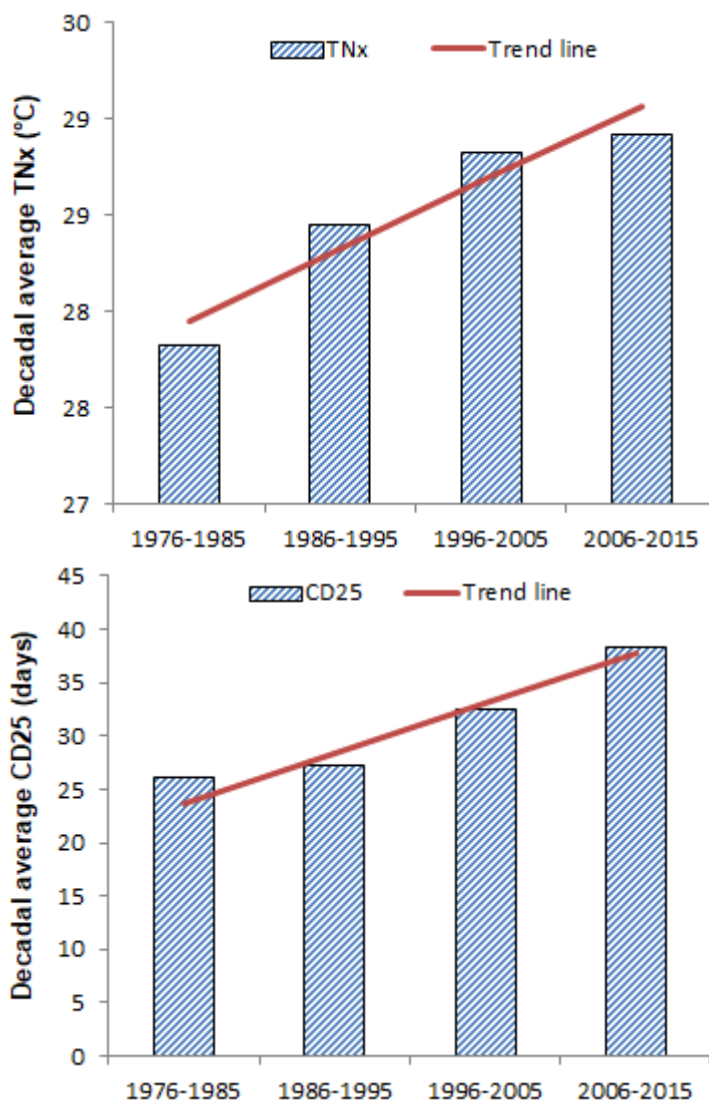


Fig 4. Decadal trends of hot index TNx (annual maximum daily minimum temperature (TN)) and cold index CD25 (days with TX < 25 °C) at Rajshahi

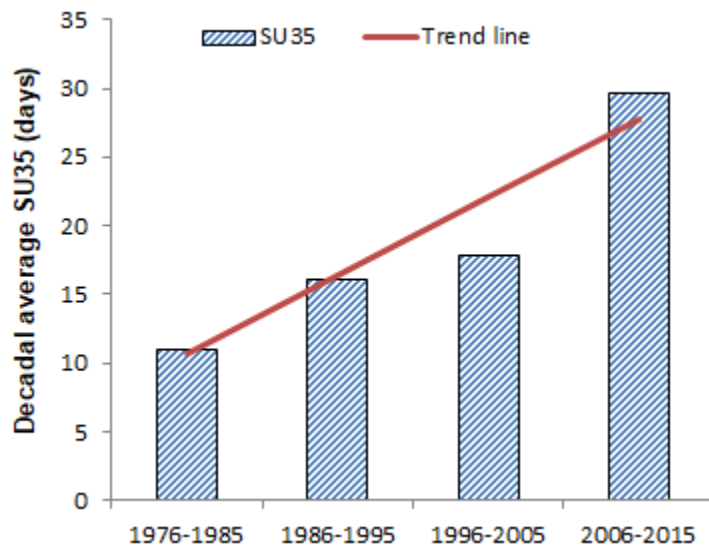


Fig 5. Decadal trend of hot index SU35 (days with daily maximum temperature > 35 °C) at Barisal

Conclusion

Climate extreme is now an important research topic because the study of climate extremes is crucial to characterize the nature of climate change and its impacts. Contemplating this, trends of some temperature related hot and cold extreme indices were analyzed using daily maximum and minimum temperature recorded at two weather stations in coastal and drought-prone areas of Bangladesh. Statistically significant variations were observed in both hot and cold indices. Specifically, some of the hot indices like extreme hot days and hot nights increased significantly in both study sites. Besides, a clear evidence of converting moderate hot days into extreme hot days was noticed at Rajshahi. Among cold indices, both cold days and cold nights showed significant upward trends at Rajshahi, but no significant trend was observed at Barisal. Significant rising trend of diurnal temperature range was found at Rajshahi because the rate of increase in daily maximum temperature was higher than that in daily minimum temperature. Generally, this study provides strong evidence of the increasing trend of hot extremes in both areas. In contrast, drawing firm conclusions about the changes of cold extremes are difficult even though some cold temperature indices showed significant increasing trends at Rajshahi, the north-western part of the country. Results of this study will enhance the knowledge about recent changes in the climate and climate-related extreme events, their impacts on different sectors and possible adaptation actions. The present study used only two weather stations data, so further research is needed including data of more weather stations covering whole country. Study of precipitation related extremes is also needed for general understanding of climate extremes.

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