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Observed trends in climate extremes over Bangladesh from 1981 to 2010

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ABSTRACT: Bangladesh regularly faces various extreme events (floods, droughts, cyclones, and heat waves), but there is a knowledge gap between average climate and climate extremes over the country. The purpose of this study is to quantify the trends over Bangladesh for the period 1981–2010 using the extreme temperature and precipitation indices developed by the CCl/WCRP/JCOMM Expert Team on Climate Change Detection and Indices. We used precipitation and temperature data from 26 meteorological stations, calculated trends in the indices using Sen's slope estimator, and tested significance using the non-parametric Mann-Kendall trend test. For the temperature indices, we found an overall increasing warming trend. Average annual maximum and minimum temperatures increased by 0.3 and 0.4°C decade^{-1} respectively. A faster rise of both maximum and minimum temperature was found compared with previous studies. The frequency of warm days increased by 12 days decade^{-1}. The frequency of warm (cold) nights increased (decreased) by 7 (11) days decade^{-1}. The overall warming was accelerated at the end of the climatic period (2001–2010). Precipitation indices showed an overall decreasing trend, in contrast to other studies in this region. Trends in consecutive dry days (CDD) indicated a drying tendency at a rate of 10 days decade^{-1}. A decreasing rate of about 84 mm decade^{-1} was observed in annual average total precipitation. Except for CDD, most of the precipitation trends were statistically not significant and spatially incoherent. Statistically significant change was observed in extreme temperature events, with a strong and consistent spatial pattern. Our results pave the way for further investigations into future changes using results from climate simulations.

KEY WORDS: Extreme indices · Expert Team on Climate Change Detection and Indices · ETCCDI · Bangladesh · Observed records · Climate change

1. INTRODUCTION

Climate change is often defined as an increase in mean global temperature (Allen et al. 2009, Matthews et al. 2009, Raupach et al. 2011). While this is a general way to identify climate change (Friedlingstein et al. 2014), the impact of climate change is not directly evident from this indicator. One might argue that it is not climate change that does the harm, but the natural disasters that accompany it, from which society suffers significant losses. Therefore, it is important to understand the potential future change in natural disasters (Piontek et al. 2014), the extreme events of the climate system.

Climate extremes are the events that appear in the tailend of the distribution of climate variables (e.g. precipitation, temperature, wind, pressure, humidity, solar radiation). When reporting on climate, mean and variance can be very representative statistics. When considering climate extremes, one needs to examine the values that are in the tails of the distribution, the rare events of climate systems. The choice

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of distribution and the threshold play the most important role in determining whether an event is to be considered extreme or not (Zhang et al. 2011).

Several studies have been undertaken to assess changes in observed extreme events across different continents. These studies have reported observed shifts in frequency and intensity of climate extremes (Frich et al. 2002, Alexander et al. 2006, Choi et al. 2009, Mishra et al. 2015). The main challenge to this effort is the availability of daily datasets. Extreme events cannot be directly evaluated using mean monthly or yearly data and explicitly require daily records. Alexander et al. (2006) first compiled such a large dataset of observed extremes across the globe. Using daily data from 2223 temperature stations and 5948 precipitation stations, they showed a significant warming tendency throughout the 20th century, accompanied by wetter conditions.

At the regional scale, understanding the trend and associated mechanics of extreme events can provide invaluable insight to policymakers, system planners, and resource managers. Due to the paucity of good observational data, reliable climate extremes indices are a valuable contribution. A large number of local studies have been conducted on climate extremes indices (Osborn et al. 2000, Frei & Schär 2001, Aguilar et al. 2005, Moberg & Jones 2005, Vincent et al. 2005, Zin et al. 2010, Dos Santos et al. 2011, Soltani et al. 2016). For example, Zhang et al. (2000) studied the trends in temperature and precipitation indices in Canada during the 20th century and identified a pattern of cooling in the northeast and warming in the south and the west of Canada. They identified an overall increase in precipitation by 5 to 35%. Salinger & Griffiths (2001) studied the extremes in New Zealand using 6 temperature indices and 3 rainfall indices over a period of 48 yr. No significant trend was found in maximum temperature extremes, but a significant increasing trend was observed in minimum temperature extremes. A decrease in frost days of 5 to 15 d was also observed. In the Middle East, a coherent increase in temperature and decrease in precipitation has been identified (Zhang et al. 2005). In China, Qian & Lin (2005) analyzed daily rainfall from 494 stations during 1961–2000 and found distinctive regions with coherent increasing and decreasing trends. They identified a warm–wet, warm–dry, and cold–wet climate state in northwest, north-northeast, and southeast China respectively. Jain & Kumar (2012) analyzed the trend of rainfall and temperature data for India using Sen's non-parametric slope estimator (Sen 1968). While they could not find a consistent precipitation trend in the region, they observed a significant decreasing trend in annual rainfall when the extremes were evaluated per subregion. According to their study, the south, central, and western part of India showed a warming tendency, while the north and northeastern part showed a cooling tendency. For the northeast region of India, an increasing trend was reported in annual rainfall and a decreasing trend in annual rainy days. This result suggests an increase in heavy precipitation days. Jain & Kumar (2012) also focused on the need for a good observational network to capture the spatial variation in such a big country. Panda et al. (2016) studied the monsoon season using the Expert Team on Climate Change Detection and Indices (ETCCDI) precipitation indices. They found a transition of wet to dry over north-central India. Similar to the findings of Jain & Kumar (2012), the result was not spatially consistent. These spatially varying results around the Indian subcontinent stress the need for narrowing the scope and for undertaking local studies.

A few studies on precipitation and temperature indices have been conducted over Bangladesh, which is very vulnerable to climate change-related impacts (Mirza et al. 2003, Karim & Mimura 2008, Shahid 2011b). Shahid (2010a) studied trends for daily extreme rainfall indices of Bangladesh using data from 9 meteorological stations for the period 1958–2007. A significant increase was reported in annual and pre-monsoon rainfall, with an increasing trend in heavy precipitation days and a decreasing trend in consecutive dry days. According to his findings, northwest Bangladesh showed coherent significant change. Ahmed et al. (2016) divided the country into 7 regions and studied the long-term trend in annual and seasonal precipitation from 1948 to 2012. A significant monotonic trend of 4.87 mm yr^{-1} was reported for the country. The trends were significant mostly in the monsoon season. No station showed any trend in the post-monsoon season, while only 1 station showed a significant increasing trend in the pre-monsoon season. They also found that spatially and temporally, rainfall in Bangladesh has no significant correlation with the El Niño-Southern Oscillation (ENSO) index, though a stronger teleconnection was reported for the Indian Ocean Dipole (IOD). This teleconnection with IOD is also supported by Rahman et al. (2013).

The ETCCDI — made up of the Commission for Climatology (CCl), the World Climate Research Programme (WCRP), and the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) — has recommended a suite of 27 indices to measure climate extremes (Zhang et al. 2011). In recent years, an effort has been made to assess climate extremes using these standardized climate extremes indices (Alexander et al. 2006, 2007, Zhou & Ren 2011, Tao et al. 2014). Previous studies on Bangladesh either did not explore the full suite of indices or did not follow a standardized calculation procedure. One study by Nowreen et al. (2015) made use of 12 of the 27 indices and the study area was limited to the northeast basin areas. Using climate projection instead of station data, they showed a growing variability in rainfall indices in this region. Basher et al. (2018) also assessed the trend of monsoon and pre-monsoon rainfall in the northeast region using a limited number of climate indicators.

Due to its unique geographical location, Bangladesh is faced with various extreme events like floods, droughts, cyclones, and heat waves (Gray & Mueller 2012, Shaw et al. 2013). Like many other developing countries, Bangladesh is vulnerable to extreme events due to its limited ability to cope with their impacts (Lein 2009, Poncelet et al. 2010). The changes in extreme events and their frequency and intensity have a far more detrimental effect on society than the change in average climate (Thornton et al. 2014). The impacts of such changes in the severity and intensity of climate extremes are quite daunting, and an assessment must be made to aid in sound and economical decisions. It is thus essential to fill the knowledge gap between the average climate and climate extremes in Bangladesh.

The main purpose of this study is to quantify the trends (spatially and temporally) in the ETCCDI extreme temperature and precipitation indices over Bangladesh during 1981–2010. A summary of the changes in the study area and possible future implications of these changes for policymakers, water resource managers, major stakeholders, and donor agencies is also provided. The results of this study can pave the way for further investigations into future changes using results from climate simulations.

2. DATA AND METHODS

2.1. Study area

Bangladesh is a small country in South Asia and a hotspot of climate change and related impacts (Dasgupta et al. 2010, Ericksen et al. 2011). The country lies between 20°–27° N and is surrounded on 3 sides by India. To the south lies the Bay of Bengal, and there is a small boundary with Myanmar in the southeast (Fig. 1). Bangladesh is dominated by an extremely flat delta (<5 m altitude) with some hilly areas in the northeast (Sylhet) and southeast (Chittagong). The average elevation of the Chittagong Hills ranges between 600 and 900 m above mean sea level. The country has 4 distinct seasons, namely pre-monsoon, monsoon, post-monsoon, and winter (Khatun et al. 2016). The monsoon has a significant command over the climate of the country. About 80 % of the total rainfall is received during the monsoon season (Shahid 2010a, 2011a). Being a subtropical country, the climate is moderately warm. The normal monthly maximum (minimum) temperature ranges from 24°C (16°C) in January to 35°C (30°C) in May (Khatun et al. 2016).

2.2. Datasets

The Bangladesh Meteorological Department (BMD) maintains a network of 46 observatories distributed over Bangladesh for measuring an array of meteoro-

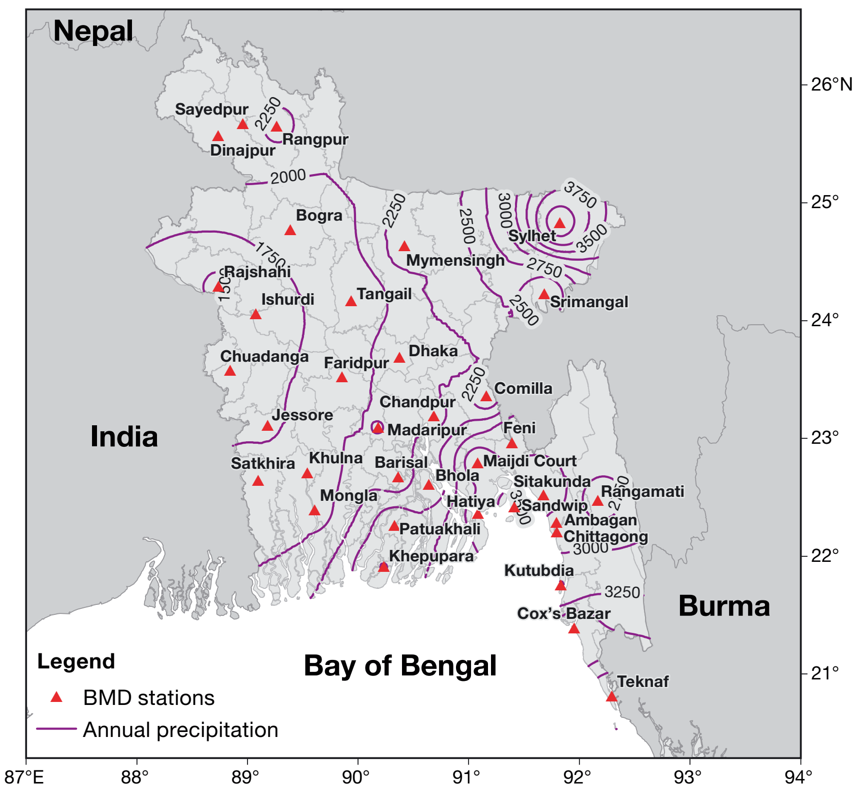

Fig. 1. Study area and locations of the Bangladesh Meteorological Department's (BMD) meteorological stations. Contour lines: distribution of annual average precipitation

Table 1. Meteorological observatory stations of Bangladesh, and data availability during 1981–2010. M.Court: Maijdi Court; na: not available; Pr: precipitation; T_{max}: maximum temperature; T_{min}: minimum temperature

Station	Latitude (°N)	Longitude (°E)	Elevation (m)	Start year	Missing data (%) Pr	T_{max}	T_{min}
Ambagan[a]	22.35	91.816667	na	1999	60.00	60.00	60.01
Barisal	22.75	90.36667	2.1	1981	0.06	0.19	0.13
Bhola	22.68333	90.65	4.3	1981	0.05	2.14	0.26
Bogra	24.85	89.36667	17.9	1981	0.03	0.31	0.12
Chandpur	23.26667	90.7	4.9	1981	0.03	0.26	0.10
Chittagong[b]	22.27	91.82	5.5	1981	4.86	11.08	11.15
Chuadanga[a]	23.65	88.81667	11.6	1989	27.43	26.80	26.70
Comilla	23.43333	91.18333	7.5	1981	0.03	0.26	0.10
Cox's Bazar	21.45	91.96667	2.1	1981	0.32	1.38	0.86
Dhaka	23.76667	90.38333	8.5	1981	0.03	0.26	0.10
Dinajpur	25.65	88.68333	37.6	1981	0.03	0.31	0.12
Faridpur	23.6	89.85	8.1	1981	0.03	0.26	0.25
Feni	23.03333	91.41667	6.4	1981	0.65	1.44	0.93
Hatiya[b]	22.43333	91.1	2.4	1981	0.43	1.20	2.01
Ishurdi	24.13333	89.05	12.9	1981	0.07	0.22	2.63
Jessore	23.18333	89.16667	6.1	1981	0.03	0.26	0.10
Khepupara	21.98333	90.23333	1.8	1981	0.02	0.33	0.17
Khulna	22.78333	89.53333	2.1	1981	0.28	0.41	0.35
Kutubdia[a]	21.81667	91.85	2.7	1985	4.86	11.08	11.15
M.Court	22.86667	91.1	49.0	1981	0.43	1.20	2.01
Madaripur[b]	23.16667	90.18333	7.0	1981	1.41	3.03	6.12
Mongla[a]	22.46667	89.6	1.8	1989	27.43	26.80	26.70
Mymensingh	24.71667	90.43333	18.0	1981	0.03	0.31	0.12
Patuakhali	22.33333	90.33333	1.5	1981	0.02	0.33	0.17
Rajshahi	24.36667	88.7	19.5	1981	0.03	0.31	0.12
Rangamati	22.53333	92.2	68.9	1981	0.32	1.38	0.86
Rangpur	25.73333	89.23333	32.6	1981	0.03	0.31	0.12
Sandwip[b]	22.48333	91.43333	2.1	1981	4.86	11.08	11.15
Satkhira	22.71667	89.08333	4.0	1981	0.28	0.41	0.35
Sayedpur[a]	25.75	88.91667	39.6	1991	33.33	33.62	33.56
Sitakunda	22.58333	91.7	7.3	1981	0.26	0.18	1.86
Srimangal	24.3	91.73333	22.0	1982	0.07	0.22	2.63
Sylhet	24.9	91.88333	33.5	1981	0.07	0.22	2.63
Tangail[a]	24.25	89.93333	10.2	1987	20.06	21.05	20.97
Teknaf	20.86667	92.3	5.0	1981	0.32	1.38	0.86

[a]Removed due to short data series
[b]Removed due to missing data

logical parameters. Among these, 9 stations were established very recently, while 35 have long historic time series data (Table 1). Three parameters essential for this study, namely, rainfall, maximum temperature, and minimum temperature, were collected in ASCII table form and reshaped to time series. However, one of the main problems with the data series in Bangladesh is missing data.

Several stations have a large percentage of missing data during the analysis period 1981–2010 (Table 1). For instance, Ambagan (Chittagong region), Chuadanga, Syedpur, Kutubdia, and Tangail stations were not available at the beginning of the analysis period. For Mongla station, rainfall data are available without any missing entries since 1991, whereas temperature data are available since 1989. Sandwip station has records missing from 15 to 21 June 1987, 10 d after a strong low-pressure zone crossed the area on 5 June 1987. Another long missing record for this station is for the period 1 April to 8 May 1991. The record is probably lost due to the cyclone and tidal surge that hit the coast of Bangladesh on 30 April, which claimed >100000 people's lives and caused widespread destruction of property. The station was also out of operation from 1 August 2002 to 31 December 2003. Kutubdia station was also in intermittent operation from 30 April to 25 May 1991 due to the 1991 cyclone. A nearby station, Hatiya, which is an old station operating since 1966, has a long period of missing records, each about 1 yr long. These missing records of Hatiya station could not be connected with natural disasters and the station is assumed to have been not operating during these periods. Long periods of inactivity and no data are also found in Chittagong, an important coastal district station. The records are presumably missing for storm events during December 1981, June 1987, and April–May 1991, and the station was out of operation from 2004 to 2007.

For a robust statistical calculation, stations which started operating after 1981 were removed from the calculation of extreme indices. Outliers and erroneous records can seriously impact the process of hydrological analysis (You et al. 2008). Therefore, quality control is an essential step before calculating indices and performing trend analysis. We checked the data for negative rainfall values, a negative difference in maximum and minimum temperature values, and outliers. Unrealistic rainfall values in the winter season were also checked. Station-by-station time series and histogram plots were developed to visually identify any problematic data entry.

To test homogeneity, we employed the double mass curve and looked for non-linearity in the curve, which is an indicator of deviation (Searcy & Hardison 1960). The most nearby station was used for this analysis. For all stations, almost straight lines were found and no breakpoint was detected in the time series of precipitation or temperature.

2.3. Climate indices

A suite of 27 indices of extreme climate based on daily data recommended by the ETCCDI was used (Table 2). Calculations of the indices were made using RClimDex, which is based on the statistical analysis software R and developed by Zhang & Yang (2004).

These indices can be divided into 4 distinct types: (1) fixed threshold type indicators where the yearly number of events are counted, (2) percentile type indicators where the percentage of time is calculated for temperature indices and the total is calculated for precipitation, (3) spell type indicators where the spell of an event is considered, and (4) other indicators like total precipitation amount or simple daily intensity index.

Table 2. The 27 extreme temperature and precipitation indices suggested by the Expert Team on Climate Change Detection and Indices (ETCCDI) (after Zhang & Yang 2004). NH: Northern Hemisphere; SH: Southern Hemisphere; TG: daily mean temperature (°C); TN: daily minimum temperature (°C); TX: daily maximum temperature (°C); PRCP: daily total precipitation (mm)

Index	Long name	Definition	Units
Temperature indices			
GSL[a]	Growing season length	Annual (1 Jan–31 Dec in NH, 1 Jul–30 Jun in SH) count between first span of at least 6 d with TG > 5°C and first span after 1 Jul (1 Jan in SH) of 6 d with TG < 5°C	Days
SU25	Summer days at 25°C	Annual count when TX > 25°C	Days
SU35[b]	Summer days at 35°C	Annual count when TX > 35°C	Days
TR20	Tropical nights at 20°C	Annual count when TN > 20°C	Days
TR25[b]	Tropical nights at 25°C	Annual count when TN > 25°C	Days
TXx	Max T_{max}	Monthly maximum value of daily maximum temperature	°C
TNx	Max T_{min}	Monthly maximum value of daily minimum temperature	°C
TN90p	Warm nights	Percentage of days when TN > 90th percentile	% Days
TX90p	Warm days	Percentage of days when TX > 90th percentile	% Days
WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX > 90th percentile	Days
CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN < 10th percentile	Days
DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C
FD0[a]	Frost days	Annual count when TN < 0°C	Days
ID0[a]	Ice days	Annual count when TX < 0°C	Days
TXn	Min T_{max}	Monthly minimum value of daily maximum temperature	°C
TNn	Min T_{min}	Monthly minimum value of daily minimum temperature	°C
TX10p	Cold days	Percentage of days when TX < 10th percentile	% Days
TN10p	Cold nights	Percentage of days when TN < 10th percentile	% Days
Precipitation indices			
RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
RX5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
SDII	Simple daily intensity index	Annual total precipitation divided by number of wet days (defined as PRCP ≥ 1.0 mm) in the year	mm d^{-1}
R10	Number of heavy precipitation days	Annual count of days when PRCP ≥ 10 mm	Days
R20	Number of very heavy precipitation days	Annual count of days when PRCP ≥ 20 mm	Days
R40[b]	Number of days above 40 mm	Annual count of days when PRCP ≥ 40 mm	Days
R100[b]	Number of days above 100 mm	Annual count of days when PRCP ≥ 100 mm	Days
CDD	Consecutive dry days	Maximum number of consecutive days with PRCP < 1 mm	Days
CWD	Consecutive wet days	Maximum number of consecutive days with PRCP ≥ 1 mm	Days
R95p	Very wet days	Annual total PRCP when PRCP > 95th percentile	mm
R99p	Extremely wet days	Annual total PRCP when PRCP > 99th percentile	mm
PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (PRCP ≥ 1 mm)	mm

[a]Not evaluated in the present study
[b]User-defined indices for the present study

The implementation of RClimDex developed by Zhang & Yang (2004) includes some built-in logic to decide on how to calculate an index from an incomplete dataset. For instance, the threshold values of percentile type indices are calculated when the missing values are not more than 30% of the data present. Monthly and annual values are calculated if no more than 3 days in a month and 15 days in a year are missing, respectively.

Indices were not calculated for a particular year if at least 1 mo of continuous data was missing. However, the impact of sudden missing data is not clear. A sensitivity test was conducted by artificially setting a random subset of data to missing value and running the RClimDex software. To take into account the possible bias from a single random selection, we computed the indices 50 times for each percent of records set to missing. To incorporate complete randomness, no particular seed was set for random number generation. However, with a large number of simulations, comparable variation in the range of values is expected. We found that for up to about 2% of the random missing data, indices were being calculated for all available years. After that, the number of years decreased sharply. On the other hand, the magnitude of the trend showed a considerable deviation even after 1% of data was removed. Based on this, Hatiya station was excluded from further analysis.

Bangladesh is a subtropical country and not all indices are suitable for the study area. Frost days (FD0), ice days (ID0), and growing season length (GSL) were thus removed from our analysis. The first 2 of these are not found in this particular climate, while GSL is essentially constant over the data period.

2.4. Statistical methods

Sen's slope was calculated to estimate the regression coefficient for the time series. Sen's slope is based on Kendall's tau estimate, which is a robust estimation method of a monotonic trend (Sen 1968). Significance of the trend was analyzed using the Mann-Kendall trend test. This is a non-parametric test and has proven to be useful in determining significance at different confidence levels. Autocorrelation is a very common feature of hydrological data series and affects the detectability of trend (Zhang et al. 2000, Yue et al. 2002a), which most previous trend analysis studies on Bangladesh did not consider. We calculated autocorrelation using the method proposed by Zhang et al. (2000), where the trend is calculated first. If a trend is found to be significant, it is removed and then autocorrelation is calculated. The resulting series is then passed again through the same workflow until the difference between the estimated slope and lag-1 autocorrelation is smaller than 1% in 2 consecutive iterations. The significance of the trend was tested against a 95% confidence interval. A description of the Mann-Kendall trend test and Sen's slope estimation can be found in Yue et al. (2002b).

3. RESULTS

3.1. Changes in temperature extremes across Bangladesh

3.1.1. Mean and frequency of extreme temperature

The average annual and seasonal temperature anomalies are presented in Fig. 2. Annual temperature increased steadily at a rate of about 0.3°C decade^{-1}. An increasing trend of 0.3 and 0.4°C decade^{-1} was found in the annual average maximum and minimum temperature respectively. Both of these trends are statistically significant at a 95% confidence interval. However, during the last climatic normal period, the minimum temperature increased more than the maximum temperature, meaning that a rise in average temperature was accompanied by a decrease in the diurnal temperature range. The smoothed pattern of the seasonal anomaly plot reveals that except for the winter season, all other seasons showed an increasing anomaly at the end. The anomaly is most prominent in the pre-monsoon season, with a value of 0.4°C decade^{-1}. The temperature anomaly in winter shows the lowest trend of 0.2°C decade^{-1}. The trend of the temperature anomalies in both monsoon and post-monsoon season are about 0.3°C decade^{-1}.

An increasing trend was found in the average frequency of warm temperature indices, while a decreasing trend was found in that of cold temperature indices over Bangladesh (Fig. 3). The percentage of number of warm days increased at a rate of 0.30% yr^{-1} or about 11 days decade^{-1}. On the other hand, the percentage of number of cold days decreased at a rate of 0.15% yr^{-1}, which corresponds to 5 days decade^{-1}. A similar trend was seen in the number of warm nights and cold nights. An increasing trend of 9 days decade^{-1} or 0.26% yr^{-1} was found in the percentage of warm nights. The percentage of number of cold nights decreased at a rate of 14 days decade^{-1}. The increasing trend in warm indices and

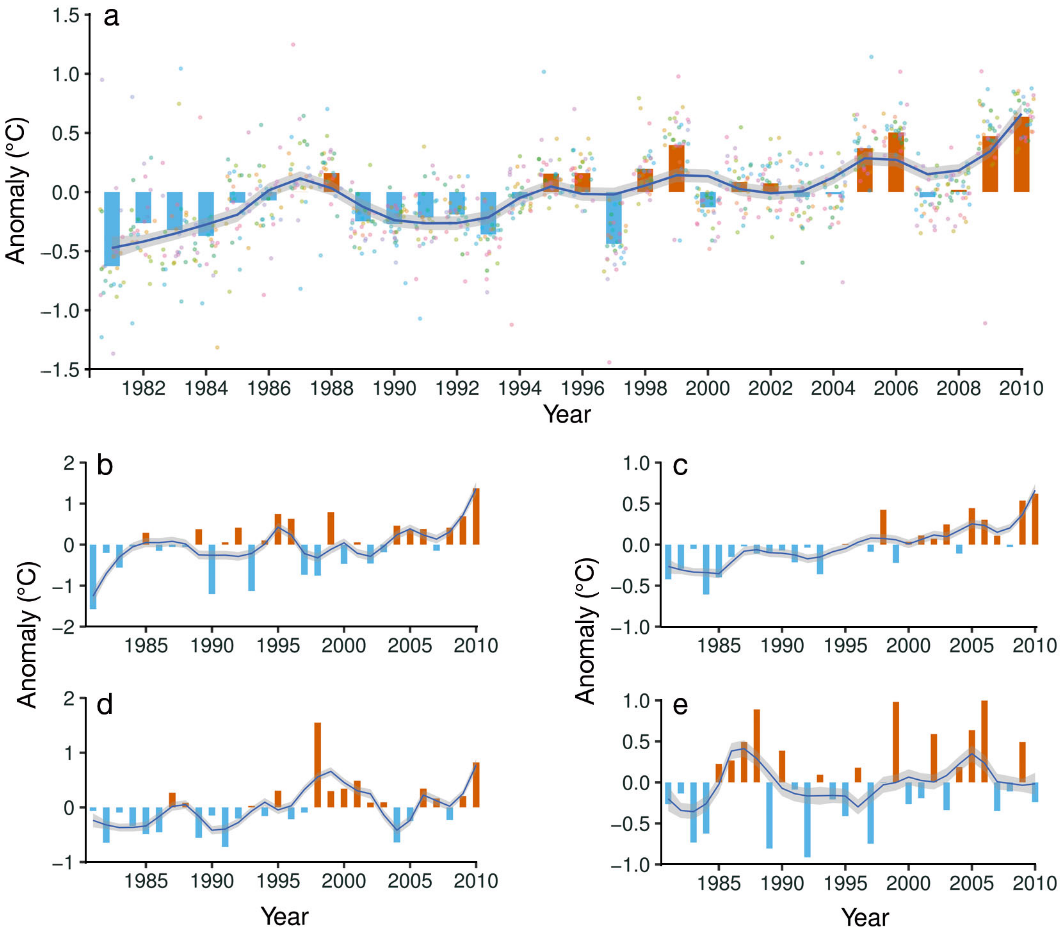

Fig. 2. Changes in average daily mean temperature for the (a) annual, (b) pre-monsoon (Mar–May), (c) monsoon (Jun–Sep), (d) post-monsoon (Oct–Nov), and (e) winter (Dec–Feb) seasons. Individual bars: average anomaly of temperature from the mean (orange = positive anomaly, blue = negative anomaly); dots: the spread of the individual stations; solid line: running biannual trend; grey shading: 95 % confidence interval

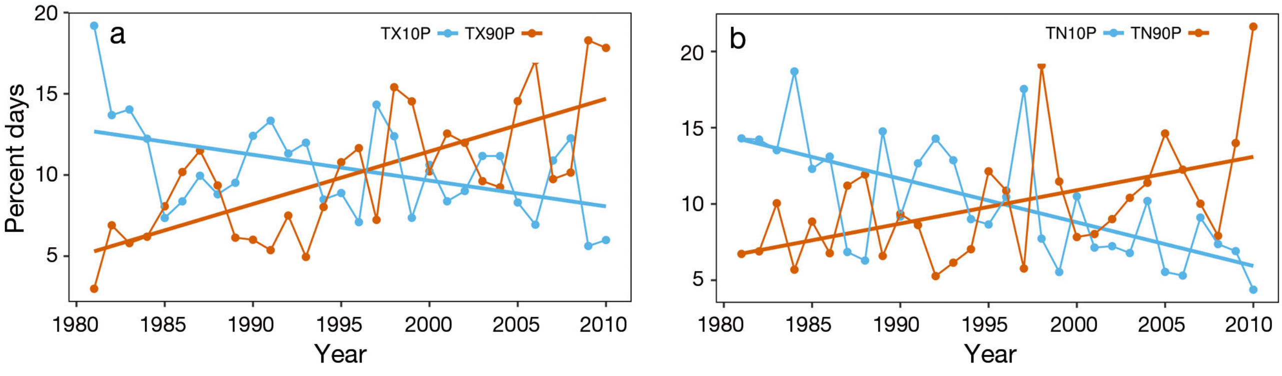

Fig. 3. Regional average changes and trends of (a) warm (TX90P) and cold days (TX10P), and (b) warm (TN90P) and cold nights (TN10P). Solid straight lines are the trend lines found from Sen's slope estimate. See Table 2 for definitions

decreasing trend in cold indices suggests an overall increase in the warming of the country over the last decades.

To detect temporal changes, we divided the study period into 3 equal decadal subsets of 10 yr each and plotted a density distribution function (Fig. 4). A systematic shift in the average and spreading of the indicators was seen from one decade to another. If the mean value is considered, the shift is most prominent during the last decade (2001–2010).

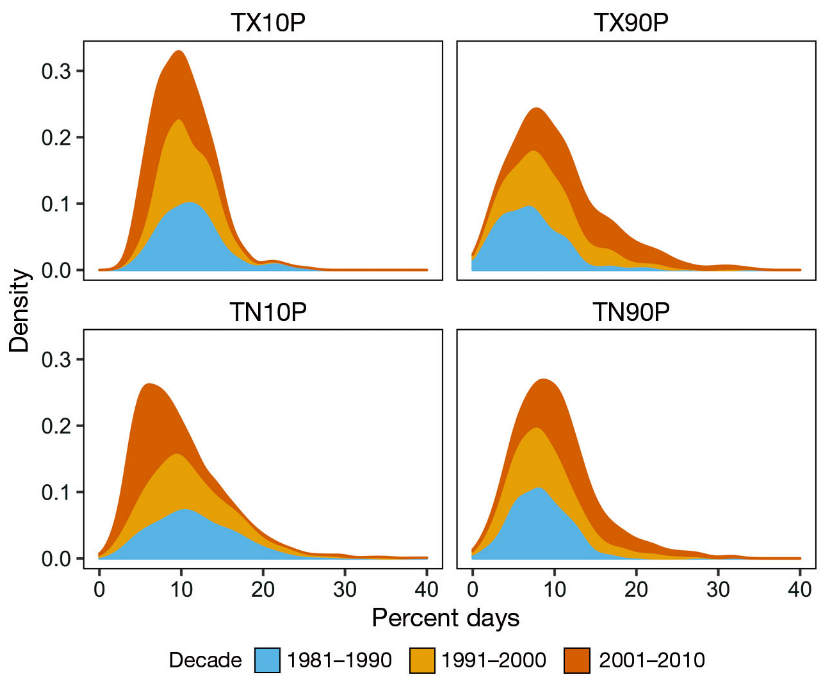

Fig. 4. Probability distribution function of annual frequency of cold days (TX10P), cold nights (TN10P), warm days (TX90P) and warm nights (TN90P) for 3 decades: 1981–1990, 1991–2000, and 2001–2010. See Table 2 for definitions

3.1.2. Changes in hot extreme temperature

Spatial distribution maps of the trend of the maximum and minimum temperature are presented in Figs. 5 & 6 respectively. The magnitude of the values at individual stations is shown in Table S1 in the Supplement at www.int-res.com/articles/suppl/c077p045_supp.pdf.

The yearly maximum of minimum temperature (TNx) showed an increasing trend at all station locations. Twelve of them showed a statistically significant trend at the 95% level. The yearly maximum of the maximum temperature (TXx), on the other hand, had a significant positive trend in the south and northeast regions, a negative trend in the central region, and no trend over the northwest region of the country. Although not statistically significant, a negative trend in TXx was found at 6 stations. Overall positive trends around the country were found for warm nights (TN90P) and warm days (TX90P). An increasing trend for TX90P was seen for all locations except Feni, and 17 of them are statistically significant. For warm nights, on the other hand, 16 stations had a significant positive trend.

Summer days (SU) indices were calculated for 2 different thresholds. A 25°C threshold (SU25) is defined by the ETCCDI and is a standard index, and we also used a 35°C threshold (SU35) corresponding to the 90th percentile maximum temperature. We saw a statistically significant increasing trend clustered in the eastern parts of the country, but no trend in the northwest parts of the country. Both increasing and decreasing trends were found in the southwest and central parts of the country. Only 6 stations showed a decreasing trend for SU35. Trends were significant at a 95% confidence level in the southern parts of the country. On the other hand, of the 6 stations with negative but non-significant trends, 5 are located in the northern parts of the country.

Tropical nights (TR) indices were also calculated for 2 different thresholds. The 20°C threshold (TR20) is the standard index, and we also used a 25°C threshold (TR25) that corresponds to the 90th percentile of the daily minimum temperature. In both cases, a consistent and similar trend was observed over the whole country. Almost all stations show a statistically significant increasing trend for TR20. For TR25, a positive trend was observed at all stations, of which 16 were statistically significant. On the other hand, warm spell duration shows virtually no trend at most stations, except Sylhet, Srimangal, and Ishurdi.

3.1.3. Changes in cold extreme temperature

The trends in the minimum of the minimum temperature (TNn) and the minimum of the maximum temperature (TXn) both exhibited unexpected results. A scattered and incoherent pattern over the country was found for the trend of TNn at all stations. The number of stations showing increasing and decreasing trends is almost equal, and 5 stations showed no trends for TNn. For TXn, an overall decreasing trend was observed at all stations. The trends in the northern parts of the country are significant while the trends in the southern parts of the country are not significant. An increasing but insignificant trend of TXn was found for Sylhet station in the northeast and 3 stations in the southeast, namely Cox's Bazar, Kutubdia, and Teknaf. While the overall average temperature had an increasing trend, the maximum temperature in the winter season was not increasing but decreasing for most of the stations. In

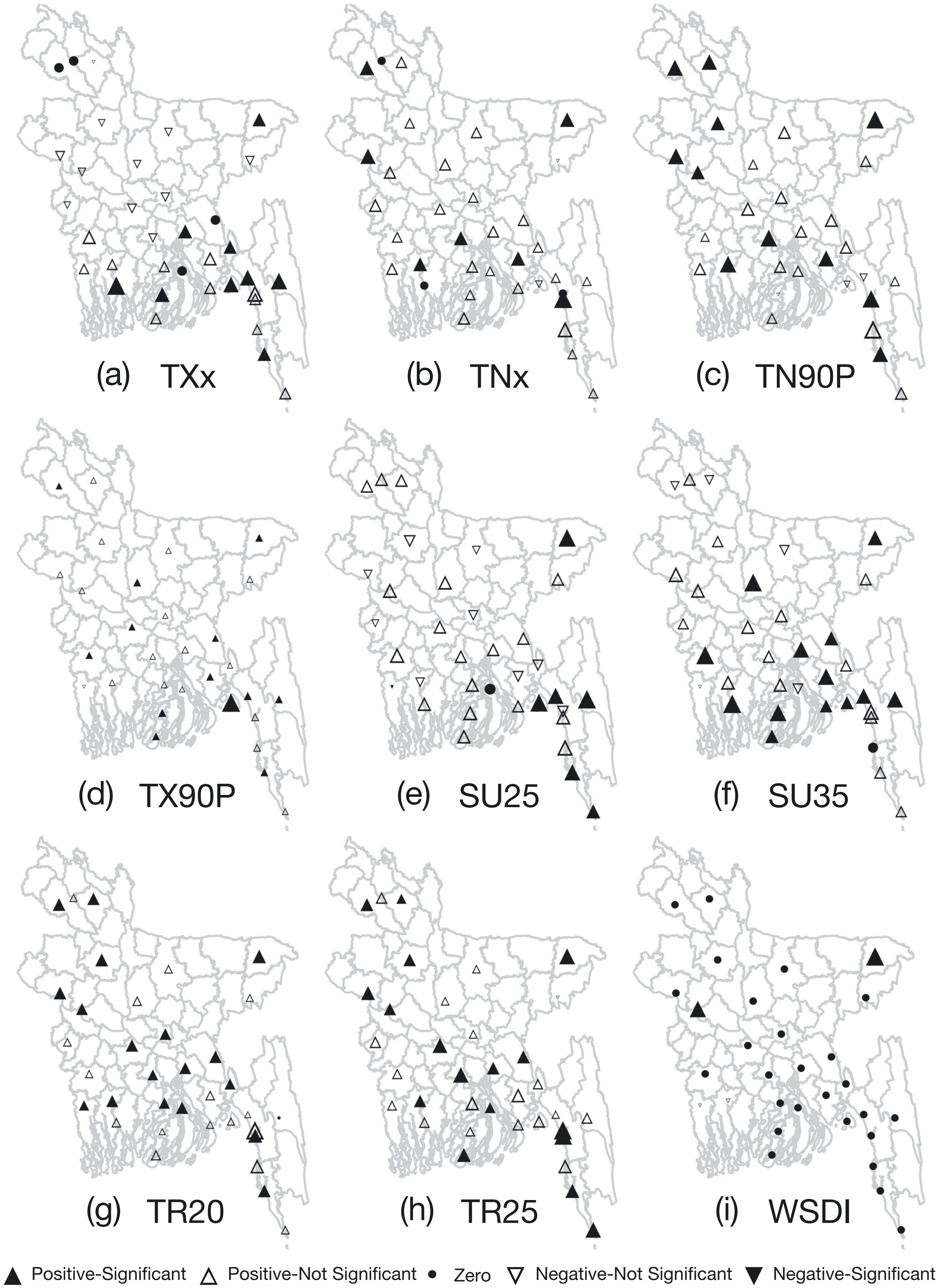

Fig. 5. Spatial distribution of hot temperature indices: (a) TXx, (b) TNx, (c) TN90P, (d) TX90P, (e) SU25, (f) SU35, (g) TR20, (h) TR25, (i) WSDI. See Table 2 for definitions

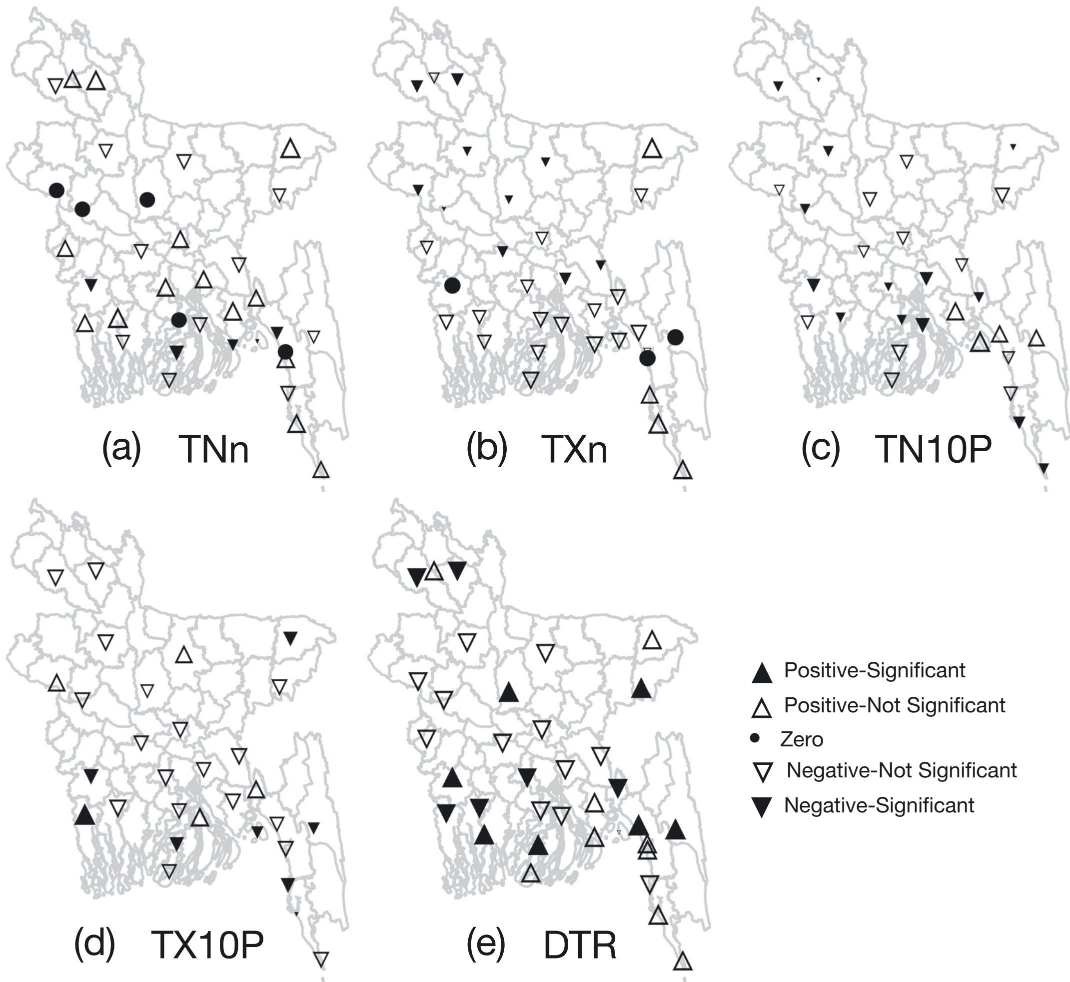

Fig. 6. Spatial distribution of cold extreme temperature indices: (a) TNn, (b) TXn, (c) TN10P, (d) TX10P, (e) DTR. See Table 2 for definitions

other words, the cold extremes are heading towards a warmer condition with a decrease in both magnitude and frequency.

Positive trends were found for both for cold days (TX10P) and nights (TN10P), which is consistent with a warming climate. Coherent decreasing trends over the country were observed in both TX10P and TN10P. In a warming climate, it is to be expected that the number of cold days and cold nights will be lower. Compared to TX10P, TN10P showed significant positive trends in many stations. Increasing trends were seen for TX10P all over the country, while stations in a clustered region in the southeast had positive trends in TN10P.

The trends in the diurnal temperature range (DTR), which is the average difference between the daily maximum and daily minimum temperature, were mixed. An almost equal number of positive (negative) as well as significant (non-significant) trends was found. A negative trend in DTR means that daily minimum temperature is increasing more than daily maximum temperature. A positive trend indicates the opposite, i.e. that daily maximum temperature is increasing faster than daily minimum temperature.

The change of trends in warm (TX90P) and cold indicators (TN90P) requires closer examination to understand the relationships between them. To facilitate this, we performed linear regression analysis between the trend of cold and warm indices (Fig. 7). Trends per 100 days were plotted instead of the original percentage of the trend values. The negative regression line between warm days (TX90P) and cold days (TX10P) indicates that both indicators show a warming trend. While warm days are increasing, cold days are decreasing accordingly. A similar situation was found for warm nights (TN90P) and cold nights (TN10P), decreasing number of cold nights (TN10P) and increasing number of warm nights

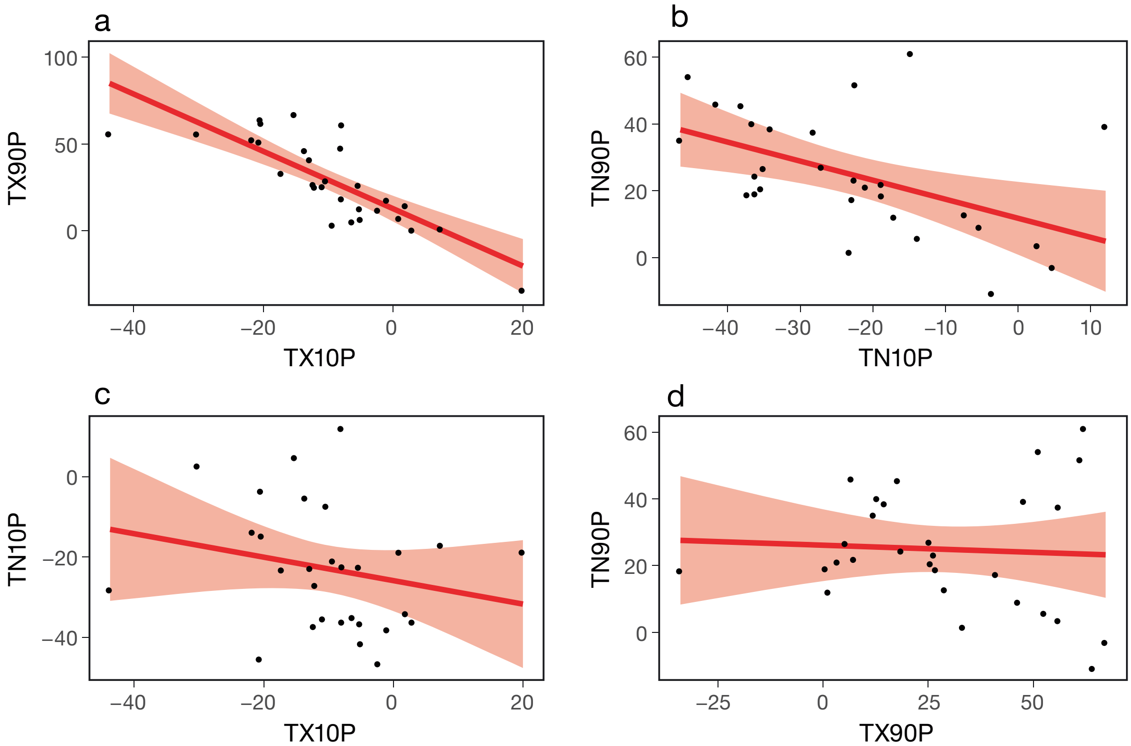

Fig. 7. Comparison between trends of extreme temperature indices: (a) warm days (TX90P) vs. cold days (TX10P), (b) warm nights (TN90P) vs. cold nights (TN10P), (c) cold nights (TN10P) vs. cold days (TX10P), and (d) warm nights (TN90P) vs. warm days (TX90P). See Table 2 for definitions. The unit of the trend is the number of days per 100 days. Red straight line: regression line; shaded area: 95% confidence interval of the regression

(TN90P) was found for the whole country. The cross-correlation between cold nights (TN10P) and cold days (TX10P) is a somewhat flat relationship. The same is true for warm nights (TN90P) and warm days (TX90P).

3.2. Changes in precipitation extremes across Bangladesh

3.2.1. Annual and seasonal total precipitation

Annual and seasonal precipitation anomalies are presented in Fig. 8. A not-significant decreasing trend in the annual rainfall anomaly of 10.6 mm yr^{-1} was found. During the monsoon season, a decreasing trend in rainfall anomaly of 3.9 mm yr^{-1} was observed, which is second to the pre-monsoon season where rainfall anomaly changed at a rate of a 4.8 mm yr^{-1}. Indian summer monsoon rainfall is reportedly decreasing since the 1950s. Such a decrease has been associated with the declining gradient between land and ocean temperatures (Jin & Wang 2017). The trend has been found to be increasing since 2002 over central India. In the present study, we found an increasing trend in rainfall during the post-monsoon of 2.5 mm yr^{-1}. The anomaly in rainfall during winter was comparatively small and did not show much change, except a small decreasing trend of 0.8 mm yr^{-1}. We note that, except for the pre-monsoon season, all the trends were statistically not significant at a 95% confidence interval.

3.2.2. Changes in extreme precipitation indices

The spatial maps of significance and direction of the trends in extreme precipitation indices are presented in Fig. 9. The values of the trends in the extreme precipitation indices for each station over Bangladesh are available in Table S2 in the Supplement.

A very similar distribution of the direction of the trend over Bangladesh was found in the trends in threshold-based precipitation extremes such as heavy precipitation days (R10) and very heavy precipitation days (R20). Trends in these 2 indices indicate that there is a region-wide decreasing tendency of the number of such rainfall events. Trends in both R10 and R20 were predominantly negative. Significant negative trends occurred in both indices at 2

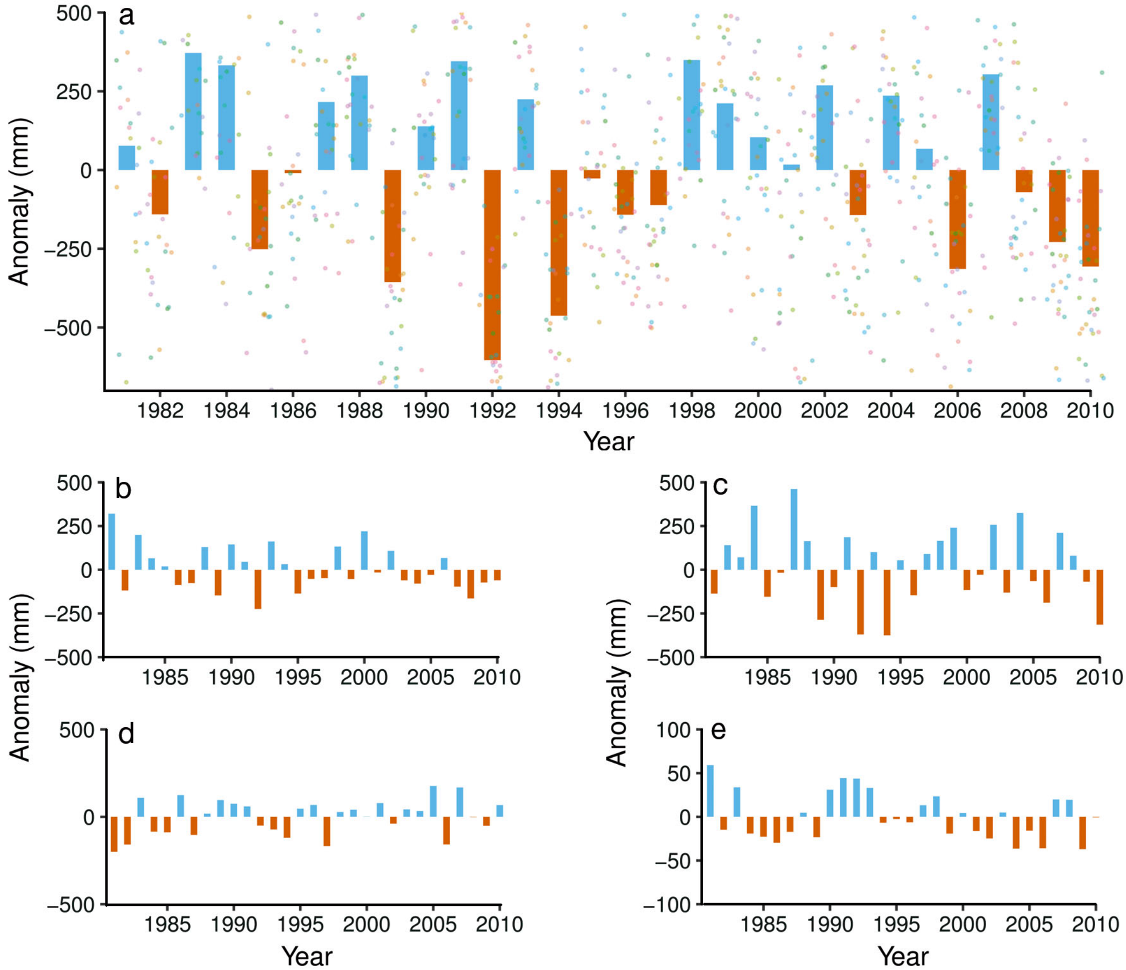

Fig. 8. Precipitation anomaly for (a) annual, (b) pre-monsoon, (c) monsoon, (d) post-monsoon, and (e) winter seasons. Bar: average value of all stations (orange = positive anomaly, blue = negative anomaly); dot: an individual station value for a particular year

locations in the northeast region, where annual rainfall is comparably higher. It is also interesting to mention that, incidentally, the 20 mm threshold also corresponds to the average 90th percentile rainfall. The R40 index is a user-defined indicator which indicates the number of days with rainfall corresponding to the average 95th percentile rainfall. A negative trend in R40 was observed in almost all the regions, except for the southwest region. However, the trends in R40 for all stations, except for the Faridpur and Madaripur stations, were not statistically significant. For the R100 index, which roughly corresponds to 99th percentile rainfall amount, no trend over the country was seen. Negative trends in R100 were found for a few stations in the south and northeast regions, but these were not statistically significant.

We found no significant trend over the country in 2 percentiles-based indices, namely, very wet days (R95p) and extreme wet days (R99p). No trend in R99p for a large number of stations indicates that the total precipitation when the precipitation amount is more than the 99th percentile has not changed over the past decades. On the other hand, a general increasing trend was shown for the precipitation amount more than the 95th percentile over the country, except the northeast region.

For annual total precipitation (PRCPTOT), we found a decreasing trend for the 1981–2010 period. At 3 station locations, situated in the southeastern coastal and hill-tract region, a positive non-significant trend was observed. Unlike for the PRCPTOT, a positive non-significant trend was seen in the simple daily intensity index (SDII), which is the daily wet day average of total rainfall.

Maximum 1-day precipitation showed an increasing trend along the path of monsoon progression. The trend was statistically significant in the southeast stations, namely, Rangamati, Cox's Bazar, and

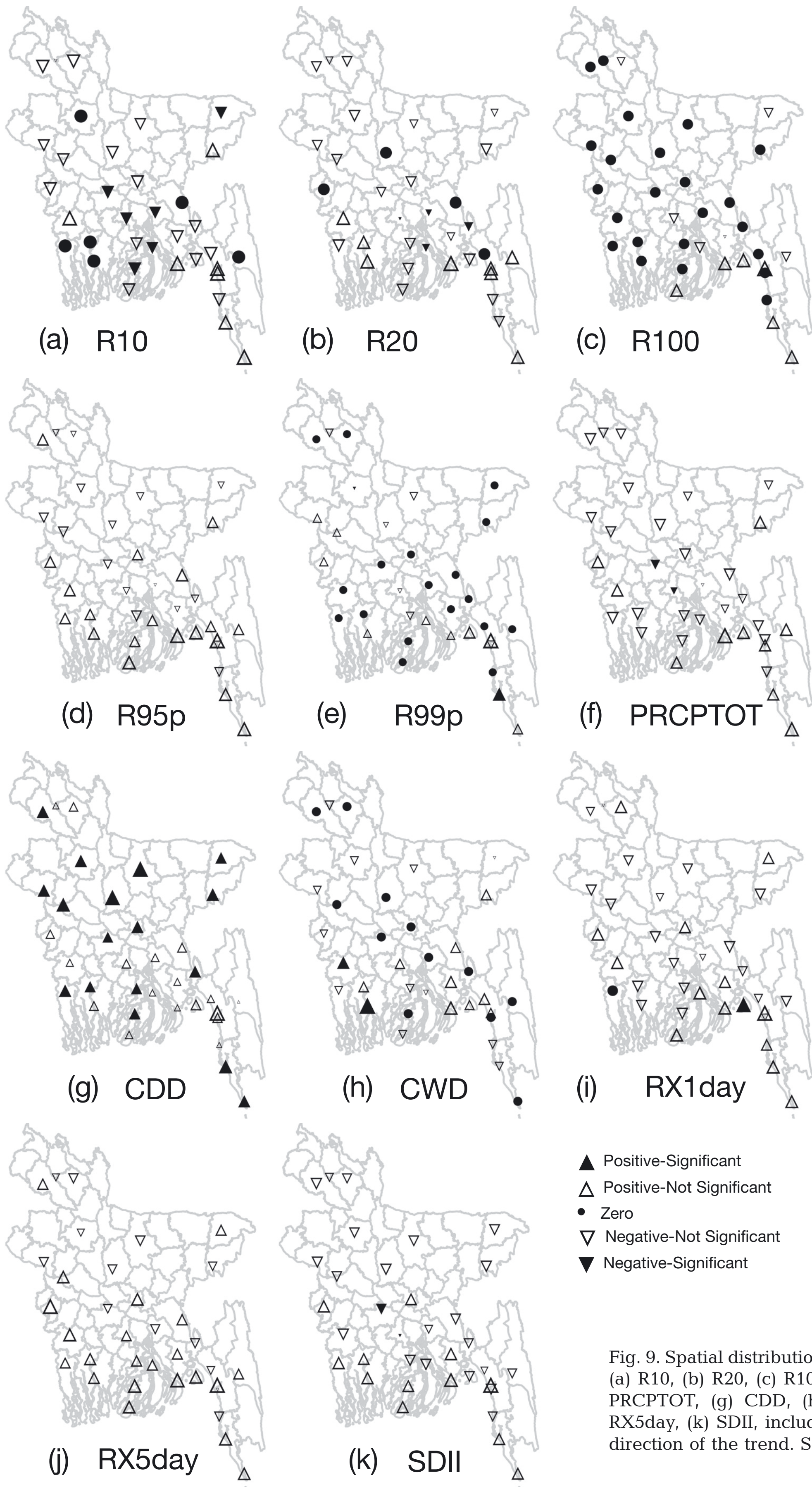

Fig. 9. Spatial distribution of precipitation indices: (a) R10, (b) R20, (c) R100, (d) R95p, (e) R99p, (f) PRCPTOT, (g) CDD, (h) CWD, (i) RX1day, (j) RX5day, (k) SDII, including the significance and direction of the trend. See Table 2 for definitions

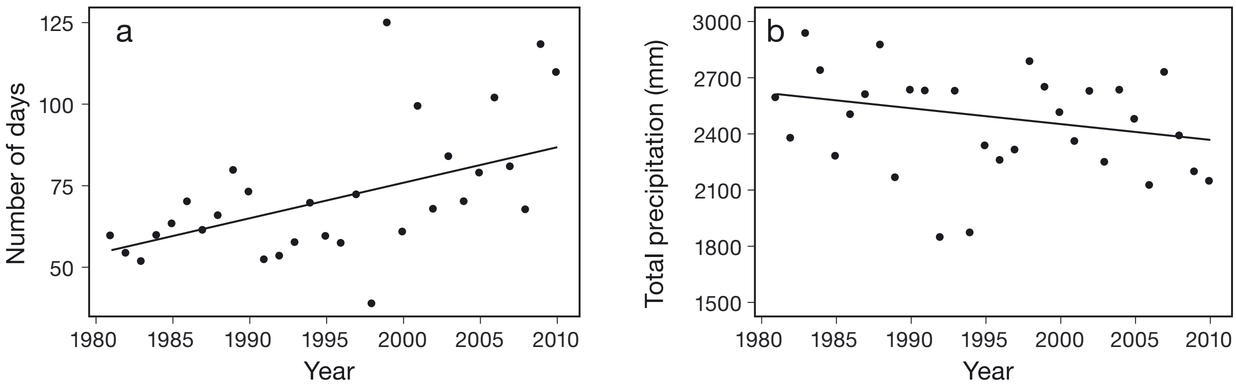

Fig. 10. Trends in spatially averaged time series of (a) CDD and (b) PRCPTOT. See Table 2 for definitions. The black line is the fitted trend line

Teknaf. For maximum 5-day precipitation, an overall increasing trend was observed over the country but was not statistically significant. Increasing but not statistically significant trends were found in both 1-day and 5-day maximum precipitation. This indicates that there is a tendency of rainfall events happening with very high precipitation. Such heavy 1-day and 5-day rainfall events can cause events like landslides and waterlogging. A devastating landslide occurred on 12 June 2017, when a heavy rainfall of >340 mm triggered a series of land collapses and killed >150 people, destroying >5000 households (Islam et al. 2017).

A tendency of a decreasing amount of rainfall over the study area was found when we considered all the rainfall indices. Consecutive dry days (CDD), which measures the largest number of consecutive days in a year with <1 mm rainfall, agrees with this trend of rainfall and showed an overall increasing tendency. Among 26 station locations, 19 of them showed a statistically significant increasing trend. The wet counterpart of the index, consecutive wet days (CWD), showed no trend over the northwest and central region. A statistically significant negative trend in CWD was found in 3 locations in the southwest, namely, Rangamati, Teknaf, and Cox's Bazar. It is worth mentioning that a positive but not significant trend in CDD was found in these 3 stations. Maijdi Court was the only place where a significant positive trend in CWD as well as a positive but not significant trend in CDD was observed.

For a closer look at the drying tendency, time series were plotted for 2 indices, namely CDD and PRCPTOT (Fig. 10). The average number of the longest consecutive dry days increased at a rate of 1 d yr^{-1}. Average PRCPTOT, on the other hand, decreased at a rate of about 11.3 mm yr^{-1}. The trend in CDD is statistically significant at a 95% confidence interval.

4. DISCUSSION

This study focused on extreme indices for Bangladesh, for which not much literature is available. In this section, the major findings of the present study will be compared with previous studies.

The rising trends in both maximum and minimum temperature are similar to previous studies (Islam 2009, Shahid et al. 2012). Using data from 1948 to 2007, Islam (2009) found increasing trends in maximum and minimum temperature of 0.06 and 0.15°C $decade^{-1}$ respectively. Shahid et al. (2012) used a dataset from 1961 to 2008 and found an increasing trend of 0.11 and 0.15°C $decade^{-1}$ for maximum and minimum temperature respectively. The present study reports an increasing trend of 0.3°C $decade^{-1}$ for maximum temperature and 0.4°C $decade^{-1}$ for minimum temperature. This indicates that, during the last century, the trends in both the maximum and minimum temperature have been increasing steadily, with a faster rise in minimum temperature. The present study also reports a similar trend in the diurnal temperature range (DTR) as Shahid et al. (2012).

An increase in temperature is also associated with an increase in power consumption. Shahid (2012) showed that power consumption and peak power demand is elevated especially during the pre-monsoon hot-summer season. The hot-summer season also coincides with high mortality in urban areas (Burkart et al. 2011). Increase in temperature is reported to increase renal diseases (Hansen et al. 2008). Consistent rise in summer days (SU25 and SU35) is indicative of a potential increase in such health issues. In most cases, the victims of these health-related impacts are from the most vulnerable lower socioeconomic group of the population (Hashizume et al. 2009, Shahid 2010b). It is also to be noted that consistent increases in tropical nights (TR20, TR25), warm days (TX90P), and warm nights (TN90P) are suggestive of increasing hot weather extremes. An increasing incidence of heat stroke has been reported among rickshaw pullers and industry workers in recent years (Begum & Sen 2004).

Precipitation and related indices exhibit a general negative drying trend over Bangladesh during the period 1981 to 2010. This result is in disagreement with Shahid (2011a), who reported an overall increasing trend using data from 1958 to 2007. This disagreement could be due to the selection of the period, as reported by Kripalani et al. (1996). They found that during the period 1901–1960, there was an overall decreasing tendency of precipitation. The following period 1963–1977, on the other hand, showed an increasing tendency. The present study shows that the trend is following a drying trend considering the period 1981–2010.

Although total precipitation shows a negative trend since 1981, Bangladesh has faced a number of heavy precipitation-related disasters. The monsoon floods in 1987, 1988, 1998, and 2007 are the most notable of these (Brammer 1990, Mirza 2002, Islam et al. 2010). Flooding in Bangladesh is mostly due to the precipitation in the vast basins of Ganges and Brahmaputra, most of which are outside Bangladesh (Mirza 2002, Ahmad & Ahmed 2003). The northeast region is also prone to flash flooding due to continuous heavy precipitation in the Meghalaya hill tracts in the Meghna basin (Sarker & Rashid 2013). The present study also found an increasing trend in both RX1day and RX5day at Sylhet station in the northeast region, although they were not statistically significant. Landslides are another common disaster in the southeast hill tract region (Sarker & Rashid 2013). Continuous precipitation in these regions triggers such events and causes a high number of casualties (Islam et al. 2017). The present study also found a statistically significant trend in RX1day in the hill tract area.

Changes in precipitation and temperature have a multi-dimensional effect on people and society. With the rise in temperature as well as evapotranspiration, agriculture will require more water for irrigation. This phenomenon will affect the Boro (winter) crops most in Bangladesh (Mahmood 1997, Shahid 2011b). An overall increase in consecutive dry days (CDD), as well as decrease in total precipitation (PRCPTOT), also indicates that the country is trending toward a warmer and drier climate. However, an increase of 1-day maximum precipitation has increased the chances of urban flooding and consequent landslides.

5. CONCLUSIONS

This study analyzed the trends of extreme climate over Bangladesh using several temperature and rainfall indices. Based on analysis of the historical observed data from stations located across the country, the following conclusions can be made.

(1) Annual temperature has increased steadily at a rate of about 0.3°C decade^{-1}. Trends for annual maximum and minimum temperature are about 0.3°C decade^{-1} and 0.4°C decade^{-1}, respectively.

(2) A decreasing trend for SU35 was found in only 6 stations. Almost all the stations showed a statistically significant increasing trend for TR20. The consistent increases in the summer days (SU25 and SU35) and tropical nights (TR20 and TR25) are also suggestive of increasing hot weather extremes.

(3) The average annual total precipitation (PRCPTOT) decreased at a rate of about 11.3 mm yr^{-1}. However, an increasing trend was found in the maximum 1-day precipitation (RX1day) which occurred during the monsoon season.

(4) The average number of longest consecutive dry days (CDD) is increasing at a rate of 1 d yr^{-1}. No significant trend was found in the consecutive wet days (CWD) for many regions of Bangladesh.

The results indicate that there is a significant trend of warming and change in extreme events in Bangladesh. The current scientific understanding and analysis of observed records suggests that with the warming of the globe, the intensity and frequency of the climatic extremes are also expected to rise in various parts of Bangladesh in the future. Further investigation is required to identify such probable future changes of extreme climate and quantify their impacts wherever possible. In this study, extreme indices were developed based on temperature and precipitation records. Changes in extreme wind, sunshine hours, mean sea level pressure, and relative humidity should also be studied in the future in order to gain a broader understanding of the regional climate trends and associated impacts.

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