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Extreme Temperature Events and Rice Production in Bangladesh

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Abstract

The extreme climatic events are increasing because of climate change impacts and thus likely to influence global agricultural production. Regional assessments on various abiotic factors and its influences on biological entities in diverse geographic locations are needed for understanding uncertainties. Rice grain yields and daily temperature data from 1971–2015 were used to quantify extreme temperature events in different regions of Bangladesh and their impacts on rice yields growing in three seasons of Bangladesh. The regional averaged trends in temperature extremes were consistent with global warming. The occurrence summer days (SU), tropical nights (TR), warm days (TX_{90}), and nights (TN_{90}) and a warm spell duration indicator (WSDI) increased by 0.388 ($P_{0.00001}$), 0.103 ($P_{0.19}$), 0.520 ($P_{0.00000}$), 0.269 ($P_{0.0004}$), 0.147 ($P_{0.0001}$), days yr^{-1}, respectively. The frequencies of cold days (TX_{10}) and nights (TN_{10}), and cold spell duration indicator (CSDI) showed decreasing trends of −0.143 ($P_{0.0006}$), −0.254 ($P_{0.001}$), and −0.04 ($P_{0.227}$) day yr^{-1}, respectively. Sharp increases of TR and TN_{90} indices took place in 1985–2000. Principal component analysis showed that SU, TX_{90}, TN_{90}, WSDI, TX_{10}, TN_{10} and diurnal temperature range (DTR) were the main influencing factors for seasonal variations in rice yield. Warm and cold nights played a vital role in reducing rice yields. It can be concluded that extreme temperature events will be increased in Bangladesh and thus necessitating heat and cold tolerant rice varieties with appropriate management options for sustained future rice production in Bangladesh.

Keywords: Extreme temperature events, warm extremes, cold extremes, rice yield, Bangladesh

1. Introduction

Global food demand is increasing, while natural resources are decreasing in many countries to support such process. Moreover, climate change impacts are also playing a negative role in producing more food. Recent extreme climatic events are also concern for the world community because of its potential severe effects on agriculture, water resources, human life and natural ecosystems (Aguilar et al., 2009; Zwiers et al., 2013). It is reported that warm days and nights are very likely to increase on the global scale (IPCC, 2013). The frequency of heat waves is likely to increase in greater parts of Europe, Asia and Australia. On the other hands, cool days and nights are likely to decrease, but heavy precipitation events in many mid-latitude regions are likely to increase (Wang et al., 2012). Such events, although rare, will increase vulnerability in agriculture and natural ecosystems (Kharin et al., 2007; Marengo et al., 2009) and thus would cause significant damage to crop yields; increase soil erosion and flooding in different regions of the world (Ren et al., 2011; Liu et al., 2013). Future prediction of such changes require understanding based on past records; some of which are available in Africa (Aguilar et al., 2009), America (Haylock et al., 2006), and Asia (Ren et al., 2011).

Model based estimation showed decreasing yield trends because of climatic variation although uncertainty and regional variability existed (Rosenzweig et al., 2014; Knox et al., 2012). Studies on the relationships between historical weather data and crop yields indicated that temperature and precipitation are the key factors for predicting yields (Lobell et al., 2011; Maniruzzaman et al., 2018). However, not much study has been conducted to analyze the impact of extreme events on yields of major food crops. A few studies, for example, showed that maize yields in the United States is sensitive to drought (Lobell et al., 2014); wheat yield in India reduces beyond 34°C (Lobell et al., 2012); heat stress on rye and wheat reduced yields in Germany (Siebert et al., 2014);

and higher night temperature (32°C) affected rice yield in United States (Mohammed & Tarpley, 2009). Deryng et al. (2014) also reported double losses of maize and spring wheat yields due to increase in heat stress at anthesis. Above stated limited literature indicates that understanding climate extremes in relation to crop yield is vital in delineating adaptation strategies for growing rice, the principal food crop for about 50 percent of the global population.

Among rice growing seasons, *Boro* crop (dry season irrigated crop) face both cool and dry conditions at the early growth stages, and hot and humid environment in the flowering and harvesting stages. Pre-monsoon and wet season rice crop are mostly exposed to hot and humid conditions. Since climate change impacts are visible in this part of the world, an assessment on extreme temperature events, especially on its intensity, frequency and duration and its relationship with rice productivity was evaluated to construct future ecology for rice production sustainably.

2. Materials and Methods

2.1 Study Area

Bangladesh lies in between 20°34' and 26°38' north latitude and 88°01' and 92°41' east longitude having sub-tropical monsoon climate. Winter, summer and monsoon seasons are prominent. Average temperature varies from 7–13°C (minimum) to 24–31°C (maximum). The highest maximum temperature was 37°C although it can rise up to 41°C (BBS, 2016). Average annual rainfall varies from 1429 to 4338 millimetres, the maximum in the coastal areas of Chittagong and northern part of Sylhet district; while the minimum in the western and northern parts of the country (BBS, 2016).

2.2 Data Sources, Quality Controls and Analytical Methods

Meteorological data from 36 stations of Bangladesh Meteorological Department (BMD) was collected of which 26 stations were considered to have long-term observations from 1971 to 2015 (Figure 1). Collected data were checked whether the daily minimum temperature exceeded the maximum temperatures. The selected data quality was controlled by using *RClimDex* 1.0 (Zhang & Yang, 2004) and 11 climate extreme indices were calculated (Table 1). These indices can reflect the changes in intensity, frequency, and duration (Alexander et al., 2006).

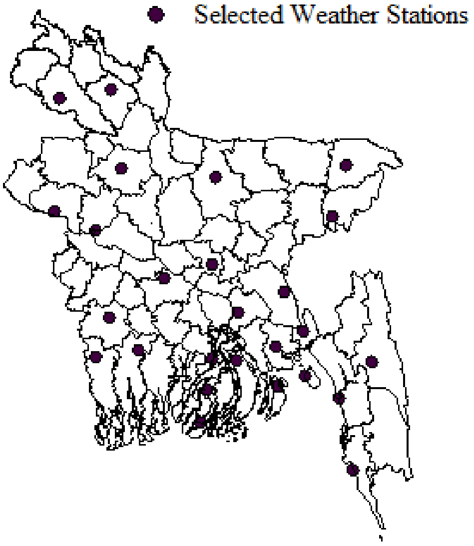


Figure 1. Selected weather stations and their distribution in Bangladesh

The extreme temperature indices were divided into three groups- (i) the absolute indices, including summer days, tropical nights, very cold days based on original observation and fixed thresholds; (ii) the relative indices, including warm days and nights and cold days and nights based on percentile approach and (iii) warm and cold spell duration indicators, the diurnal temperature range, and the growing season length. The regional averages were calculated as arithmetic means. Linear tendency estimate method was used to analyze extreme trends events and correlations among events were established based on regional averages by using STAR (Statistical Tool for Agricultural Research) software package (STAR, 2014).

The crop yields were recorded from the different issues of Yearbook of Bangladesh Agricultural Statistics. Crop yields showed positive trends due to technological innovation, improvements in seeds, changes in growing practices, etc. Because of extremes occur rarely by definition, one would expect to only have a few occurrences over several decades in a single location. Therefore, rather than analyze each district individually, we have pooled all the district data to evaluate the impact of extremes events on crop yields.

Table 1. Indices of temperature extremes used in the study

Index	Description	Definition	Unit
SU	Summer days	Annual count of days when TX>35ºC	days
TR	Tropical night	Annual count of days when TN>20ºC	days
TX90	Warm days	Days when TX>90th percentile	days
TN90	Warm nights	Days when TN>90th percentile	days
WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX>90th percentile	days
VCD	Very Cold days	Annual count of days when TN<10ºC (Rice)	days
TX10	Cold days	Days when TX<10th percentile	days
TN10	Cold nights	Days when TN<10th percentile	days
CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN<10th percentile	days
GSL	Growing season length	Annual count between the first period of at least 6 consecutive days with TG>5°C and the first period after July 1 of 6 consecutive days with TG<5°C	days
DTR	Diurnal temperature range	Annual mean difference between TX and TN	ºC

TX denotes the daily maximum temperature, TN is the daily minimum temperature, TG is the daily mean temperature. The reference period for the percentiles is 1971–2015. All indices were calculated at annual scale from January to December.

2.3 Mann–Kendall (MK) Trend Test

The MK test assumed that the climatic series is independent and not robust against autocorrelation, which is a major source of uncertainty in testing and interpreting trends (Li et al., 2014). The Mann–Kendall trend test (Mann, 1995) was used to detect trends in the time series data and the test statistic distribution was explained according to Kendall (1975). More details of the Mann-Kendall test and its statistical ability are documented by Yue et al. (2002). In the present study, confidence levels considered were 99%, 95% and 90%. Mann-Kendall test for trend and Sen's slope estimates MAKESENS was used for detecting and estimating trend (Salmi et al., 2002).

2.4 Principal Component Analysis (PCA)

The PCA was performed using SPSS (2014) (version 20.0) for 10 extreme temperature indices (excluding of GSL). The objective of PCA was to obtain minimum data set but without loss of information (Armenise et al., 2013). Principal components (PC) with high Eigen values were considered best representatives explaining the variability (Li et al., 2013). The PCs with Eigen values ≥1 were selected since PC with Eigen value <1 account for less variation than generated by a single variable. The retained PCs were subjected to varimax rotation to maximize the correlation between PC and temperature extreme indices by distributing the variance (Waswa et al., 2013). Under each PC, highly weighted variables were selected as the influential indicators for rice production. Multivariate correlation coefficients were used to check for redundancy and correlation between the variables. If the parameters were significantly correlated, then the one with the highest loading factor was retained in the MDS and all others were eliminated from the MDS to avoid redundancy. The variables with the highest factor loading (0.70) were retained as indicator among the well-correlated variables (Andrews & Carroll, 2001).

3. Results and Dissuasion

3.1 Extreme Temperature Events

3.1.1 Warm Temperature Extremes (SU, TR, TX_{90}, TN_{90} and WSDI)

Summer days (SU), warm days (TX_{90}), warm nights (TN_{90}) and warm spell duration indicator (WSDI) have increased significantly in Bangladesh from 1971 to 2015. The annual trends in SU, TX_{90}, TN90 and WSDI were 0.388 ($P_{0.00001}$), 0.520 ($P_{0.0000}$), 0.269 ($P_{0.0004}$) and 0.147 ($P_{0.0001}$) day yr^{-1}, respectively (Figures 2a, c, d, e). The tropical nights (TR) was also increasing, although insignificant, at 0.103 day yr^{-1} ($P_{0.19}$) for the same period (Figure 2b). The recent decadal trends (2005 to 2015) for TR and TN_{90} showed sharp decline (Figures 2b & d). There was significantly increased spatial distribution trends for SU, TR, TX_{90} and TN_{90} in 77%, 35%, 81% and 69% of stations, respectively (Table 2 and Figures 3a, b, c & d); whereas significantly decreasing trends were observed for TR and TN_{90} by 15% and 8%, respectively (Table 2 and Figures 3b & d). The SU and TR increased significantly for all over the country (Figures 3a & b). The significant increases in TX_{90} over time were concentrated in southern, north-eastern and northern part of Bangladesh (Figure 4c); but increased TN_{90} were distributed in all over Bangladesh (Figure 4d). Sun et al. (2016) also reported increased trend of warm extremes over the Loess Plateau in China during 1960–2013. A combination of increased temperature and reduced rainfall resulted in increased evapotranspiration, which is detrimental to crop growth. Besides, increased surface temperature will lead to release of more carbon from the topsoil, which in turn will reduce soil fertility (Hossain et al., 2017).

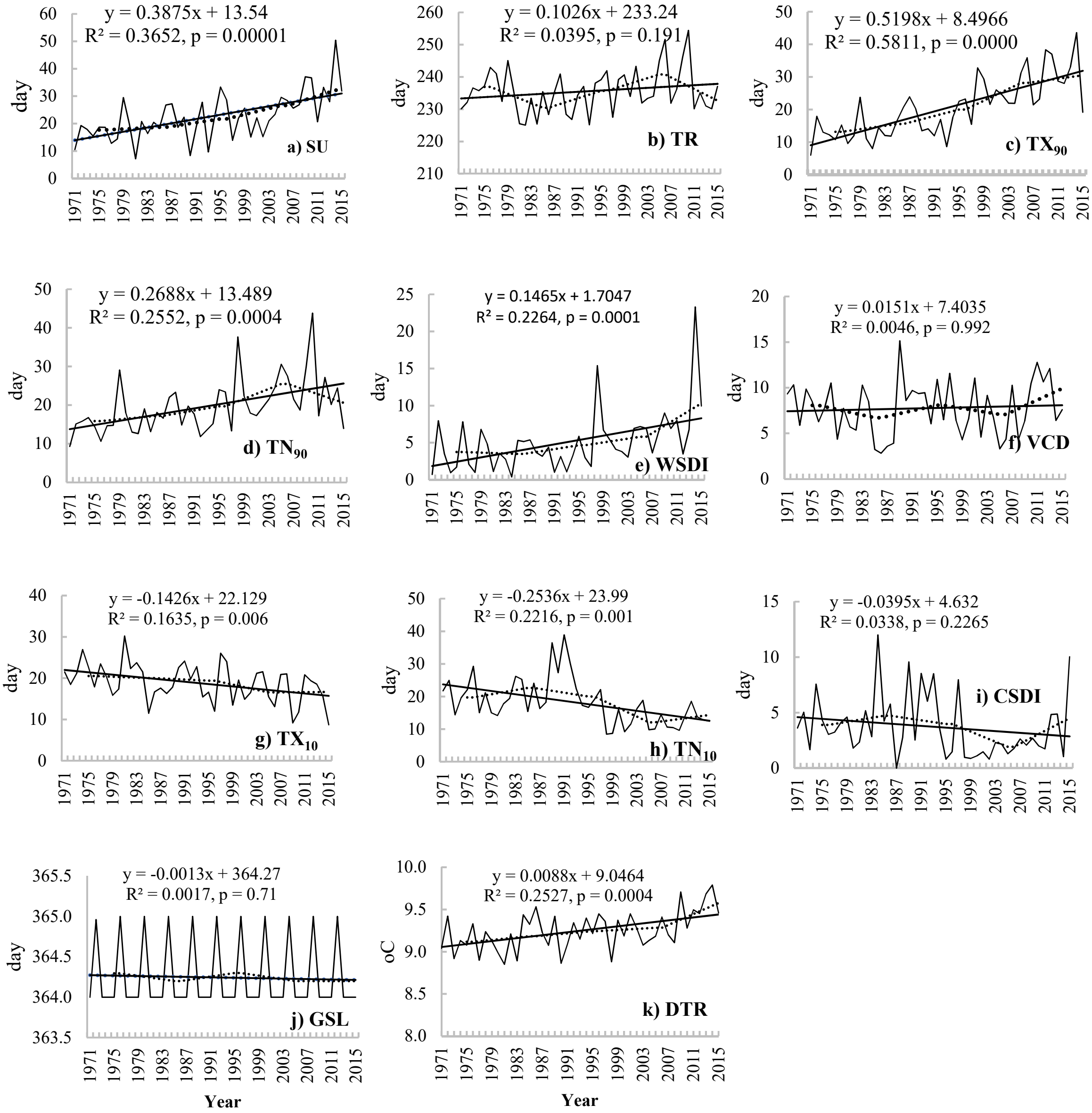


Figure 2. Annual and decadal extreme temperature events in Bangladesh; straight line represents linear regression and dotted line indicates decadal average during 1971–2015

3.1.2 Cold Temperature Extremes (VCD, TX_{10}, TN_{10}, CSDI)

The annual changes in cold extremes in Bangladesh during 1971–2015 are shown in a similar way in Figures 2f, g, h & i. Among the cold extremes, the spatial variability of TX_{10} and TN_{10} indicators are shown in Figures 3e & f. We have considered 10°C or less as very cold days (VCD) for rice, which has slightly increased in during the past 45 years. The annual trends in VCD were 0.015 ($P_{0.991}$) day yr^{-1} in 1971–2015 (Figure 2f). The VCD has sharply increased in last decade (Figure 2f).

Country average cold days (TX_{10}) and cold nights (TN_{10}) decreased significantly by -0.143 ($P_{0.006}$) and -0.254 ($P_{0.001}$) day yr^{-1}, respectively (Figures 2g & h) in about 54% and 73% of stations for the last 45 years (Table 2 and Figures 3e & f). The significant decrease in TX_{10} in most areas varied from −0.45 to −0.15 day yr^{-1} (Figure 3e), while most of the stations showed significant decreases in TN_{10} rates between −0.70 to −0.25 day yr^{-1} (Figure 3f). Though not significant, the cold spell duration indicator (CSDI) decreased by −0.04 day yr^{-1} ($P_{0.227}$) during 1971–2015 and the rate sharply increased in the recent decade (Figure 2i). Similar findings were also reported by Sun et al. (2016) for the Loess Plateau of China. There is an indication that cool night frequencies are reducing more quickly in northern Bangladesh. There is also a trend towards fewer cool days and more warm days, although with lower confidence level. Dastagir (2015) reported higher confidence level for the reduction of cool night numbers but increased number of warm nights over 1970–2009.

Table 2. Decadal extreme temperature indices (MAKESENS test) for different regions in Bangladesh during 1971-2015

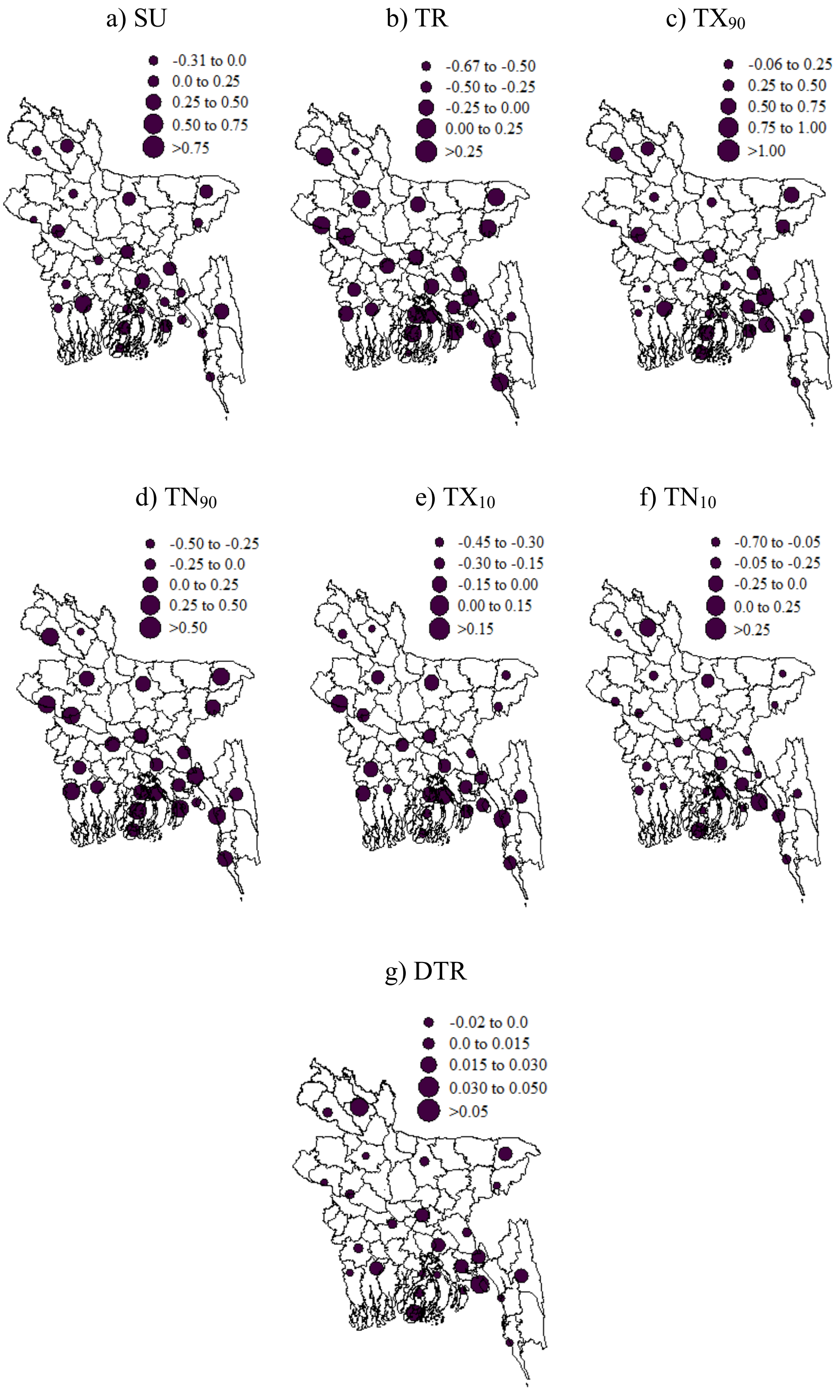
Location	SU	TR	TX_{90}	TN_{90}	TX_{10}	TN_{10}	DTR
Bogra	0.200	0.343**	0.441***	0.376***	-0.043	-0.521***	-0.008
Dinajpur	-0.306	0.012	0.139	0.414***	0.135	-0.139	-0.017**
Ishwardi	0.214	0.250**	0.165*	0.222**	-0.077	-0.331***	-0.012
Rajshahi	0.869***	0.000	0.355**	0.060	-0.060	-0.069	0.015*
Rangpur	0.000	0.167	0.102	0.472***	0.136	-0.111	-0.016**
Barisal	0.468***	0.045	0.517***	0.099	-0.248**	-0.363**	0.011
Bhola	0.148*	0.222	0.305***	0.197*	-0.126*	-0.316***	-0.002
Chandpur	0.582***	0.000	0.553***	0.238**	-0.131*	-0.141	0.024**
Chittagong	0.134**	0.360**	0.529***	0.639***	-0.238*	-0.549***	0.000
Comilla	0.278***	0.048	0.502***	0.225*	-0.135	-0.308**	0.007
Cox’s Bazar	0.182***	0.418***	1.237***	0.490***	-0.135	-0.618***	0.025***
Dhaka	0.427*	0.400***	0.480***	0.640***	-0.190*	-0.481***	-0.010
Faridpur	0.574**	0.400**	0.798***	0.556**	-0.171**	-0.370***	0.005
Feni	0.130*	-0.231	0.051	-0.017	-0.016	-0.218**	0.003
Hatia	0.057**	-0.455*	0.595***	-0.016	-0.251***	0.132	0.042***
Jessore	1.108***	-0.065	0.860***	0.002	-0.263***	-0.427***	0.021***
Khepupara	0.222**	-0.155	0.457***	0.142***	-0.137*	-0.021	0.026***
Khulna	0.633**	0.000	0.395*	0.346**	-0.004	-0.143	0.000
Maijdicourt	0.648***	0.442**	0.994***	0.563***	-0.293**	-0.419***	0.014
Mymensingh	-0.071	0.333**	0.080	0.584***	0.164	-0.264*	-0.020***
Patuakhali	0.909***	-0.290*	0.528***	0.136	-0.100*	-0.228**	0.018***
Rangamati	0.400**	-0.667***	0.553***	-0.524***	-0.447***	0.298**	0.071***
Sandwip	0.182***	-0.397*	0.842***	-0.187*	-0.195	0.297*	0.053***
Satkhira	0.046	0.102	-0.058	0.514***	-0.003	-0.249***	-0.014
Srimongal	0.250*	0.232	0.461**	0.304**	-0.282*	-0.408***	-0.002
Sylhet	0.632***	0.472**	1.022***	0.723***	-0.352***	-0.549***	0.015**
Bangladesh	**0.365*** **	**0.098**	**0.504*** **	**0.252*** **	**-0.132** **	**-0.230*** **	**0.009** **

* $P_{0.05}$; ** $P_{0.01}$; *** $P_{0.001}$

3.1.3 Growing Season Length and Diurnal Temperature Range

The growing season length (GSL) in Bangladesh was shortened at a rate of 0.0013 day yr^{-1} ($P_{0.71}$), but average annual diurnal temperature range (DTR) increased significantly ($P_{0.0004}$) at 0.0088°C yr^{-1} (Figures 2j & k). About 35% of stations for DTR showed significantly increasing trends and about 12% of stations showed significantly decreasing trends. In southern part of the country, the coastal belt, the diurnal temperature is in increasing trend, and similar trends were found in Rangpur and Sylhet areas (Figure 3g). Our findings are the opposite of the report of Sun et al. (2016). It is most likely that there will be regional variability for increase in temperature (Maniruzzaman et al., 2017).

On an average, the increasing trends for warm extremes were larger than cold extremes. For example, the changes in annual trends for SU (0.389 day yr^{-1}), TX$_{90}$ (0.520 day yr^{-1}), TN$_{90}$ (0.267 day yr^{-1}) and WSDI (0.147 day yr^{-1}) were higher than VCD (0.015 day yr^{-1}), TX$_{10}$ (-0.143 day yr^{-1}), TN$_{10}$ (-0.254 day yr^{-1}) and CSDI (0.015 day yr^{-1}). These indicated that future crop agriculture is likely to be suffered from higher temperature induced loss processes in Bangladesh (Maniruzzaman et al., 2018; Basak et al., 2010).



a) SU

b) TR

c) TX$_{90}$

d) TN$_{90}$

e) TX$_{10}$

f) TN$_{10}$

g) DTR

Figure 3. Decadal spatial distribution of extreme temperature indices in Bangladesh during 1971 to 2015

3.2 Principal Component Analysis for Temperature Indices

In this study, only two PCs Eigen values (5.16 and 1.64) were found >1.0 with the variance of 51.6% and 16.4%, respectively (Table 3 and Figure 4). Only the highly weighted variables (>0.70) were retained to include in the minimum data sets, MDS (Table 3). Thus, the bold-face values in Table 3 (TX_{90}, WSDI, SU, TX_{10}, TN_{90}, and TN_{10} for PC-1, DTR for PC-2) were considered highly weighted eigen vectors and therefore were initially selected in the MDS. However, when more than one variable was retained under a particular PC, multivariate correlation matrix (Table 4) was used to determine the correlation coefficients between the parameters (Andrews et al., 2002). All the bold-faced and underlined temperature extreme parameters in Table 3 were selected in the final MDS.

Table 3. Results of principal component analysis (PCA)

	Principal Component-1	Principal Component-2
Eigen value	5.16	1.644
% Variance	51.604	16.444
Cumulative variance	51.604	68.048
Eigen vector or factor loading		
TX_{90}	**<u>0.905</u>**	
WSDI	**0.839**	
SU	**0.819**	0.387
TX_{10}	**-0.78**	
TN_{90}	**0.77**	
TN_{10}	**-0.707**	0.426
TR	0.677	
VCD	-0.456	0.41
DTR	0.491	**<u>0.776</u>**
CSDI	-0.597	0.643

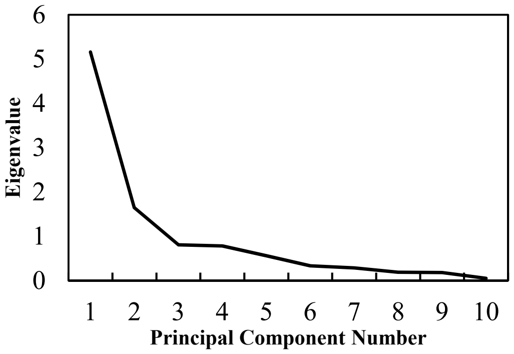


Figure 4. Scree plot of principal component analysis

3.3 Correlation Coefficients of Temperature Indices

All warm extremes (SU, TR, TX_{90}, TN_{90} and WSDI) showed positive insignificant correlation coefficients that range from 0.655 to 0.898 with mean annual temperature (TG) (Table 4). On the other hand, all cold extremes (VCD, TX_{10}, TN_{10} and CDSI) were negatively correlated with mean annual temperature. Among cold extremes, VCD (-0.371) and CSDI (-0.433) were significantly correlated with the mean annual temperature. Besides, GSL was negative and insignificant (-0.073); while DTR showed significant positive correlation (0.453) with mean annual temperature. It is indicated that warm days had the strongest correlation with mean annual temperature (0.898). In addition, there were strong correlations among the warm indices and cold indices. For example, summer days (SU) were highly related with cold nights (TN_{10}), and the tropical night (TR) were significantly correlated with TN_{10} and cold spell duration indictor (CSDI). Warm days (TX_{90}) were also significantly correlated with cold days (TX_{10}) and CSDI. Among the warm extremes, warm night (TN_{90}) and warm spell duration indicators (WSDI) were significantly correlated with TX_{10}, TN_{10} and cold spell duration indicators (CSDI). Moreover, very cold days (<10°C) were significantly correlated with cold days (TX_{10}), cold night (TN_{10}) and CSDI and TX_{10} was highly correlated with TN_{10} (Table 4).

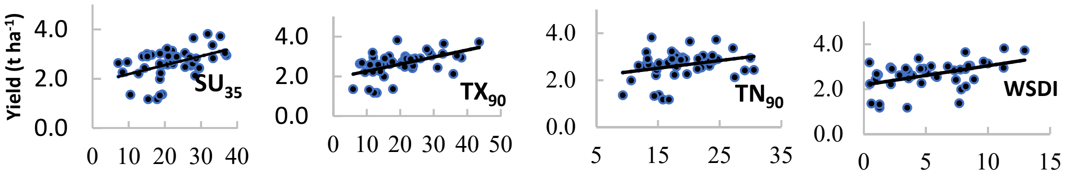
Table 4. Correlation coefficients of extreme temperature indices in Bangladesh between 1971 and 2015

	TG	SU	TR	TX_{90}	TN_{90}	WSDI	VCD	TX_{10}	TN_{10}	CSDI	GSL
TG	1										
SU	0.784	1									
TR	0.684	0.442***	1								
TX_{90}	0.898	0.791	0.497***	1							
TN_{90}	0.782	0.574	0.622	0.759	1						
WSDI	0.655	0.694	0.260	0.780	0.521***	1					
VCD	-0.371*	-0.167	-0.277	-0.238	-0.226	-0.277	1				
TX_{10}	-0.772	-0.636	-0.584	-0.566***	-0.384***	-0.424***	0.336*	1			
TN_{10}	-0.642	-0.363*	-0.451***	-0.616	-0.527***	-0.493***	0.402***	0.396***	1		
CSDI	-0.433***	-0.170	-0.400***	-0.452***	-0.445***	-0.377*	0.374*	0.185	0.588	1	
GSL	-0.073	0.030	0.029	-0.082	-0.093	-0.039	-0.075	-0.028	0.188	0.024	1
DTR	0.453***	0.637	0.069	0.568	0.059	0.414***	0.073	-0.591	-0.107	0.178	0.043

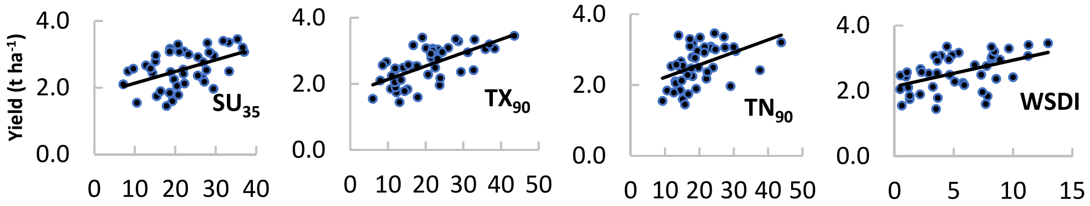
* Significant at the 0.05 level, ** Significant at the 0.01 level and *** Significant at the 0.001 level

3.4 Impact of Extreme Temperature Events on Rice Yields

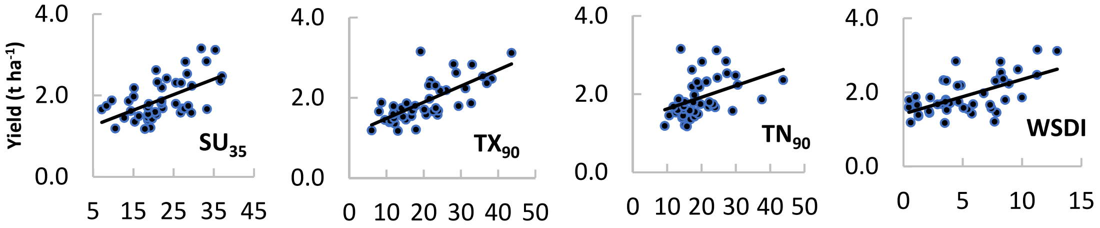
The relationship between rice yields and temperature extremes were established based on the MDS selected from PCA. Seasonal grain yield of rice showed increasing trends with SU, TX_{90}, TN_{90} and WSDI (Figure 5). *Boro* rice crop might have got favourable temperature during early growth stages. Since this crop is generally established during last week of December to first week of January, it exposed to minimum temperature of 7.2–12.8°C and maximum temperature in the range of 23.9–31.1°C. Temperature in the range of 15–30°C is congenial for rice growth and development (Krishnan et al., 2011). However, spikelet sterility takes place if temperature exceeds 35°C during flowering time and thus grain yield reduces (Kim et al., 1996). Rice production in Bangladesh is increasing (Maniruzzaman et al., 2017) because of technological advancements like use of quality seeds, better water and fertilizer managements and cultural practices, etc. Moreover, there could be cooling effects of irrigation and rainfall. Evaporative cooling (Bonfils & Lobell, 2007) play an important role in minimizing higher temperature effects. Siebert et al. (2014) also showed that irrigated crops can have 2°C less canopy temperature than non-irrigated conditions. These also indicated that warm extreme indices and the timing of extreme parameters had little influence on the harmful effects on rice production.



Dry season irrigated rice (*Boro* rice)



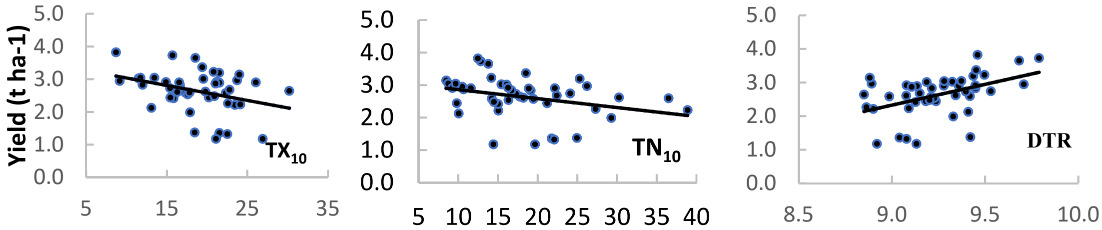
Wet season rainfed rice (*T. Aman* rice)



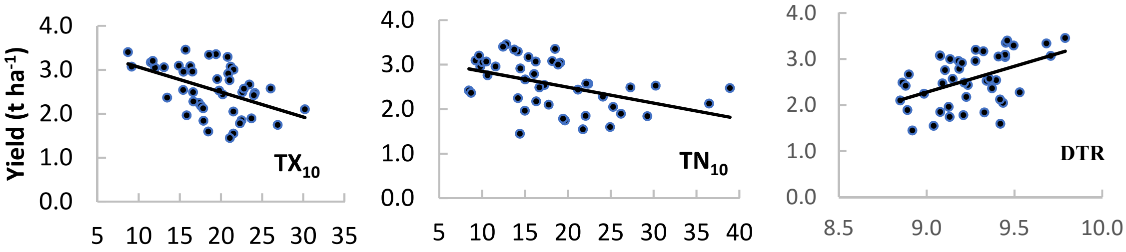
Pre-monsoon rice (*T. Aus* rice)

Figure 5. Effect of warm extreme indices on rice yields in different seasons of Bangladesh during 1971-2015

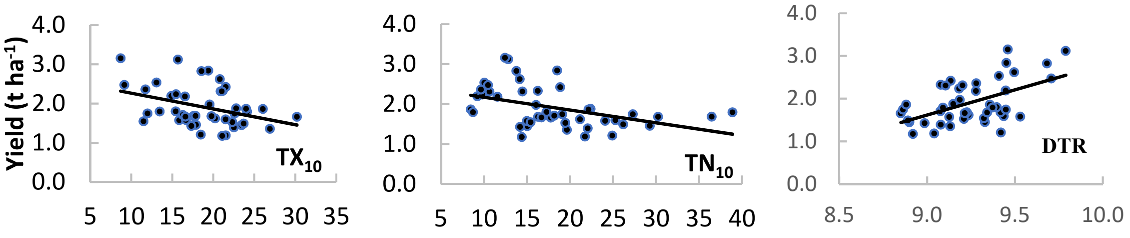
All seasonal rice yields were in decreasing trend with TX_{10} and TN_{10}, whereas it was in increasing trend with diurnal temperature range (Figure 6). At higher temperature respiratory loss increases and so does grain yield reduction takes place. Peng et al. (2004) reported that grain yield declined by 10% for each 1°C increase in minimum temperature during dry season. Under elevated temperature of 2°C and 4°C, grain yield reductions could be 13.3 and 23 percent compared to ambient temperature (Rani & Maragatham 2013; Maniruzzaman et al., 2018). Sarker et al. (2012) also showed that maximum and minimum temperature had statistically significant adverse effect on *Boro* rice yield. The country could experience an increase in average temperature of 1.4°C or more during 2050 and beyond (Biswas et al., 2017); rice production is likely to decline by 8-17% (IPCC, 2007). The possibility is that temperature extremes existed for short period of time in which period rice plants might not be in vulnerable growth stages like panicle initiation, reduction division or grain filling.



Dry season irrigated rice (*Boro* rice)



Wet season rainfed rice (*T. Aman* rice)



Pre-monsoon rice (*T. Aus* rice)

Figure 6. Effect of cold extreme indices and diurnal temperature range on seasonal rice yields of Bangladesh during 1971-2015

Most of the studied indices showed either positive or negative relationship with seasonal rice yield and thus it is difficult to know which variables are determining the change in crop yields. For example, TN_{10} was significantly correlated with SU, TR, TN_{90}, WSDI and VCD. This leads to an interesting question- which extreme event primarily affects crop yield or is there a combination of extreme indices that dictates increase or decrease in rice yield?

Grain yield of a crop depends on many factors. So, only temperature extremes can't explain its variability. Other variables, such as soil texture, soil pH, soil depth, salinity, genotypes, etc. also influence grain yields that are not considered in this study. It is possible that those variables were influential than short term extreme events. We have employed stepwise multiple regression analyses based on the MDS selected from PCA and final equations for rice yield for different seasons were as follows:

i) *Boro*, $Y= - 4.6277 + 0.0073SU + 0.0175TX_{90} - 0.0098TN_{90} + 0.0190WSDI + 0.117TX_{10} - 0.0099TN_{10} + 0.7338DTR; R^2 = 0.32^*$

ii) *T. Aman*, $Y = - 0.7807 - 0.0088SU + 0.0425TX_{90} - 0.0024TN_{90} - 0.0196WSDI - 0.0145TX_{10} - 0.0090TN_{10} + 0.3531DTR; R2 = 0.47^{**}$

iii) *T. Aus*, $Y = - 1.8106 + 0.0097SU + 0.0407TX_{90} - 0.0161TN_{90} - 0.0032WSDI + 0.0194TX_{10} - 0.0094TN_{10} + 0.3037DTR; R2 = 0.57^{**}$

Predicted *Boro* rice yield was in poor agreement with the observed yield (Figure 7a). Our analyses indicate that decrease in TN_{90} and TN_{10} will play a vital role in reducing *Boro* rice yield in future. But, the DTR is highly influencing factor followed by WSDI for increasing *Boro* rice production. The model has an F-value of 2.49 with a p-value of 0.034 indicating that the overall model result was statistically significant at 5% level of probability and 32% of variations in *Boro* rice yields can be explained by climatic variables, although none of the extreme values were significant based on the p-values.

Predicted yield of *T. Aman* rice was also in poor agreement with the observed yield (Figure 7b). It was found that most of the extreme parameters (SU, TN_{90}, WSDI, TX_{10} and TN_{10}) were insignificant but will negatively influence *T. Aman* rice yield in future. The DTR is highly influencing factor followed by TX_{90} for increasing *T. Aman* rice production. The overall model result was statistically significant at 1% level of probability (F-value 4.65, $P_{0.0008}$) and 47% of the yield variations can be explained by the climatic variables; but none of the extreme values were significant based on the p-values.

Predicted *T. Aus* rice yield was in close agreement with the observed yield (Figure 7c). In this season, TN_{90}, WSDI and TN_{10} influenced *T. Aus* yield negatively. But, the DTR was highly influencing factor followed by TX_{90} and TX_{10} for increasing *T. Aus* rice production. The overall model result was statistically significant at 1% level of probability (F-value 7.12, $P_{0.00002}$) and 57% of the yield variations can be explained by the climatic variables. None of the extreme values were significant based on the p-values.

Based on regression model, both predicted and observed yields were increasing (Figure 6) might be because of adoption of high yielding varieties, improved cultural practices, and ensure irrigation facilities during *Boro* rice growing season and supplemental irrigation at *T. Aman* and *T. Aus* seasons. To sustain *Boro* rice productivity, there is a need to identify suitable adaptation strategies, viz. Optimum sowing/transplanting window for specific region of the country, choice of suitable variety, adoption of appropriate water and nutrients management strategies, and adoption of appropriate resource conservation technologies. For this purpose, the use of INFOCROP, DSSAT models are to be integrated with relational layers of bio-physical and socio-economic aspects. We have started using these simulation tools for evaluating the impact of climate change and its variability on soil and crops' productivity and suggesting suitable mitigation and adaptation strategies for agri-sustenance.

4. Conclusions

We have determined the magnitudes of 11 extreme temperature indices for Bangladesh and their relationships were investigated with grain yields of rice for three different growing seasons. All warm extreme temperature-based indices showed increasing warming trends and all cold extreme indices except very cold days showed significantly decreasing trends in Bangladesh during 1971-2015. Furthermore, the magnitudes in trends of the warm extremes were larger than cold extremes. All warm extremes showed positive correlations and all cold extremes were negatively correlated with the mean annual temperature. Warm extremes showed positive effects on rice grain yields but cold extremes negatively influenced it. In general, changes in cold nights and warm nights will be the causes of rice yield reduction Bangladesh in future than other tested extreme events.

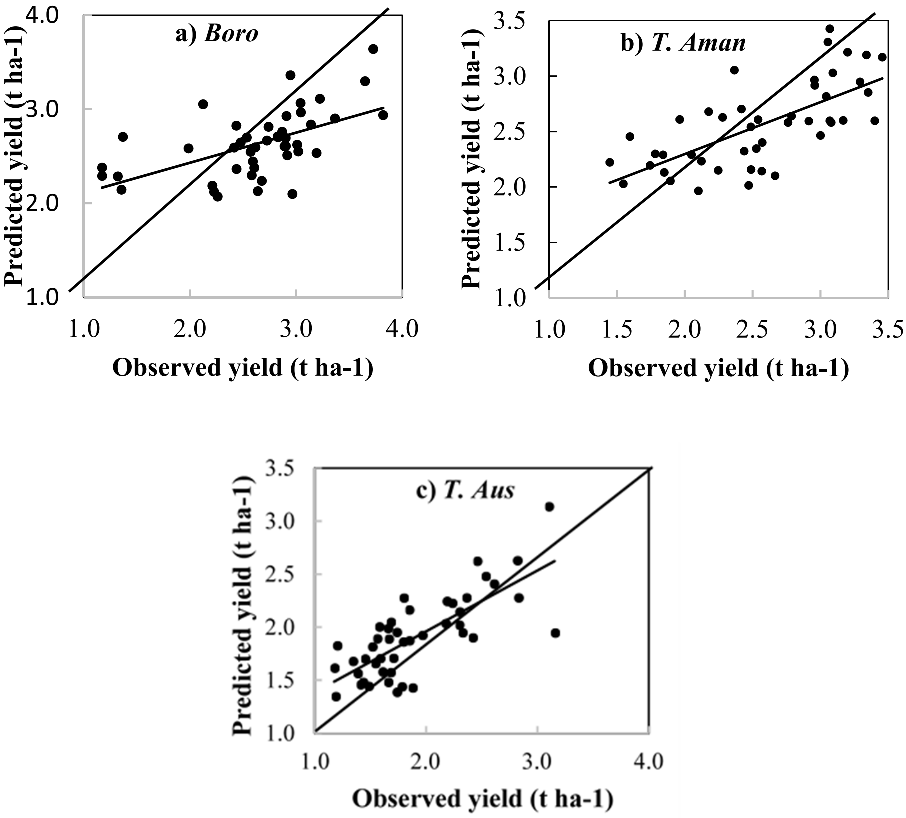


Figure 7. Relationships of predicted and observed grain yields of in different growing seasons of Bangladesh during 1971-2015

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