Variability and trends of climate extremes indices from the observed and downscaled GCMs data over 1950–2020 period in Chattogram City, Bangladesh

Lia Pervin* and Md. Sabbir Mostafa Khan
Department of Water Resources Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka 1000, Bangladesh
*Corresponding author. E-mail: liapervin@gmail.com

ABSTRACT

This study was intended to evaluate the variability and trends of climate extremes by incorporating daily data from Chattogram station and from the high-resolution Coordinated Regional Climate Downscaling Experiment (CORDEX) for two different time series. Here, we also focused on evaluating the performance of the selected RCMs (CanESM2, CSIRO, and GFDL from CORDEX) using Taylor diagrams and heat map analysis. Twenty-two extreme climate indices from ETCCDI were computed for the 1950–1989 and 1990–2020 periods. Mann–Kendall and Sen’s slope test were performed to estimate the trends from the indices from both station and RCMs data. Highly significant increasing trend for the warm days and warm nights’ frequencies were found, whereas the frequency of cold days and cold nights indicated a significantly decreasing trend. On the other hand, a mild increasing trend in 1-day and 5-day maximum rainfall was detected. Also, the average annual precipitation has increased by 6% from the 1950–1989 to 1990–2020 period. During the last three decades, the region has experienced heavier rainfall in the monsoon but increased water stress in the dry season. The two-fold effects of climate change on the local hydrology revealed by this study need to be addressed properly for the sustainable development of this region.

Key words: climate change, climate extremes, heat map, trends, variability

HIGHLIGHTS

- Performance of the selected RCMs was evaluated using Taylor diagrams and Heatmaps analysis for the Chittagong region.
- Variability of climate extremes from 1950–1989 to 1990–2020 was assessed.
- A total of 22 extreme climate indices were computed and their changes over time were investigated.
- Trend analysis was performed for the extreme rainfall and temperature indices from both station and RCMs data.
GRAPHICAL ABSTRACT

Taylor diagram for mean monthly T_max

Heat map for mean monthly T_min over 1990-2020 period

Box-whisker plots for RX1DAY over 1990-2020 period from CanESM2,CSIRO and GFDL

Plot of extreme rainfall indices R20MM over 1950-1989 and 1990-2020 period
INTRODUCTION

Chattogram, the second-largest city and the main port city of Bangladesh, has a history of suffering from floods and waterlogging in every monsoon. Frequent and prolonged waterlogging due to intense rainfall is becoming more common and is causing losses to the economy, as well as to the environment (Tang et al. 2018). Various factors, including unplanned urbanization, deterioration of natural outlets, and the poor drainage conditions in Chattogram affect this waterlogging condition. The impact of climate change in recent years has changed the magnitude and variability of the occurrences of extreme events (Raihan et al. 2015), which has elevated the waterlogging problems in Chattogram. This claim became stronger when Akter et al. (2017) found that more locations in Chattogram City have been experiencing frequent and prolonged waterlogging in recent years. Islam & Raja (2021) prepared a waterlogging inventory map to show the spatial variations of the risk by means of hazard intensity, exposure, and vulnerability to waterlogging in Chattogram, which indicated about 3.03% of the city area is highly vulnerable to waterlogging. The city has a pre-existing drainage condition, which has been getting worse in recent decades. It is suspected that climate change has altered the characteristics of extreme temperature and rainfall events over time.

Bowden et al. (2013) reported that globally extreme weather events are changing in terms of their extensiveness, severity, and frequency of occurrence. Changes in mean temperature, accompanied by a rise in minimum temperature, and increase in the frequency of extreme temperatures associated with heatwaves were reported in many regions, including Asia (Klein Tank et al. 2006). In Bangladesh, changes in temperature and rainfall patterns have also been reported (Shahid 2010; Shahid et al. 2012; Hossain et al. 2014; Nowreen et al. 2015; Chowdhury et al. 2019). An increase in annual and seasonal temperatures as well as climate-related extreme events were detected by Shahid et al. (2016) over the 1958–2012 period, whereas Bashir et al. (2018) identified a decreasing trend in the seasonal total rainfall and consecutive wet days over northeast Bangladesh for the 1984–2016 period. Mullick et al. (2019) stated that the climate of Bangladesh is getting cooler and drier for winter and, on the other hand, warmer and wetter for the rest of the year, after analyzing temperature and rainfall data from 1966 to 2015. Rahman & Lateh (2017) found upward trends in minimum temperature in the northern, northwestern, northeastern, central, and central southern parts while the greatest warming in the maximum temperature was in the southern, southeastern, and northeastern parts during 1971–2010. An upward trend of annual rainfall and downward pre-monsoon and post-monsoon rainfall trends was detected during this period.

As reflected in the literature, in recent years, climate change has created new challenges. However, not many studies were reported focusing on the extreme indices and variabilities of local climate in Chattogram. Besides, how this trend and variabilities could have been affected by the ongoing climate change also remain undetermined. Comprehensive scientific knowledge-based studies are required to understand the effect of climate change on the local hydroclimatic system. As noted, there are certain limitations and inconsistencies in the previous studies. Most of the studies were conducted based on various station data to identify the trends of temperature and/or rainfall over a certain period of time, however, their findings were not aligned. It seems more appropriate to assess the temperature and rainfall characteristics from two different epochs (past and present) to gain more comprehensive knowledge on the rate and pattern of changes. Dash & Maity (2019) evaluated precipitation-based climate change indices over three 35-year epochs and analyzed the spatio-temporal trend to extract the characteristics of changes for India. However, our extensive literature review found no studies for our region to investigate both temperature and rainfall events over time.

In recent years, powerful general circulation models (GCMs), commonly known as global climate models, have been developed, which can model the historical climate of Earth reasonably well. Therefore, the GCMs are considered as the base to project the future climate; however, downscaled GCMs or regional climate model (RCM) data are more competent for local climate modeling than the raw GCMs data (Pervin & Gan 2021). Still, not many studies have utilized the combination of RCMs and station data to investigate the long-term changes in the climate extremes for this region. On the other hand, selecting the appropriate RCMs for any region is the key to assessing the future climate change over that region. However, lack of information about the applicability of particular RCMs for climate change analysis was noticed for this region.

The focus of this study was to investigate the extreme climate indices and to evaluate the trends and variabilities of temperature and rainfall over two different periods, incorporating the most recent available data sets (1950–2020), from the station as well as from the high-resolution (25 km x 25 km) Coordinated Regional Climate Downscaling Experiment (CORDEX). Another objective was to evaluate the performance of the selected RCMs, and thus to offer some options for choosing the regional climate models in this region. This study will help to minimize the study gap on applicability of different RCMs for climate change analysis in this region. Evaluation of indices from two different time periods will help to compare the
pace of climate changes and to recognize their effects on the extreme climate events. The outcome from this study will contribute to the knowledge base for understanding and quantifying the potential impact of climate change and thus will identify the vulnerabilities associated with this change. Moreover, the policymaker may find the results useful to adopt revised water management policies.

**STUDY AREA AND DATA**

Bangladesh is located in South Asia and the geographic coordinates are between 20°34’ to 26°38’ N and 88°01’ to 92°41’ E. The country experiences high temperatures and humidity; it also receives a great deal of annual rainfall (average 2,900 mm/year in the last 30 years), where most of the rainfall (almost 80%) occurs during the monsoon season (June to October). Chattrogram (previously called Chittagong), being the second largest city, located in the southeastern region, is also the main port city of Bangladesh. It is also considered the major economic zone of Bangladesh. The geographical location of Chattogram is 22.13° to 22.28° N latitude and 91.45° to 91.54° E longitude. The floodplain and piedmont plains (landform created at the foot of a hill) of Chattogram are poorly drained and subject to waterlogging and flash floods during monsoon season, and each year, the climate extremes are linked with disasters, costing lives and properties in Chattogram (Brammer 2012). Figure 1(a) and 1(b) illustrate the study area location map and the rain gauge location.

In the entire Chattogram district, there are only two meteorological stations: one at Chattogram City and the other at Cox’s Bazar. The Chattogram station rainfall records have 2.3% missing data, whereas the Cox’s Bazar station has fewer (1.3%) missing data over the 1958–2007 period (Shahid 2011). However, after 2007, the missing data problems do not persist in the Chattogram station, since regular maintenance and continuous data measurement have been carried out. Shah Amanat International Airport meteorological station is the main meteorological station in the Chattogram City Corporation.

![Figure 1](http://iwaponline.com/jwcc/article-pdf/13/2/975/1013948/jwc0130975.pdf)
area and is shown in Figure 1(b). We have collected the daily rainfall data and the daily maximum and minimum temperature data for the 1950–2020 period from the Shah Amanat International Airport meteorological station. However, meteorological data at this station are found missing for several days in 1971. A commonly used simple method for estimation of missing data suggested by Sattari et al. (2016) was applied to fill in missing meteorological data. The arithmetic average of the data corresponding to the nearest weather stations was taken to compute the missing value. Data quality control was carried out before the estimation of indices. A number of checks were carried out for quality controls of data such as precipitation values below 0 mm, winter rainfall higher than 100 mm, and more than 6 consecutive dry days during monsoon. Histograms of the data reveal no existing problems for the Chattogram station rainfall distribution. The Student’s t-test was applied to the rainfall time-series data to check the homogeneity, and no significant variation was found at the 95% level of confidence.

Regional climate model data

The GCMs simulate global conditions with spatial scales of more than hundreds of kilometers; however, much finer resolution data are required for analyzing the local hydrology. CORDEX is an international effort to downscale global climate model data into a regional scale which is much finer in resolution. In recent years, studies have used the CORDEX data to assess the climate indices in various regions including India (Adayeri et al. 2019; Nengzouzam et al. 2020). The downscaled climate data from CORDEX are publicly accessible at http://cccr.tropmet.res.in/home/nex_gddp_india.jsp. The dataset includes downscaled projections for Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 from the 21 models and scenarios, for which daily scenarios were produced and distributed under CMIP5. Each of the climate projections include daily maximum temperature, minimum temperature, and precipitation for the periods from 1950 to 2100. The spatial resolution of the dataset is 0.25 degrees (~25 km × 25 km).

Several studies have been carried out in recent years to review the criterion for the selection of GCMs or multi-model ensembles over the Indian sub-continent (Pandey et al. 2019; Sreelatha & Anand Raj 2019). However, we have learned about some weaknesses of the multi-model ensembles. Bannister et al. (2017) cautioned that the multi-model ensembles are not capable of considering the relative strengths and weaknesses of each model as an ensemble invariably hides the substantial variations between the individual models. Alexandru & Sushama (2015) found the CanESM2-driven simulations of precipitation were more consistent than the other selected models (MPI-ESM-LR)-driven simulations in India. Panjwani et al. (2019) evaluated 12 CMIP5 GCMs over India for precipitation, minimum temperature, and maximum temperature. They the fuzzy analytic hierarchy process (FAHP) and reliability index to assess their ability. Indicators employed were agreement index (AI), RMSE, and CC. FAHP was found suitable to rank GCMs: NorESM1-M for maximum temperature; MIROC5, GFDLCM3, FIO-ESM, and IPSL-CM5A-LR for minimum temperature; IPSL-CM5A-LR, GFDL-ESM2M, HadGEM2, MIROC5, and CSIRO for precipitation were found suitable. However, no studies were found to suggest the most suitable GCMs for Bangladesh, since the application of GCMs and use of climate change scenarios from high-resolution RCMs are very limited in Bangladesh. As Bangladesh is a part of the Indian sub-continent, based on Indian literature we consider CanESM2, GFDL, and CSIRO for the current study.

The CanESM2 was developed by the Canadian Centre for Climate Modelling and Analysis (CCcma) of Environment and Climate Change Canada and is one of the high performing GCMs used by many researchers around the world (Gao et al. 2021; Javaherian et al. 2021; Pervin et al. 2021). The CSIRO model was first developed in Queensland Climate Change Centre, Australia and has been used by many researchers around the globe (Silva et al. 2017). The GFDL model results were extensively evaluated by Held et al. (2019) against observations from various locations and found to have high-performing results. We preferred these three individual RCMs based on their performance to represent the long-term climate over the Indian region. The historical data from CanESM2, CSIRO, and GFDL are available for the 1950–2005 period and for the 2006–2020 period the data are considered as projected. In this study, we have utilized the climate change scenario RCP 4.5 for the 2006–2020 period, as RCP 4.5 signifies moderate warming level. It was reported that the International Energy Agency (IEA) scenarios agree much more closely with scenarios like RCP 4.5 than the high-end no-policy RCP 8.5 scenario (https://www.pnas.org/content/117/45/27791, last accessed 21/10/2021). Moreover, Hausfather & Peters (2020) found that both near-term and long-term fossil CO2 emissions are overestimated in emission scenarios associated with 8.5 W/m² forcing pathway.

Analysis techniques

Climate change indices

‘Confidence has increased that some extremes will become more frequent, more widespread and/or more intense during the 21st century’ (IPCC 2014). As a result, the need for scientific research-based information on weather and climate extremes is
rising. To gain a uniform perspective on observed changes in weather and climate extremes, the joint Expert Team on Climate Change Detection and Indices (ETCCDI) has defined a core set of descriptive indices of extremes. The indices describe particular characteristics of extremes, including frequency, amplitude, and persistence. The core set includes 27 extremes indices for temperature and precipitation. The ETCCDI resource and information website (http://etccdi.pacificclimate.org/) is maintained by the University of Victoria, Canada. We have carefully chosen 22 ETCCDI indices for this study; their short descriptions are given in Tables 1 and 2.

**Trend analysis**

In most reported studies on hydrological time series analysis, the regression and/or Mann–Kendall (MK) tests are applied for trend detection (Machiwal & Jha 2012). The MK test is the classic non-parametric test used in the literature to assess monotonic trends in a time series (Mann 1945). The non-linear trend, as well as the turning point, can be derived from Kendall test statistics (Kendall 1975). The MK test has been found to be an excellent tool for trend detection and to find whether the existing trend is statistically significant or not (Ilori & Ajayi 2020; Praveen et al. 2020). Details of regression test for linear trend and the MK non-parametric trend test for hydrological time series data analysis can be found in Maity (2018). If a linear trend is present in a time series, then the true slope of the trend is estimated by using a simple non-parametric procedure proposed by Sen (1968) and Theil (1950).

**RESULTS AND DISCUSSION**

**Evaluation of the selected RCMs**

We have extracted the daily maximum temperature, daily minimum temperature, and daily rainfall data from the downscaled CanESM2, CSIRO, and GFDL models for the 1950–2020 period over the Chattogram station location. The data are analyzed and compared with the measured daily Tmax, daily Tmin, and daily rainfall data from the Chattogram station for the same period. Taylor diagrams are plotted using the subsequent statistics from each data set. Figure 2(a) illustrates the Taylor diagram for the mean monthly maximum temperature (Tmax) using the station data as the reference value for 1990–2020.

**Table 1 | Definitions of 11 temperature indices used in this study**

| Indices notation | Indices name | Units | Description |
|------------------|--------------|-------|-------------|
| TXX              | Monthly maximum value of daily maximum temperature | °C | Let TXkj be the daily maximum temperatures in month k, period j. Then, TXX = max (TXkj) |
| TNX              | Monthly maximum value of daily minimum temperature | °C | Let TNkj be the daily minimum temperatures in month k, period j. Then, TNX = max (TNkj) |
| TXN              | Monthly minimum value of daily maximum temperature | °C | Let TXkj be the daily maximum temperatures in month k, period j. Then, TXN = min (TXkj) |
| TNN              | Monthly minimum value of daily minimum temperature | °C | Let TNkj be the daily minimum temperatures in month k, period j. Then, TNN = min (TNkj) |
| TN10p            | Cold nights | % days | Percentage of days when TN <10th percentile of the threshold |
| TN90p            | Warm nights | % days | Percentage of days when TN >90th percentile of the threshold |
| TX10p            | Cold days | % days | Percentage of days when TX <10th percentile of the threshold |
| TX90p            | Warm days | % days | Percentage of days when TX >90th percentile of the threshold |
| WSDI             | Warm spell duration index | days | Annual count of days with at least 6 consecutive days when TX >90th percentile of the threshold |
| CSDI             | Cold spell duration indicator | days | Annual count of days with at least 6 consecutive days when TN <10th percentile of the threshold |
| DTR              | Diurnal temperature range | °C | Monthly mean difference between daily maximum and minimum temperatures |
period. The station data for the 1990–2020 period have fewer missing values than that of the 1950–1989 period, and hence the recent data set was considered for evaluation purposes. Similarly, Figure 2(b) and 2(c) represent the Taylor diagrams for the mean monthly minimum temperature (Tmin) and mean monthly rainfall, respectively.

In Figure 2(a), the CanESM2, CSIRO, and GFDL data statistics are denoted by points 1, 2, and 3, respectively. The correlation coefficient for CanESM2 mean monthly maximum temperature (Tmax in °C) is 0.98, standard deviation 2.0, and the root mean square error is around 0.4. Whereas, the correlation coefficient for CSIRO mean monthly maximum temperature (Tmax in °C) is around 0.98, standard deviation 1.85, and RMSE is around 0.39, and the same statistics for GFDL are 0.97, 1.9, and 0.45, respectively. Figure 2(b) illustrates the correlation for mean monthly minimum temperature (Tmin in °C) using the CanESM2, CSIRO, and GFDL data sets which are denoted by numbers 1, 2, and 3, respectively. It is observed from Figure 2(b) that there exist good correlations between the observed data and the model data. For all the three data sets (CanESM2, CSIRO, and GFDL) the correlation coefficients are around 0.99, whereas the standard deviations are around 4 and the RMSEs are around 0.3. In the case of mean monthly rainfall (in mm), the correlation coefficients are around 0.97, and the standard deviation for CanESM2 is 250, for CSIRO it is 255, and for GFDL it is 280. The RMSE is 50, 55, and 60 for CanESM2, CSIRO, and GFDL, respectively. The evaluation of RCMs using the standard matrix, as mentioned above, signifies reasonable agreement with the measured data.

Heat maps are created using the mean of monthly maximum temperature, minimum temperature, and the rainfall for the station data, CanESM2 data, CSIRO data, and GFDL data over the 1990–2020 period. Figure 3(a)–3(c) illustrate the heat map for each month, showing the mean value of monthly maximum temperature (°C), monthly minimum temperature (°C), and rainfall (mm), respectively. From Figure 3(a)–3(c), it is observed that the mean values from the station data and from the RCMs are quite comparable for mean Tmax and mean Tmin. However, mean monthly rainfall from CanESM2, CSIRO, and GFDL reveal some variations from the observed data sets, mostly in heavy rainfall season. Figure 3(c) illustrates that the RCMs slightly overestimate the rainfall for July and August, and underestimate for May and June. As observed here, the performance of daily rainfall from RCMs is not as high as temperatures; similar observations were made by Wu et al. (2020).

Owing to a lack of studies on performance evaluation of various RCMs in Bangladesh, we have considered the studies from India. Using three standard metrics, the correlation coefficient (COR), standard deviation, and the root mean square error

| Indices notation | Indices name | Units | Description |
|------------------|--------------|------|-------------|
| PRCPTOT          | Annual total wet-day precipitation | mm   | Annual total PRCP in wet days (RR ≥1 mm) |
| R95p             | Very wet days | mm   | Annual total PRCP when RR >95th percentile of the threshold |
| R99p             | Extremely wet days | mm   | Annual total PRCP when RR >99th percentile of the threshold |
| RX1day           | Max 1-day precipitation amount | mm   | Let RRj be the daily precipitation amount on day i in period j. The maximum 1-day value for period j is R × 1 day = max (RRj) |
| RX5day           | Maximum 5-day precipitation | mm   | Let RRk be the precipitation amount for the 5-day ending k, period j. The maximum 5-day values for period j are: R × 5 day = max (RRk) |
| R10 mm           | Number of heavy precipitation days | days | Annual count of days when precipitation ≥10 mm |
| R20 mm           | Number of very heavy precipitation days | days | Annual count of days when precipitation ≥20 mm |
| R100 mm          | Number of extreme precipitation days | days | Annual count of days when precipitation ≥100 mm |
| CWD              | Maximum length of wet spell | days | Let RRj be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where: RRj ≥1 mm |
| CDD              | Maximum length of dry spell | days | Maximum number of consecutive days with precipitation <1 mm |
| SDII             | Precipitation intensity index | mm   | Let RRw be the daily precipitation amount on wet days w in period j. If W represents number of wet days in j. Then, SDII = (∑RRw)/W |
(RMSE), the performance of RCMs (CanESM2, CSIRO, and GFDL) was found to be generally consistent with the findings from previous studies over the Indian region (Alexandru & Sushama 2015; Panjwani et al. 2019).

**Observed climate variability in Chattogram**

The observed daily maximum temperature (Tmax in °C), daily minimum temperature (Tmin in °C), and daily rainfall (mm) data from Chattogram station were analyzed over the 1950–1989 period and the 1990–2020 period. Some climate change studies separated the 1990–2020 period as the recent period (Hausfather & Peters 2020). In this study, the 1990–2020 period is taken as the recent period, hence, the remaining available period 1950–1989 is treated as the historical period. To investigate the variability of Tmax, Tmin, and rainfall from the historical period to the recent period, box plots were generated for each data set. Box plot, a graphic display of distributions of data, is capable of characterizing the scatterings of data efficiently (Graedel 1977). Figure 4(a) illustrates the box plots using the measured daily Tmin for two different time periods,
1950–1989 and 1990–2020. Similarly, Figure 4(b) and 4(c) depict the box plots for daily Tmax and daily rainfall over the 1950–1989 and 1990–2020 period, respectively. It is noticeable from Figure 4(a) that, in the recent period, the measured daily minimum temperature has increased and the median of Tmin for each month has scaled up; the increment ranges from 0.2 °C to 1.1 °C over the months for the 1990–2020 period. Figure 4(b) illustrates the variability of mean daily maximum temperature, where the median has increased through all the months, ranging from 0.32 °C to 1.32 °C in recent years from the historic period. In the case of mean daily rainfall, it is seen from Figure 4(c) that some months got more rainfall in recent years than before, while some months have lower rainfall than the historic period. April, August, and November are the months having less rainfall in recent years. The mean rainfall anomaly ranges from −2.0 mm/day to 2.87 mm/day for different months; however, the average change of mean daily rainfall is positive over the 1990–2020 period. The average annual rainfall has increased about 6% from 1950–1989 to 1990–2020.

A brief summary of the salient features for the measured temperature and rainfall changes in Chattogram station is provided in Tables 3–5, where Table 3 gives the maximum value, minimum value, mean and the standard deviations of daily Tmin for 1950–1989 and 1990–2020 periods. Tables 4 and 5 provide the same information but for daily Tmax and daily rainfall, respectively, over the 1950–1989 and 1990–2020 periods. Table 3 reveals that the mean of the minimum daily temperature has increased in each month, while the month of February has the highest increment (1.09 °C) from the historic period to the recent period. Again, the maximum and minimum of the daily Tmin are higher in the recent period than the historic period for each month. It is observed from Table 4 that the mean of maximum daily temperature has increased over all the months in the 1990–2020 period from the 1950 to 1989 period. Rise of temperature for both summer and winter seasons was observed and the highest increment of daily Tmax was found in November (1.32 °C) and then in February.
Hence, it is clear from the analysis that the winter is warming up more pronouncedly than summer in recent years and the temperature for both Tmin and Tmax has increased significantly. On the other hand, daily rainfall has changed both positively and negatively, although most of the months, especially the monsoon season, have experienced increased mean daily rainfall, while the dry season has faced reduced daily rainfall in recent years.
Analysis of climate variability from the RCMs

The selected RCMs from CORDEX were analyzed to investigate the variability of the temperature and rainfall between the 1950 and 2020 periods. The means of the minimum temperature per month (TMINMEAN) are plotted in Figure 5(a)–5(c) for the 1950–1989 and 1990–2020 periods. From Figure 5 it is observed that the average minimum temperature has increased significantly for each month in the 1990–2020 period; for the CanESM2 data the average increment is about 1.5 °C. Similar results were obtained utilizing the CSIRO and GFDL data, where the average minimum temperature has increased about 1.2 °C and 1.0 °C, respectively, in recent decades. From Figure 6(a)–6(c) a predominant increase in the median value along with highest values of the mean of the maximum temperature per month (TMAXMEAN) was found over the 1990–2020 period. Consequently, TMAXMEAN from the CanESM2 data exhibits, on average, around 2.0 °C warming in the 1990–2020 period from the 1950 to 1989 period. Similarity has been detected for CSIRO and GFDL temperature data; in both cases the highest and lowest values have risen along with the median value. From the box and whiskers plot (Figure 6), it can be stated that the median value of TMAXMEAN for CSIRO and GFDL has increased about 2.0 °C and 1.8 °C, respectively, from the historical period.

From this analysis, it is notable that the mean Tmax and Tmin for each month in the 1990–2020 period have higher values than that of the historical period. However, the monthly mean of the 1-day maximum rainfall (RX1DAY) has not developed any particular pattern; most of the months got a higher amount of rainfall while a few other months exhibited a lower amount of rainfall in the recent period. From Figure 7(a), the box and whisker plots from the CanESM2 data sets reveal that May and July have become wetter, while June has become drier, and in some other months there are no significant changes. A similar trend was also observed from CSIRO and GFDL data sets (Figure 7(b) and 7(c)); there are some months that have experienced heavier mean daily rainfall while a few other months have experienced lighter mean daily rainfall in recent decades. Therefore, from this analysis, it can be stated that July and August have more rainfall than before, and the overall maximum increment is about 20–30 mm in a month over the 1990–2020 period. The results obtained from the CanESM2, CSIRO, and GFDL are comparable with the results from the station data over the same period.

### Table 4 | Summary statistics for daily Tmax from Chattogram station over 1950–1989 and 1990–2020 periods

| Stat | Period  | Jan   | Feb   | Mar   | Apr   | May   | Jun   | July  | Aug   | Sep   | Oct   | Nov   | Dec   |
|------|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Max  | 1950–1989 | 32.2  | 33.1  | 35.8  | 39.3  | 36.7  | 37    | 35.2  | 39.3  | 37    | 37    | 35.1  | 32.2  |
|      | 1990–2020 | 32.80 | 37.50 | 38.40 | 40.70 | 39.50 | 37.00 | 36.00 | 35.80 | 36.80 | 37.20 | 35.50 | 32.60 |
| Min  | 1950–1989 | 13.55 | 19.10 | 14.45 | 22.00 | 24.70 | 24.30 | 24.20 | 24.40 | 22.80 | 22.30 | 19.10 | 16.40 |
|      | 1990–2020 | 11.40 | 16.30 | 16.00 | 17.80 | 23.00 | 23.20 | 24.10 | 24.00 | 23.20 | 21.20 | 16.30 | 14.20 |
| Mean | 1950–1989 | 25.86 | 27.97 | 30.59 | 31.82 | 32.27 | 31.12 | 30.58 | 30.75 | 31.29 | 31.03 | 29.17 | 26.52 |
|      | 1990–2020 | 26.50 | 29.09 | 31.37 | 32.35 | 32.59 | 31.70 | 31.02 | 31.41 | 31.90 | 32.01 | 30.49 | 27.58 |
| Std  | 1950–1989 | 1.70  | 2.04  | 1.80  | 1.64  | 1.63  | 2.13  | 1.88  | 1.74  | 1.67  | 1.88  | 1.78  | 1.71  |
|      | 1990–2020 | 3.16  | 3.12  | 3.05  | 2.66  | 2.40  | 2.52  | 2.28  | 2.03  | 2.20  | 2.73  | 2.62  | 2.89  |

All the temperature data are in °C.

### Table 5 | Summary statistics for daily rainfall from Chattogram station over 1950–1989 and 1990–2020 periods

| Stat | Period  | Jan   | Feb   | Mar   | Apr   | May   | Jun   | July  | Aug   | Sep   | Oct   | Nov   | Dec   |
|------|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Max  | 1950–1989 | 20.00 | 68.00 | 254.0 | 138.0 | 194.00| 325.00| 417.00| 511.00| 269.00| 281.0 | 185.0 | 91.00 |
|      | 1990–2020 | 55.00 | 72.00 | 130.0 | 156.0 | 262.00| 438.00| 264.00| 247.00| 177.00| 284.0 | 113.0 | 37.00 |
| Min  | 1950–1989 | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  |
|      | 1990–2020 | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  |
| Mean | 1950–1989 | 0.16  | 0.43  | 1.68  | 3.54  | 7.56  | 20.15 | 22.80 | 17.40 | 8.91  | 6.67  | 1.81  | 0.23  |
|      | 1990–2020 | 0.25  | 0.78  | 1.67  | 4.10  | 10.43 | 20.50 | 23.09 | 15.40 | 10.52 | 7.88  | 1.59  | 0.36  |
| Std  | 1950–1989 | 1.70  | 2.04  | 1.80  | 1.64  | 1.67  | 1.64  | 1.63  | 2.13  | 1.88  | 1.74  | 1.67  | 1.88  |
|      | 1990–2020 | 3.16  | 3.12  | 3.05  | 2.66  | 2.40  | 2.52  | 2.28  | 2.03  | 2.20  | 2.73  | 2.62  | 2.89  |

All the rainfall data are in mm.
Extreme indices evaluation from the observed data

Temperature indices

Extreme temperature indices, mentioned in Table 1, were calculated annually using the daily maximum and minimum temperature data from the Chattogram station for 1950–1989 and 1990–2020 periods. The RClimDex package in R programming language was utilized to estimate all 22 climate indices. The present period, 1990–2020, was considered for threshold. Figure 8(a)–8(j) illustrate the variation of different indices with time, where a linear regression line was also added to visualize its tendency. Figure 8(a) and 8(b) demonstrate that the monthly maximum value of daily maximum temperature (TXX) and monthly minimum value of daily maximum temperature (TXN), which were flat or downward in the historic period, have gained a positive slope in recent years, indicating both maximum and minimum temperature have increased in the 1990–2020 period.

The percentage of warm days (TX90p) has grown and shown increasing trends while the percentage of cold days (TX10p) has reduced, indicating decreasing trends in Figure 8(c) and 8(d), respectively. It can be stated that the increasing warm days, and declining cold days, are further evidence of temperature rise and effects of climate change in recent years. The indices TNX and TNN in Figure 8(e) and 8(f) represent the behavior of monthly maximum value of daily minimum temperature and...
monthly minimum value of daily minimum temperature, respectively. From the analysis, it is notable that in both cases the average values have increased from the historic period, whereas TNX has a mild decreasing slope and TNN has a mild increasing slope. On the other hand, the percentage of warm nights (TN90p) has increased and exhibits increasing trends in Figure 8(g). However, Figure 8(h) shows that the cold nights (TN10p) have decreased with a sharp downward slope.

Observed maximum and minimum temperatures recorded in recent decades have their values elevated compared to the previous decades. This is confirmed by verifying the annual diurnal temperature range (DTR) in Figure 8(i); it has increased significantly and exhibits positive trends in the percentage of days with the lowest (below 10th percentile) and highest (above 90th percentile) maximum and minimum temperature. Figure 8(j) and 8(k) reveal the behavior of indices related to the duration of cold (CSDI) and warm periods (WSDI). The negative trend of consecutive days with Tmin below the 10th percentile, associated with the positive trends of the number of consecutive days in which Tmax exceeded the 90th percentile, suggests that over the last decades prolonged and strong heat waves dominated over this region. The analysis of the above-mentioned indices indicates more accelerating trends of daily maximum temperature when compared to daily minimum temperature in this region.

**Rainfall indices**

Both increasing and decreasing patterns were observed for the extreme rainfall indices (calculated annually). From Figure 9(a), it is found that the observed data from the Chattogram station correspond to an increased extreme rainfall in
a single day (RX1DAY), while the index RX5DAY represents a positive trend in 5-day accumulated rainfall per month over
the last three decades in Figure 9(b). These indices offer evaluation of rainfall extremes at a particular station, hence, it can be
stated that in recent decades the extreme rainfall events are intensifying. The index for yearly total rainfall (PRCPTOT) is the
one that best represents the areas with increasing or decreasing trends of rainfall. In Figure 9(c), the PRCPTOT index reveals a
mild positive slope, indicating an increasing tendency of total rainfall per year. The patterns among R100 mm (Figure 9(d)),
R20 mm (Figure 9(e)), and R10 mm (Figure 9(f)) were found to be very similar, with positive slope dominating the region in
recent decades; however, they exhibited some negative slope in historic periods. The contribution to the sum of the annual
rainfall of the days in which the daily rainfall exceeds the 99 percentiles (R99P) indicates an upward trend of extremely wet
days in the recent period (Figure 9(g)). Therefore, it is an important understanding that, in the last three decades, the heavy
rainfall events have risen significantly, contributing to the increment of total annual rainfall. Also, in the recent period, the
consecutive wet days CWD are computed with mild increasing slope, although it was a slightly negative slope in the historic
period (Figure 9(h)). Figure 9(i) reveals that the consecutive dry days, CDD, have risen in recent decades, which was the oppo-
site in the past. From this study, it is observed that the total yearly rainfall has increased, including heavy and extremely heavy
rainfall events. The number of extremely wet days in recent decades also exhibits an increasing tendency, ultimately causing
the extreme rainfall indices to rise in the recent period.

As identified from the above illustrations, the patterns for most of the indices have changed with time. In the 1990–2020
period, the changes of extreme indices are sharper than the historical period. It is evident that climate change is impacting
the extreme climate disproportionately by adding frequent and intense heavy rainfall events and causing higher vulnerabili-
ties to floods and waterlogging in this region.

Figure 7 | Box and whisker plots for RX1DAY over 1950–1989 and 1990–2020 periods from (a) CanESM2 (b) CSIRO and (c) GFDL.
Figure 8  (a)–(k) Plot of temperature indices over 1950–1989 and 1990–2020 periods. (continued).
Figure 8 | continued.
Figure 9 | (a)–(i) Plot of rainfall indices over 1950–1989 and 1990–2020 periods. (continued).
Trend analysis of extreme indices from the observed data

Trend analysis was performed utilizing the annually calculated temperature and rainfall indices from the station data. The MK non-parametric trend tests were conducted based on the values of extreme indices to detect the temporal trends and significant levels for the recent (1990–2020) period. In this study, a 5% two-sided significance level was used to classify the trends as ‘significant increasing,’ ‘significant decreasing,’ and ‘no significant’ trend. Another non-parametric test known as Sen’s slope estimator was used to determine the magnitude of change while the MK test reveals the direction of change or trend. Sen’s method is used to find the true slope of an existing trend, if there is any. This analysis will eventually help to detect the impact of climate change on the trends of extreme climate indices.

Table 6 depicts the results of the MK trend test and the Sen’s slope at 5% significance level for the temperature and rainfall indices. MK test results across the 1990–2020 period reveal that the percentage of warm days (TX90p) has a highly significant increasing trend ($p < 0.0005$), and the Sen’s slope is estimated as $0.3817\% \text{day/year}$. It is found that the diurnal temperature range (DTR) also exhibits a rising trend which is statistically significant ($p < 0.005$), the value of the Sen’s slope is $0.0209 \, ^\circ\text{C/} \text{year}$. The trend of monthly maximum value of daily maximum temperature (TXX) implies statistically significant increment with Sen’s slope $0.0666 \, ^\circ\text{C/} \text{year}$. However, the percentage of cold days TX10p possesses a significant decreasing trend ($p < 0.01$), as expected, and the Sen’s slope is calculated as $-0.175\% \text{day/year}$. Of other extreme temperature indices, the percentage of warm nights, TN90p, also demonstrates a significant increasing trend ($p < 0.05$), with Sen’s slope $0.2154\% \text{day/} \text{year}$, whereas the percentage of cold nights, TN10p, possesses significant decreasing trend ($p < 0.05$) with Sen’s slope $-0.1804\%$
The other temperature indices TNN, TXN, WSDI demonstrate an upward trend; however, they are not statistically significant. On the other hand, TNX and CSDI exhibit a decreasing trend, although they cannot be claimed as statistically significant.

Annual rainfall amount, PRCPTOT, in Chattogram generally exhibits an upward trend, which is not statistically significant. Increasing trends are observed for annually calculated 1-day maximum rainfall (RX1day) and the 5-day maximum rainfall (RX5day). However, none of the indices have statistically significant trend at 95% confidence level. The largest rate of increment of 1-day maximum rainfall, RX1day (0.888 mm/year) and 5-day maximum rainfall, RX5day (1.5454 mm/year) were estimated from Sen’s slope test. From the analysis it was found that all the extreme precipitation indexes, R10MM (the number of 10 mm or more precipitation days in a year), R20MM (number of 20 mm or more precipitation days in a year), R100MM (number of 100 mm or more precipitation days in a year), R95P (very wet days), and R99P (extremely wet days) exhibit increasing trends over the 1990–2020 period; however, they are not statistically significant at 95% confidence interval. On the other hand, consecutive wet days (CWD), consecutive dry days (CDD), and daily intensity index, SDII (these three indexes were obtained for annual daily precipitation) reveal increasing tendency during the 1990–2020 period. Although the extreme rainfall indices examined here do not have statistically significant trends, they clearly indicate the rising tendency of the extreme events in the recent period. Similar results were identified by Akter et al. (2017). Thus, the observed changes in characteristics of extreme climate indices could be described as the potential impact of climate change and the increased heavy rainfall events could be linked to the frequent floods and prolonged waterlogging problems in Chattogram.

### Trend analysis of extreme indices from the RCMs data

Trends of all the 22 indices were examined for the three selected RCMs. Bias correction methods were not considered here as the focus was on investigating the competency of the selected high-resolution raw RCMs to assess the climate change. Like

| Indices   | z     | p     | Sen’s slope | Remarks                  |
|-----------|-------|-------|-------------|--------------------------|
| TXX       | 2.4005| 0.0163| 0.0666      | Significant increasing trend |
| TNX       | −0.1543| 0.8773| 0           | Not significant decreasing trend |
| TXN       | 0.2216| 0.8246| 0.01        | Not significant increasing trend |
| TNN       | 0.49435| 0.6211| 0.0154      | Significant increasing trend |
| TN10p     | −2.1755| 0.0295| −0.1804     | Significant decreasing trend |
| TN90p     | 2.2609| 0.0237| 0.2154      | Significant increasing trend |
| TX10p     | −2.6174| 0.0088| −0.175      | Significant decreasing trend |
| TX90p     | 3.7228| 0.0001| 0.3817      | Significant increasing trend |
| WSDI      | 1.1528| 0.249 |             | Not significant increasing trend |
| CSDI      | −0.1407| 0.8881| 0           | Not significant decreasing trend |
| DTR       | 2.8573| 0.0042| 0.0209      | Significant increasing trend |
| PRCPTOT   | 0.6118| 0.5406| 5.2         | Not significant increasing trend |
| R95p      | 0.5098| 0.6101| 5.9375      | Not significant increasing trend |
| R99p      | 0.7368| 0.4612| 6.84        | Significant increasing trend |
| RX1day    | 0.4589| 0.6463| 0.8888      | Not significant increasing trend |
| RX5day    | 0.5098| 0.6101| 1.5454      | Not significant increasing trend |
| R10 mm    | 0.7337| 0.4631| 0.1111      | Not significant increasing trend |
| R20 mm    | 0.4097| 0.682 | 0.0476      | Not significant increasing trend |
| R100 mm   | 0.7046| 0.4811| 0           | Not significant increasing trend |
| CWD       | 0.9226| 0.3562| 0.0833      | Not significant increasing trend |
| CDD       | 1.7174| 0.0859| 1.3461      | Not significant increasing trend |
| SDII      | 0.30611| 0.7595| 0.036363    | Not significant increasing trend |

Table 6 | Summary of MK test and the Sen’s slope estimator at 5% significant level for extreme temperature and rainfall indices from station data over 1990–2020 period
station data, all the indices from RCMs are estimated annually. Significant rising trends are obtained from Table 7 using CanESM2 data for TXX and TNX with Sen’s slope value 0.0466 °C/year and 0.0492 °C/year, respectively. TN90P and TX90P exhibit significantly increasing trends, which are similar to those from the station data. In contrast to significant decreasing trend for CSDI, considerable increasing trend was observed for WSDI. In the case of TN10P and TX10P, significant decreasing trend was established; however, TXN and DTR have no significant increasing trend here. The observed pattern of rainfall extremes using the CanESM2 data also reveals rising trends over the 1990–2020 period. The other rainfall indices, R95P, R99P, R100MM, RX5DAY, and SDII have positive trends, although they are not statistically significant. However, R10MM, R20MM, CWD, and CDD show non-significant decreasing trend over the present period.

Analysis of trends from the temperature and rainfall indices using CSIRO and GFDL data sets were also performed. Table A1 shows the MK and Sen’s slope test results for CISRO and Table A2 represents the MK and Sen’s slope test results for GFDL. Significant positive trend for TNX and TN90 was found from both CSIRO and GFDL indices; however, TXN and TNN do not exhibit any significant rising trend for both cases. TN10p and TX10p revealed a substantial decreasing trend from both CSIRO and GFDL data sets. However, variations of trends from these two data sets were observed. DTR have a mild increasing trend from Table A1, whereas a mild decreasing trend was observed from Table A2. In the case of rainfall indices from CSIRO, increasing but not significant trend was observed for R95P, R99P, RX1DAY, RX5DAY, CWD, and R100MM and mild negative trends for PRCPTOT, R10MM, R20MM, and SDII. On the other hand, GFDL shows only increasing trends for all the rainfall indices over the 1990–2020 period.

Comparison of trends from the observed and the RCMs

Extreme temperature and rainfall indices calculated from the station data, CanESM2, CSIRO, and GFDL data were analyzed to find the existing trends over the 1990–2020 period, and the results are compared in Table A3. Table A3 is self-explanatory

Table 7

| Indices        | z       | p        | Sen’s slope | Remarks               |
|----------------|---------|----------|-------------|-----------------------|
| TXX            | 2.0736  | 0.03812  | 0.04659     | Significant increasing trend |
| TNX            | 4.691   | 2.7 × 10⁻⁶ | 0.04927     | Significant increasing trend |
| TXN            | 1.9376  | 0.05267  | 0.06235     | Not significant increasing trend |
| TNN            | 2.0736  | 0.03812  | 0.03953     | Significant increasing trend |
| TN10p          | −4.2151 | 2.5 × 10⁻⁵ | −0.56       | Significant decreasing trend |
| TN90p          | 4.8465  | 1.26 × 10⁻⁶ | 0.86778     | Significant increasing trend |
| TX10p          | −3.4848 | 4.9 × 10⁻⁴ | −0.547      | Significant decreasing trend |
| TX90p          | 4.691   | 2.7 × 10⁻⁶ | 0.72154     | Significant increasing trend |
| WSDI           | 3.5423  | 3.9 × 10⁻⁴ | 0.8125      | Significant increasing trend |
| CSDI           | −3.7924 | 1.49 × 10⁻⁴ | −0.5294     | Significant decreasing trend |
| DTR            | 0.6295  | 0.529    | 0.0025      | Not significant increasing trend |
| PRCPTOT        | 0.16996 | 0.865    | 3.84        | Not significant increasing trend |
| R95p           | 1.3937  | 0.1634   | 11.225      | Not significant increasing trend |
| R99p           | 0.99916 | 0.3177   | 3.14        | Not significant increasing trend |
| RX1day         | 0.44191 | 0.6586   | 0.4254      | Not significant increasing trend |
| RX5day         | 1.3257  | 0.1849   | 3.19908     | Not significant increasing trend |
| R10 mm         | −0.79972| 0.4259   | −0.26667    | Not significant decreasing trend |
| R20 mm         | −0.28934| 0.7723   | −0.0714     | Not significant decreasing trend |
| R100 mm        | 0.85428 | 0.393    | 0           | Not significant increasing trend |
| CWD            | −0.98712| 0.3256   | −0.4782     | Not significant decreasing trend |
| CDD            | −0.34045| 0.7355   | −0.1666     | Not significant decreasing trend |
| SDII           | 0.8163  | 0.4143   | 0.04        | Not significant increasing trend |
and compares the examined trends of all 22 extreme climate indices from the four data sets. It is recognized from all the data sets that significant increasing trends are dominant among the extreme temperature indices. It implies accelerated heatwaves and more warm days were experienced in the last three decades. Extreme rainfall indices investigated here also exhibit positive trends from both station and RCMs data sets. However, some discrepancies in trends are observed from the temperature and rainfall indices using the observed and the RCMs data. The two RCMs, CanESM2 and GFDL, produced similar regional precipitation-related climate extremes, however, CSIRO showed some disagreement with the observed. Therefore, CanESM2 and GFDL can be considered as high-performing RCMs among those selected. This evaluation of extreme climate indices from the selected RCMs revealed the strength of representing the local climate extremes by the high-resolution regional climate models. Hence, the promising results from the selected RCMs demonstrate their competency to assess the impact of climate change in this region.

**DISCUSSION**

With the available observed data set at Chattogram station, the three RCMs from CORDEX were implemented to investigate the effects of climate change on the extreme temperature and rainfall over two different time periods (1950–1989 and 1990–2020). It was a priority to evaluate the selected RCMs CanESM2, CSIRO, and GFDL before considering them for assessing the climate change indices and finding the trends. As noted earlier, there is a lack of information about the applicability of different RCMs in Bangladesh, and hence this study intended to offer some guidance for selecting the RCMs in this region to perform climate change analysis. The evaluation of model performance makes use of three standard metrics, the correlation coefficient and the root mean square error and the standard deviation, where all the three RCMs demonstrated promising performance. Using these three RCMs along with the station data, the variabilities of daily temperatures and rainfall over 1950–2020 were investigated. Analysis confirmed that the mean temperature has increased sharply, and the winter warming is more pronounced in recent decades (1990–2020) than the historical period (1950–1989). The variations in rainfall patterns are quite substantial as well, mostly the monsoon season received more rainfall, while the dry season became drier in the recent decades. Similar observations were made by Mullick et al. (2019), who found the wet season is becoming wetter and the dry season is becoming drier with the increment of temperature by analyzing the observed temperature and rainfall data from 1966 to 2015 over Bangladesh.

By comparing different indices between the two periods, their changing characteristics were revealed. In recent decades most of the extreme indices show sharper changes than the historical period, which signifies the growing frequency and extensiveness of extreme climate in this region. Increased climate-related extreme events over Bangladesh were detected by Shahid et al. (2016) during the 1958–2012 period using station data. However, no studies were reported to investigate the pattern of changes for extreme indices from two epochs: historical to present. Moreover, we investigated the trends of climate change indices from both station data and the RCMs data. The selected RCMs were validated, and they provided reliable results representing the local climate. By comparing the outcomes of trend analysis from the 22 climate change indices, we found that CanESM2 and GFDL have more promising results in resembling the observed trends than CSIRO. The overall performance of the selected RCMs is consistent, and they can be recommended for further climate change analysis in this region.

This study offers a better understanding of the effects of climate change on extreme indices, and how their patterns have changed over time. The increasing trends of extreme temperature and rainfall indices are steeper in recent decades than the historical period, justifying the causes of frequent and prolonged water logging situations in the monsoon, and scarcity of water during the dry season in Chattogram. The observed changes in different attributes from the computed daily temperature and rainfall indices exposed a brand-new challenge in managing the regional hydroclimatic risks in drainage and agricultural sectors. The findings here suggest the need for better regional water management strategies at the national level.

**SUMMARY AND CONCLUSION**

Chattogram has a long history of waterlogging in the monsoon season due to intense rainfall. Evidence shows that climate change is adding more challenges and this region is likely to undergo immense pressure from climate change on its rainfall and temperature pattern. To improve the Chattogram City waterlogging condition, better planning and management of the city drainage system is crucial, which requires a scientific knowledge-based understanding of its local climate pattern and the recent trends and variabilities.
Therefore, in this study, an attempt has been made to evaluate various aspects of temperature and rainfall extremes including the variability and trends. This study also intended to incorporate the most recent available data sets (1950–2020) from the station as well as from the RCM’s high-resolution data sets from CORDEX, to evaluate the performance of the selected RCMs as well as to analyze the effect of climate change on the extreme rainfall and temperature pattern. By analyzing different characteristics of temperature and rainfall from the 1950 to 1989 and 1990–2020 periods, the observations are as follows:

(i) The overall performance of CanESM2, CSIRO, and GFDL are found compatible to represent the local climate of the Chittogram region.
(ii) The consistent incremental trends of monsoon rainfall were observed, while declining trends of dry season rainfall were uncovered.
(iii) Increment of heavy rainfall events in the monsoon acted as one of the key driving forces for floods and the prolonged waterlogging situation of Chottogram City.
(iv) Significant increment of mean daily temperature was observed, where the rise of the mean minimum temperature is higher than the mean maximum temperature over the last three decades.
(v) Both TMINMEAN and TMAXMEAN from CanESM2, CSIRO, and GFDL have scaled up in each month, ranging from 1.0 °C to 1.5 °C and 1.8 °C to 2.0 °C, respectively, from the 1950–1989 to 1990–2020 period.
(vi) Different sets of indices plotting have indicated that the extreme temperature indices have increased in the recent period from the historical period, demonstrating accelerating tendency for both minimum and maximum temperature. However, the extreme precipitation indices indicated mild increasing tendency over the 1990–2020 period.
(vii) The MK non-parametric trend test and the Sen’s estimator for 1990–2020 period revealed that warm days (TX90p) and warm nights’ frequencies (TN90p) have significantly increased (0.3817%day/year) and (0.2154%day/year), respectively. Again, the diurnal temperature range (DTR) also exhibits a significant increasing trend (0.0209 °C/year). As expected, the frequency of cold days and cold nights exhibited a significantly decreasing trend (−0.175%day/year) and (−0.1804%day/year), respectively. Other extreme indices TNN, TXN, TR20, CDD, and CWD demonstrate the upward trend; however, they are not statistically significant. On the other hand, mild increasing trend in 1-day and 5-day maximum rainfall (0.888 mm/year) and (1.5454 mm/year) was detected and total annual precipitation in Chottogram was also found to be rising, although the trend was not statistically significant.
(viii) MK and Sen’s analysis from the RCMs also indicated increasing trends for most of the extreme temperature and rainfall indices, where CanESM2 and GFDL show more competency than CSIRO to represent the realistic trends.

This study revealed that the climate variability and trends from the selected RCMs resembled the trends and variability from the observed data. Therefore, CanESM2, GFDL, and CSIRO from CORDEX can be considered for climate change analysis in this region. From the detected trends and variability of temperature and rainfall, it can be stated that impacts of climate change on extreme events are recognizable and should be considered thoroughly. The knowledge earned from this study will help to understand vulnerabilities associated with the change of extreme temperature and rainfall patterns in Chottogram City. Thus, the city planners may find this study useful for considering the climate change impact in planning and management strategy.

CONFLICTS OF INTEREST

The authors declare no potential conflict of interests.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

REFERENCES

Adeyeri, O. E., Lawin, A. E., Laux, P., Ishola, K. A. & Ige, S. O. 2019 Analysis of climate extreme indices over the Komadugu-Yobe basin, Lake Chad region: past and future occurrences. Weather and Climate Extremes 23, 100194. https://doi.org/10.1016/j.wace.2019.100194.

Akter, A., Mohit, S. A. & Chowdhury, M. A. H. 2017 Predicting urban storm water-logging for Chittagong city in Bangladesh. International Journal of Sustainable Built Environment 6 (1), 238–249. https://doi.org/10.1016/j.ijsbe.2017.01.005.
Pervin, L., Gan, T. Y., Scheepers, H. & Islam, M. S. 2021 Application of the HBV model for the future projections of water levels using dynamically downscaled global climate model data. *Journal of Water and Climate Change* 12, 2364–2377. https://doi.org/10.2166/wcc.2021.302.

Praveen, B., Talukdar, S., Shahfahad Mahato, S., Mondal, J., Sharma, P., Islam, A. R. M. T. & Rahman, A. 2020 Analyzing trend and forecasting of rainfall changes in India using non-parametrical and machine learning approaches. *Scientific Reports* 10 (1), 1–21. https://doi.org/10.1038/s41598-020-67228-7.

Rahman, M. R. & Lateh, H. 2017 Climate change in Bangladesh: a spatio-temporal analysis and simulation of recent temperature and rainfall data using GIS and time series analysis model. *Theoretical and Applied Climatology* 128 (1), 27–41. https://doi.org/10.1007/s00704-015-1688-3.

Raihan, F., Li, G. & Harrison, S. P. 2015 Detection of recent changes in climate using meteorological data from south-eastern Bangladesh. *Journal of Climatology and Weather Forecasting* 3 (1), 127. doi: 10.4172/2332-2594.1000127.

Sattari, M. T., Rezzazadeh, J. A. & Kusiak, A. 2016 Assessment of different methods for estimation of missing data in precipitation studies. *Hydrology Research* 48 (4), 1032–1044. https://doi.org/10.2166/nh.2016.364.

Sen, P. K. 1968 Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association* 63, 1379–1389. http://dx.doi.org/10.1080/01621459.1968.10480934.

Shahid, S. 2010 Rainfall variability and the trends of wet and dry periods in Bangladesh. *International Journal of Climatology* 30 (15), 2299–2315. https://doi.org/10.1002/joc.2053.

Shahid, S. 2011 Trends in extreme rainfall events of Bangladesh. *Theoretical and Applied Climatology* 104 (3), 489–499. https://doi.org/10.1007/s10113-010-0363-y.

Shahid, S., Harun, S. B. & Katimon, A. 2012 Changes in diurnal temperature range in Bangladesh during the time period 1961–2008. *Atmospheric Research* 118, 260–270. https://doi.org/10.1016/j.atmosres.2012.07.008.

Shahid, S., Wang, X. J., Harun, S. B., Shamsudin, S. B., Ismail, T. & Minhans, A. 2016 Climate variability and changes in the major cities of Bangladesh: observations, possible impacts and adaptation. *Regional Environmental Change* 16 (2), 459–471. https://doi.org/10.1007/s10113-015-0757-6.

Silva, R. S., Kumar, L., Shabani, F. & Picanço, M. C. 2017 Assessing the impact of global warming on worldwide open field tomato cultivation through CSIRO-Mk3-0 global climate model. *The Journal of Agricultural Science* 155 (3), 407–420. https://doi.org/10.1017/S0021859616000654.

Sreelatha, K. & Anand Raj, P. 2019 Ranking of CMIP5-based global climate models using standard performance metrics for Telangana region in the southern part of India. *ISH Journal of Hydraulic Engineering* 27, 556–565. https://doi.org/10.1080/09715010.2019.1654648.

Tang, X., Shu, Y., Lian, Y., Zhao, Y. & Fu, Y. A. 2018 Spatial assessment of urban waterlogging risk based on a Weighted Naïve Bayes classifier. *Science of the Total Environment* 630, 264–274. doi: 10.1016/j.scitotenv.2018.02.172.

Theil, H. 1950 A rank invariant method of linear and polynomial regression analysis, i, ii, iii. *Proceedings of the Koninklijke Nederlandse Akademie Wetenschappen, Series A Mathematical Sciences* 53, 386–392. 521–525, 1397–1412.

Wu, J., Han, Z., Xu, Y., Zhou, B. & Gao, X. 2020 Changes in extreme climate events in China under 1.5 °C–4 °C global warming targets: projections using an ensemble of Regional Climate Model simulations. *Journal of Geophysical Research: Atmospheres* 125 (2). https://doi.org/10.1029/2019JD031057

First received 31 August 2021; accepted in revised form 18 November 2021. Available online 28 December 2021