



Analysis of reference evapotranspiration (ET_0) trends under climate change in Bangladesh using observed and CMIP5 data sets

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Abstract

ET_0 is an important hydro-meteorological phenomenon, which is influenced by changing climate like other climatic parameters. This study investigates the present and future trends of ET_0 in Bangladesh using 39 years' historical and downscaled CMIP5 daily climatic data for the twenty-first century. Statistical Downscaling Model (SDSM) was used to downscale the climate data required to calculate ET_0 . Penman–Monteith formula was applied in ET_0 calculation for both the historical and modelled data. To analyse ET_0 trends and trend changing patterns, modified Mann–Kendall and Sequential Mann–Kendall tests were, respectively, done. Spatial variations of ET_0 trends are presented by inverse distance weighting interpolation using ArcGIS 10.2.2. Results show that RCP8.5 (2061–2099) will experience the highest amount of ET_0 totals in comparison to the historical and all other scenarios in the same time span of 39 years. Though significant positive trends were observed in the mid and last months of year from month-wise trend analysis of representative concentration pathways, significant negative trends were also found for some months using historical data in similar analysis. From long-term annual trend analysis, it was found that major part of the country represents decreasing trends using historical data, but increasing trends were observed for modelled data. Theil–Sen estimations of ET_0 trends in the study depict a good consistency with the Mann–Kendall test results. The findings of the study would contribute in irrigation water management and planning of the country and also in furthering the climate change study using modelled data in the context of Bangladesh.

1 Introduction

The anticipated impacts of climate change due to global warming are expected to cause different levels of changes in climatic variables like solar radiation, temperature, precipitation, wind speed and humidity (IPCC 2007). For temperature, Intergovernmental Panel on Climate Change (IPCC) has reported a global average increase of 0.85 °C during the period 1880–2012 (IPCC 2013). The changes found in different studies were not uniform globally and many studies

have made similar findings for different regions (Solomon et al. 2007; Nick et al. 2009; Ji et al. 2014; Lorentzen 2014). Bangladesh is already experiencing the effects of climate variability and climate change (Ali 1996; Mirza 2002; Karim and Mimura 2008; Climate Change Cell 2008). The country's unstable agriculture-based economy, unique geographical locations, low-lying flat topography, high population density and lower adaptation capacity due to its poor infrastructural condition are considered as the main reasons for its high vulnerability to the effects of climate change (IPCC 2007). In the past 100 years, Bangladesh has warmed by an average of 0.5 °C, and the trend is likely to continue in future (Ericksen et al. 1996). According to IPCC's business as usual (BAU) emission scenario of 1990, Bangladesh may warm by 0.5–2 °C than the present decade by 2030. Changes in rainfall trends due to climate change of the country have also been studied by many researchers (Ahmed and Karmakar 1993; Ahmed and Kim 2003; Immerzeel 2008; Rahman and Lateh 2015; Rahman et al. 2017).

Approximately 80% of the total rainfall in Bangladesh is experienced during June to October rainy season (Das et al. 2005) and the remaining period of the year records very little

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or no rainfall. Dry season rice (*Boro*), cultivated during the months from December to April, is the main contributor to food grain production of the country and it requires a huge amount of irrigation water, which is sourced from groundwater. Net irrigated area has increased up to four times in the past 40 years, where groundwater is contributing 88% to this increase (Amarasinghe et al. 2014). Thus, managing irrigation water from groundwater sources, especially for rice cultivation, is already under stress because of rapid water level decline, and the issue has become the single most challenge for the country's agriculture sector. Reference evapotranspiration (ET_0), which is the rate of evapotranspiration from a reference surface is closely connected with the crops' water demand and measures the integrated effects of climatic parameters (Karim et al. 2008). ET_0 has a pivotal role in the assessment of irrigation water demand and the importance is in rise under the changing climatic condition of Bangladesh. Since a key issue in the coming decades will be the task of increasing food production under water shortage due to climate change, studying ET_0 can play an important role in addressing the problem of managing agricultural water for ensuring food security of the country.

Changes in climatic variables have significant impacts on ET_0 and other hydrological parameters like runoff, soil moisture and groundwater (Nemec and Schaake 1982; Gleick 1986; Bultot et al. 1988; Attarod et al. 2015). Water management, irrigation demand assessment and scheduling are also related to ET_0 of any area. Goyal (2004) predicted that any change in climatic parameters due to climate change will affect ET_0 . ET_0 is influenced by different climatic parameters, including cropping pattern, and it varies from region to region. Goyal (2004) measured up to 3.6% of ET_0 change due to 5% increase of air temperature for arid region, whereas Martin et al. (1989) and Rosenberg et al. (1989) reported that a 3 °C increase in air temperature resulted in around 17% increase in ET_0 over a grassland during the summer with an air temperature range between 24 and 35 °C. Attarod et al. (2015) observed that global warming may increase the dry condition by increasing evapotranspiration. Climate change and associated impacts on ET_0 have received much significance in many other studies conducted in different parts of the globe (Moratiel et al. 2010; Khalil 2013; Zhao et al. 2015; Sun et al. 2016, 2017a, b).

Change in temperature or precipitation in Bangladesh due to global climate change has been receiving considerable attention in a number of studies as mentioned earlier. Most of the cited works herein were carried out based on the observed temperature and precipitation data. Other climatic parameters also got a little attention in a few studies. Studies on evapotranspiration in some parts of Bangladesh are found in few works (Ayub and Miah 2011; Shahid 2011; Karim et al. 2008; Mojid et al. 2015). For instance, Ayub and Miah (2011) studied ET_0 over northwest region (Bogra, Rangpur,

Dinajpur, Rajshahi, and Ishwardi) of Bangladesh using observed and PRECIS model's data. Mojid et al. (2015) also studied ET_0 over the same region, but for only two stations (Bogra and Dinajpur) using 21 years (1990–2010) of observed climatic data. Shahid (2011) used observed data for the period 1961–1990 and Model for the Assessment of Greenhouse-gas Induced Climate Change/Scenario Generator (MAGICC/SCENGEN) output for the same region to assess the irrigation water demand. Though the number of works on climate research in other countries using model data is huge, it is limited in the case of Bangladesh. In addition, spatially, the mentioned studies are limited within the northwest region of the country.

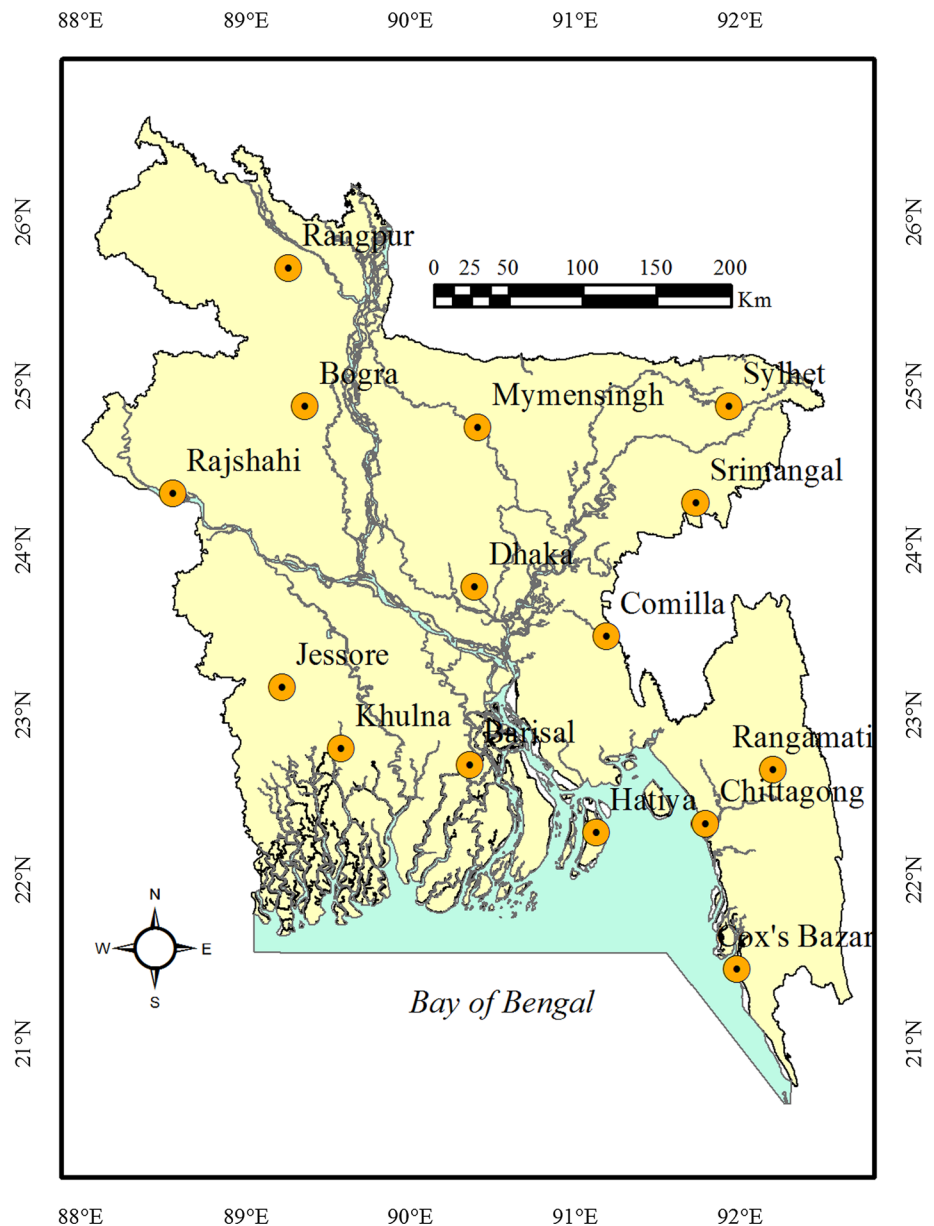
The present study investigates ET_0 trends for the whole country using a longer periods of observed climate (1975–2013) data and Coupled Model Intercomparison Project Phase 5 (CMIP5) datasets for twenty-first century. Statistical downscaling method was applied to downscale CMIP5 outputs using Statistical downscaling model (SDSM). Wilby et al. (1998), Wilby and Harris (2006), Haylock et al. (2006), Wetterhall et al. (2007), Kundu et al. (2017), among many others, have successfully used SDSM to downscale global circulation model (GCM) outputs for different parts of the world; but no study has so far focussed on Bangladesh. The specialities of the present study are using a longer period of observed data of 15 weather stations, which cover the whole country, predicting ET_0 trends for the twenty-first century and first time application of SDSM for downscaling CMIP5 output for Bangladesh. It is expected that the findings should make an important contribution to assess the climate change impacts on ET_0 and irrigation water demand for the whole country under the uncertainties of the century.

2 Methodology

2.1 Study area and data sources

Bangladesh is a sub-tropical country in South Asia situated between latitude 20°34'N and 26°38'N, and longitude of 88°01'E to 92°41'E (Fig. 1). Total area of the country is 147,570 km² with most parts being occupied by flood plain, except some hilly parts in the southeastern and eastern parts of the country. According to Köppen's climatic classification, the country is covered by four sub-categories: monsoon climate (Am), tropical savanna climate (Aw), humid subtropical climate (Cwa) and humid subtropical or subtropical oceanic highland climate (Cwb). Seasonal variations in temperature and rainfall are identical characteristics of its climate. Hot and humid summer with high rainfall, and dry and mild cold winter are the historical images of the country's climate. Three dominant seasons in the country are: pre-monsoon hot

Fig. 1 Location of the study area and the distribution of weather stations used in the study



summer (March–May), wet and humid monsoon period (April–October), and post monsoon dry winter (November–February) seasons (Rashid 1991). Historical average temperature range of the country is 18.85–28.75 °C and the mean temperature is 25.75 °C. The average minimum and maximum temperatures are 21.18 and 30.33 °C, respectively. Monthly average of minimum temperature varies from 12.5 to 25.7 °C, whereas maximum temperature range (monthly average) is 25.2 to 33.2 °C. January is the coldest month whereas April and May are the hottest months in Bangladesh (Rahman and Lateh 2015). South to north thermal gradient is observed for winter mean temperature of the country where southern areas portray 5 °C warmer than the northern parts. Mean annual rainfall of the country is 2488 mm (Rahman et al. 2017) and about

80% of the total rainfall occurs in the months of June, July and August (Das et al. 2005). Variations in other climatic parameters like cloud cover, humidity and wind speed are also observed in different seasons of the country.

Bangladesh Meteorological Department (BMD) has 34 weather stations across the country from which historical daily minimum and maximum temperatures (°C), rainfall (mm), mean relative humidity (%), wind speed (km day^{-1}) and sunshine (h day^{-1}) datasets were sourced. However, all stations do not have long-term climate records because some of them are newly established and a few stations have missing data for long periods. In this study, 15 stations' climatic data were selected (Fig. 1) to calculate ET_0 ; these stations have 39 years' (1975–2013) daily climatic records. The selected stations are almost evenly distributed all over

the country and are assumed to give a good representation of observed climate of the whole country.

For modelled data, SDSM was applied to downscale the GCM outputs. The second generation of Earth System Model, CanESM2, is the fourth generation coupled global climate model developed by the Canadian Centre for Climate Modelling and Analysis (CCCma) of Environment Canada was used in this study. CanESM2 predictors were used whereas the observed data (1975–2000) were the predictand. Multi-model ensembles were used in this study for downscaling. Obtained downscaled climatic data were from 2006 to 2099 for two scenarios, RCP4.5 and RCP8.5. Thereafter, the climatic data of each scenario were divided into two sub-scenarios (39 years each): Future 1 (F1) (2018–2056) and Future 2 (F2) (2061–2099), to show a comparative picture with ET_0 from observed data (1975–2013, 39 years).

2.2 Methods

2.2.1 Statistical downscaling

Global circulation models are the primary instrument used to predict future climate changes (Wilby and Harris 2006), but the output of the models is not enough tuned to apply it directly in the regional or local level climate assessment for the uncertain future. This is due to its coarse spatial resolution (typically of the order 50,000 km²). In order to derive a local-scale surface weather from regional-scale atmospheric predictor variables, two sets of techniques are widely used: statistical downscaling and regional climate models. Downscaling is accepted by many as an option to link the spatial and temporal resolution gaps between climate modellers' achievements and impact assessors' requirements (Wilby and Dawson 2007). It is actually the development of climate data for a point or small area from regional climate information. The regional climate data may originate either from a climate model or from observations. Downscaling models relate processes operating across different temporal and spatial scales. Several practical advantages of statistical downscaling methodologies over dynamical downscaling approaches are: low cost and rapid assessments of localised climate change impacts (Wilby and Dawson 2007). The SDSM enables the construction of climate change scenarios for individual sites at daily time-scales, using grid resolution GCM output. There are some other downscaling tools like scenario generator (SCENGEN), weather generator (WGEN), Long Ashton research station-weather generator (LARS-WG) or climate generator (CLIGEN), which usually produce relatively coarse data or do not directly employ GCM output in the scenario construction processes (Wilby and Dawson 2007). Moreover, SDSM's use is not restricted within the specialist researchers.

The second generation Canadian Earth System Model (CanESM2) is the fourth generation coupled global climate model developed by the Canadian Centre for Climate Modelling and Analysis (CCCma) of Environment and Climate Change in Canada. CanESM2 represents the Canadian contribution to the IPCC Fifth Assessment Report (AR5) and an output from CMIP5 experiments. CanESM2 predictors (with a resolution of 2.8125° × 2.8125°) and the predictand from observed data of individual station were used in the downscaling process applying SDSM 4.2 software. There are several steps in the process of downscaling using SDSM 4.2, including screening variables, calibrating the model, weather generation and scenario generation. Every time, the model calibration was done before weather and scenario generation of any station. Chosen ensemble size was 20 for the models and the mean of the ensembles was counted as the final output. Before finalizing the output of each climatic variable of individual station, summary statistical analysis, frequency analysis and result comparison were done. Two Representative Concentration Pathways (RCPs) were used in the study; RCP 4.5 and RCP 8.5 are popularly known as BAU and high emission scenarios, respectively. van Vuuren et al. (2011) give in depth information on RCPs. Details of the model's operation could be found in the user manual of SDSM 4.2 (Wilby and Dawson 2007).

2.2.2 Calibration and validation of the model

Calibration and validation of a model are always vital to ensure the quality of the climatic model data. As mentioned in the previous section, calibration of the model was done every time for different climatic variables of individual stations. For this purpose, observed climatic variables (1975–2000) were used as the predictand and National Center for Environmental Prediction (NCEP) data (resolution 2.5° × 2.5°) (1961–2000) of the respective variables were chosen as the predictor during calibration in order to train the model. Model type was 'monthly' and the processes were both conditional and unconditional. For rainfall and wind data, the process was conditional and for other variables the process was unconditional. Necessary bias correction was done where needed. Month-wise calibration results of all the stations for six variables (maximum and minimum temperature, rainfall, humidity, wind speed and sunshine) were extracted from the software that includes coefficient of determination (*R*-squared value; R^2), standard errors (SE) and Durbin-Watson tests (DW). In addition, calibration results of mean annual data were also examined for all climatic variables of all the stations. For instance, calibration results for the Dhaka station which is located in the middle of the country are presented in Table 1. R^2 value of the calibration results for maximum temperature varies in between 0.01 and 0.07 in different months of the year. The SE and

Table 1 Month-wise SDSM model calibration results (*R*², standard error and Durbin–Watson test) for all climatic parameters used to determine ET₀ of Dhaka station

	Test	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max. tem.	<i>R</i> ²	0.03	0.03	0.06	0.03	0.01	0.03	0.01	0.01	0.01	0.06	0.07	0.03
	SE	2.48	2.53	2.59	2.61	2.61	2.22	1.69	1.62	1.92	1.97	1.78	2.10
	DW	0.61	0.49	0.53	0.60	0.81	0.82	0.87	1.00	0.91	0.76	0.58	0.41
Min. tem.	<i>R</i> ²	0.01	0.03	0.05	0.01	0.03	0.01	0.01	0.01	0.01	0.23	0.19	0.05
	SE	2.31	2.83	2.89	2.52	2.36	1.64	1.11	1.05	1.19	1.69	2.19	2.23
	DW	0.59	0.51	0.59	0.92	1.08	1.24	0.95	1.15	1.01	0.70	0.45	0.38
Rainfall	<i>R</i> ²	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	SE	3.14	4.09	8.37	12.13	18.68	21.33	21.87	18.79	22.73	16.52	8.38	3.47
	DW	1.03	1.79	1.45	1.78	1.59	1.59	1.48	1.58	1.45	1.59	1.21	1.53
Humidity	<i>R</i> ²	0.02	0.03	0.02	0.05	0.01	0.03	0.02	0.02	0.01	0.09	0.03	0.01
	SE	8.16	9.54	11.23	8.08	7.31	6.09	5.82	5.24	5.73	6.92	6.73	6.72
	DW	0.72	0.74	0.65	0.71	0.64	0.78	0.66	0.89	0.87	0.62	0.62	0.63
Wind speed	<i>R</i> ²	0.01	0.01	0.02	0.04	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01
	SE	62.59	68.21	82.55	98.25	88.22	76.22	81.25	80.65	81.33	63.85	75.66	68.14
	DW	1.53	1.47	1.31	1.01	1.14	1.04	1.05	1.09	1.27	1.43	1.44	1.65
Sunshine	<i>R</i> ²	0.02	0.03	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.07
	SE	2.74	2.57	2.26	2.40	3.13	3.49	3.22	3.25	3.17	3.25	2.69	2.47
	DW	0.86	1.10	1.20	1.30	1.10	0.90	1.10	1.20	1.20	0.90	0.91	0.76

DW test scores range between 1.62 and 2.61 and 0.41 and 1.0, respectively, for the maximum temperature of the station. Annual mean of the calibrations results for maximum temperature of Dhaka station were 0.03 (*R*²), 2.18 (SE) and 0.7 (DW). For rainfall, the annual mean calibration result of the same station was 0.007 (*R*²), 13.29 (SE) and 1.050 (DW).

For validation of the model output, first summary statistics were calculated for both the observed and modelled data. These summary statistics include mean, maximum, minimum, sum and variance. Then, the summary statistics of observed and model data were compared and examined using bar or line diagrams, and quintile–quintile plots. Figure 2 represents the validation of the model output for all six climatic variables using the mean statistics of Bogra (northern), Dhaka (central) and Chittagong (southern) stations. As for Fig. 2, modelled data of all climatic variables agree well with the observed data except for rainfall data from Bogra and Chittagong stations. Thus, it is evident that the model output was within the desired quality, with little deviation for rainfall data. However, in order to justify the overall consequence of this deviation of modelled rainfall data on ET₀ of some stations, correlation coefficients between ET₀ and other climatic variables were checked. It is clear from the correlation coefficients between ET₀ and other climatic variables (Fig. 3) that ET₀ of any particular area (here it is for Barisal station in Fig. 3) is mainly dominated by temperature (correlation coefficient for *T*_{max} and *T*_{min} with ET₀ are 0.43 and 0.75, respectively), whereas solar radiation (correlation coefficient = 0.58) and precipitation have slight influences on ET₀ (correlation coefficient = −0.123). Thus,

it is conclusively established that minor quality deviation in the modelled rainfall data by SDSM would not affect the calculated ET₀ data quality.

2.2.3 ET₀ calculation

Food and Agriculture Organization (FAO) AquaCrop model was used to calculate ET₀ from both the observed and down-scaled modelled climate data in the study using Penman–Monteith equation (Allen et al. 1998) (Eq. 1):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}, \tag{1}$$

where ET₀ is reference evapotranspiration (mm day^{−1}), *R*_n is net radiation at the surface (MJ m^{−2} day^{−1}), *G* is ground heat flux density (MJ m^{−2} day^{−1}), *T* is mean daily air temperature at 2 m height (°C), *u*₂ is wind speed at 2 m height (m s^{−1}), *e*_s is the saturation vapour pressure (kPa), *e*_a is the actual vapour pressure (kPa), Δ is the slope of the saturation vapour pressure curve (kPa °C^{−1}) and γ is a psychrometric constant (kPa °C^{−1}). Equation (1) applies specifically to a hypothetical crop with an assumed height of 0.12 m, a surface resistance of 70 s m^{−1} and an albedo of 0.23. Saturation vapour pressure at air temperature *T*, *e*^o(*T*) was calculated using Eq. 2:

$$e^o(T) = 0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right). \tag{2}$$

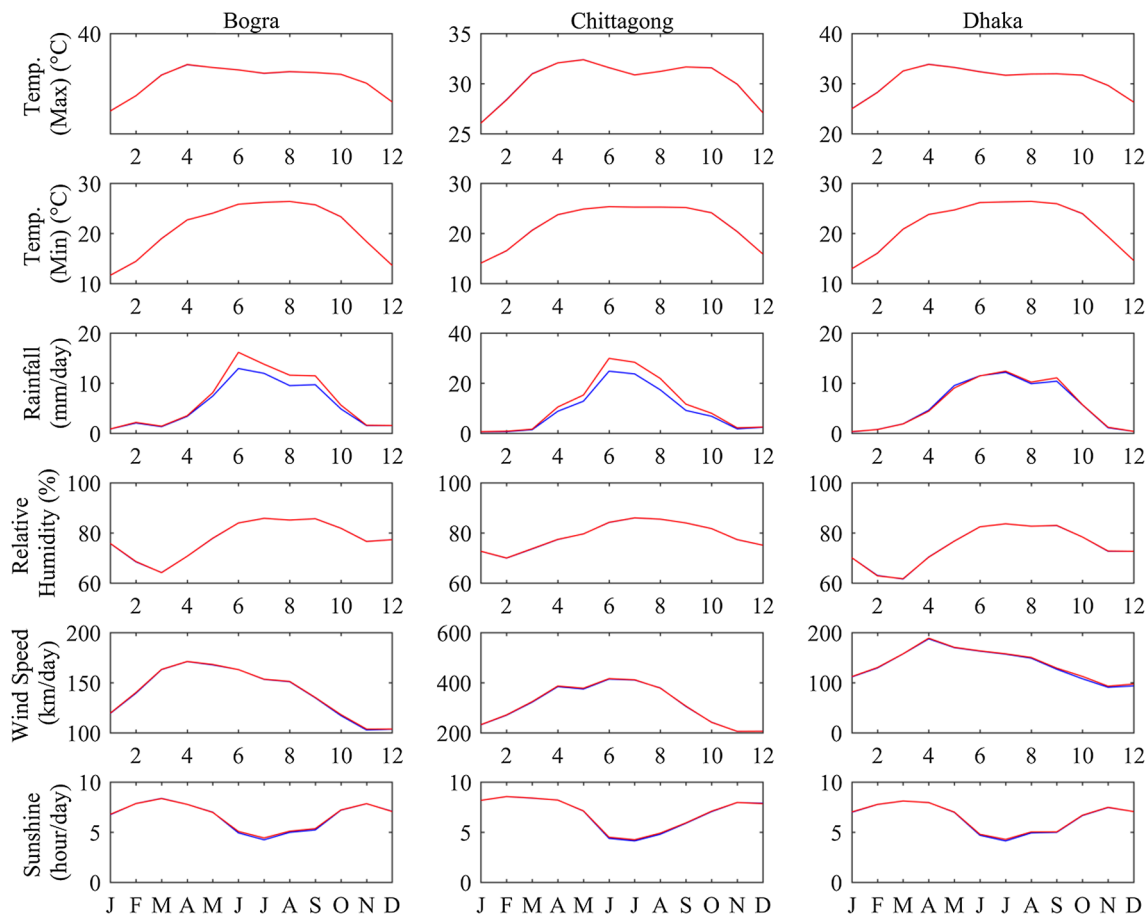


Fig. 2 Validation of the SDSM model outputs against observed climatic parameters of Bogra, Chittagong and Dhaka stations

Saturation vapour pressure for a day was estimated using Eq. 3;

$$e_s = \frac{e^\circ(T_{\max}) + e^\circ(T_{\min})}{2}, \quad (3)$$

where T_{\max} and T_{\min} are the daily maximum and minimum air temperatures ($^{\circ}\text{C}$), respectively. Actual vapour pressure was estimated using Eq. 4:

$$e_a = \frac{e^\circ(T_{\max}) \frac{HR_{\max}}{100} + e^\circ(T_{\min}) \frac{HR_{\min}}{100}}{2}, \quad (4)$$

where HR_{\max} and HR_{\min} are the daily maximum and minimum relative humidity (%), respectively.

2.2.4 Data homogeneity and autocorrelation

Observed climatic data often contain inhomogeneities as a result of many reasons. Changes in data collection method, relocating the stations, equipment changes and drifts of equipments are the major causes of data inhomogeneity

(Karl and Williams 1987; Peterson et al. 1998; Jones 1999). Data inhomogeneity within the time series may lead to a wrong prediction and wrong interpretation of extreme events. Thus, homogeneity test was carried out on climatic data using commonly used methods like the Standard Normal Homogeneity Test (SNHT) (Alexandersson 1986) and Buishand's Range (BHR) (Buishand 1982) tests. Using these two tests all stations ET_0 data were checked at a 5% significance level and it was found that the data used in the study were under useful category.

Nonparametric trend tests like Mann–Kendall (Mann 1945; Kendall 1975) give incorrect or too large rejection rates when applied to an autocorrelation time series data (Bayazit and Önöz 2008). In this regard, all data used in this study were first tested for the presence of autocorrelation coefficient at a 5% significance level, using a two-tailed test. It was found that the individual monthly data sets of every station were free from autocorrelation of significant level. However, significant autocorrelations were present in the complete daily ET_0 time series data of the stations.

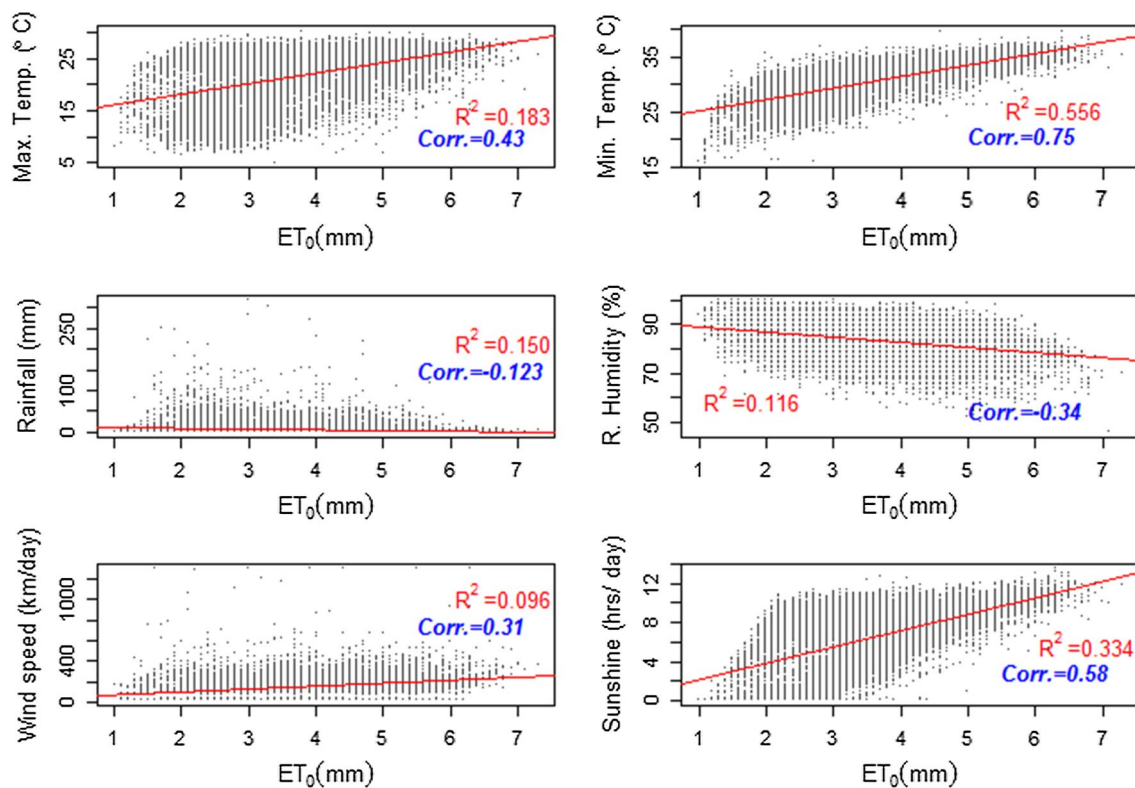


Fig. 3 Correlation and regression between ET_0 (mm per day) and other climatic parameters of Barisal station using daily data

2.2.5 Modified Mann–Kendall test

A significant number of researchers have used trend free pre-whitening (TFPW) method to remove serial dependency (Önöz and Bayazit 2012; Yaseen et al. 2013; Blain 2013; Yaseen et al. 2014; Ahmad et al. 2015). However, Kumar et al. (2009) found that the method does not give good results when data has significant correlation coefficients beyond the first lag. In this study, good number of the stations gave significant autocorrelations for more than one lag for monthly data of ET_0 . So, modified Mann–Kendall (MK) test method proposed by Hirsch and Slack (1984) and Hamed and Rao (1998) was adopted that accounts for seasonality and autocorrelation within the time series. Hamed and Rao (1998) showed that the power of the modified Mann–Kendall test is similar when compared to that of the original Mann–Kendall test (for independent data). For time series data with significant autocorrelation, accuracy of the result by the modified Mann–Kendall test is much higher than the original Mann–Kendall test (Nalley et al. 2013). The same method was adopted by others (Nalley et al. 2013, Rahman et al. 2017) to avoid significant autocorrelations of more than one lag in time series trend detection.

2.2.6 Theil–Sen estimator

Theil–Sen's nonparametric method (Theil 1950; Sen 1968), which gives a robust estimation of time series trend, was used to estimate the magnitude of trends in the ET_0 time series data. When change in time series is present but cannot be detected by using statistical tests to a satisfactory level, Theil–Sen estimator gives a better output (Radziejewski and Zbigniew 2004). Shahid (2010) and Rahman et al. (2017) successfully used the method to detect the magnitude of trends in rainfall time series of Bangladesh. The same method was adopted for this study.

The statistical test results and spatial distribution of the outputs are displayed using Matlab, R Programming and ArcGIS10.2.2 software.

3 Results

3.1 Preliminary observations and analysis

The 15 stations selected to represent the study area are spread over the country. Out of these 15 stations, 3 stations (Rajshahi, Bogra and Rangpur) are located in the

northeastern part, which area is about 20 m above mean sea level. Mymensingh of central area, Sylhet and Srimangal in the eastern areas too are above 20 m. Dhaka, the country capital, and Comilla stations' altitudes are around 10 m. All other stations' altitudes are between 4 m and 7 m except Rangamati, which is located in the eastern hilly part of the country. Barisal, Khulna, Hatiya, Chittagong and Cox's Bazar stations are in the north coast of the Bay of Bengal; these areas experience relatively higher relative humidity than other parts of the country. More than 230 rivers and numerous other types of water bodies like canals and streams criss-cross all over the country that are also the impact factors in ET_0 formation of any area. The highest mean monthly ET_0 is observed in Bogra region while the lowest is found in Hatiya (Coastal Island). Standard deviation (SD) of monthly ET_0 varies between 102.18 and 114.02 mm with a mean standard error of 5. The highest and the lowest median is 184.5 (Bogra) and 155.5 (Cox's Bazar),

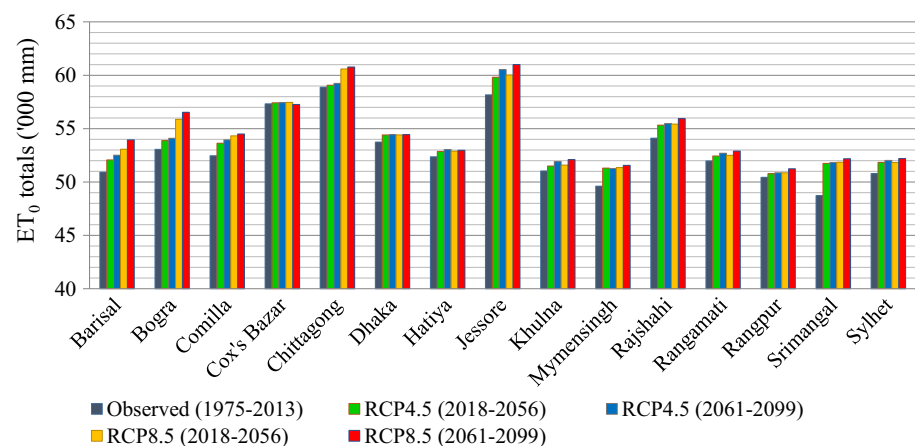
respectively. Median absolute deviations (MAD) of the stations lie between 123.06 and 151.97. Skewness of the ET_0 data sets varies between 0 and 0.2, positively skewed and are not normally distributed. Negative kurtosis results of the data sets are found; the ET_0 time series data are platykurtic and not mesokurtic. This implies that a flatter distribution was common in the ET_0 data of all the stations. Table 2 represents descriptive statistics summary of monthly ET_0 data obtained from historical climate of all the stations along with their locations, altitudes, data ranges, standard errors (SE) and coefficient of variances.

By calculating the ET_0 totals of each scenario (39 years) of individual stations, it is evident that RCP8.5F2 for 1961–2099 period will experience the highest ET_0 except Cox's Bazaar station (Fig. 4). The historical ET_0 total of 39 years (1975–2013) is the lowest in comparison to all other scenarios for the same time span. For RCP8.5F2, Jessore station will experience the maximum amount of

Table 2 Station locations, altitude and their corresponding ET_0 using observed monthly climatic data

Stations	Lat	Lon	Alt (m)	Mean (mm)	SD	Median	MAD	Range	SE	Skew.	Kurtos.	Coef. var.
Barisal	22.7	90.36	4	177.16	104.46	178.50	135.66	355	4.83	0.01	-1.25	0.59
Bogra	24.88	89.36	20	192.38	114.02	184.50	151.97	386	5.27	0.06	-1.26	0.59
Comilla	23.48	91.19	10	176.77	105.45	169.50	137.14	361	4.87	0.09	-1.25	0.60
Cox's Bazar	21.46	91.98	4	168.47	102.18	155.50	123.06	352	4.72	0.20	-1.15	0.61
Chittagong	22.34	91.79	6	173.81	103.20	163.50	126.76	362	4.77	0.17	-1.14	0.59
Dhaka	23.78	90.39	9	182.16	108.98	178.00	142.33	372	5.04	0.07	-1.23	0.60
Hatiya	22.29	91.13	4	168.58	105.94	162.50	137.14	352	4.90	0.15	-1.28	0.63
Jessore	23.17	89.22	7	183.94	112.14	176.50	143.07	380	5.18	0.13	-1.24	0.61
Khulna	22.8	89.58	4	179.26	107.80	176.50	145.29	356	4.98	0.00	-1.33	0.60
Mymensingh	24.75	90.41	19	172.46	106.24	165.50	138.62	359	4.91	0.10	-1.26	0.62
Rajshahi	24.35	88.56	20	186.96	113.30	182.50	150.48	383	5.24	0.07	-1.28	0.61
Rangamati	22.67	92.2	63	172.99	107.62	164.50	143.07	363	4.97	0.14	-1.29	0.62
Rangpur	25.72	89.26	34	186.87	110.63	177.50	142.33	382	5.11	0.07	-1.22	0.59
Srimangal	24.29	91.73	23	182.01	110.15	174.50	142.33	377	5.09	0.11	-1.24	0.61
Sylhet	24.88	91.93	35	178.62	109.58	174.50	146.04	363	5.07	0.06	-1.30	0.61

Fig. 4 Comparative ET_0 totals of the stations for different scenarios (39 year totals for each scenario)



ET₀ (61,000 mm) in total for 39 years. Considering the historical climate, Chittagong station has the maximum ET₀ (59,000 mm) total and Mymensingh station depicted the lowest amount of ET₀ totals (49,500 mm) during 1975–2013 periods. Other than the ET₀ of Cox’s Bazar station, which almost remains unchanged for all the scenarios, all other stations showed gradual increase from historical to RCP8.5F2 scenarios. However, the highest difference of ET₀ totals between historical and RCP8.5F2 scenarios is found in Bogra and Srimangal stations.

Density plots of the obtained ET₀ of all the stations for the scenarios are presented in Fig. 5. These plots depict a common feature that the highest densities of the ET₀ of all the stations are centred around 100 mm of ET₀. However, there are some exceptions, whereby the highest and the lowest densities of the ET₀ plots are around 200 and 50 mm, respectively, in most of the stations. It also implies that the occurrence of very high and very low amount of ET₀ is limited.

3.2 Month-wise ET₀ trends

Being a country of sub-tropical zone, Bangladesh experiences a moderate type of climate where mean temperature variation between the hottest (April) and the coldest (January) months is about 10 °C. However, humidity and precipitation statistics depict huge differences since summer rainfall is fully dominated by monsoon winds from the Indian Ocean. Winds are stronger in summer (8–16 km h⁻¹) than in winter (3–6 km h⁻¹). Day length variation and cloud covers which determine the incoming solar radiation also play vital role in ET₀ formation. Cloud covers vary in between 10% (winter season) and 75–90% (rainy season). Thus a variation in ET₀ is also observed in different months of the year. Figure 6 represents the month-wise ET₀ trends for historical and RCPs data calculated by applying modified Mann–Kendall tests. By analysing the historical climate, it is evident that during the months of January, March, April and December major parts of the country experienced a significant decreasing trend except for some parts of the south and south-east regions. In July, most parts of the country represent

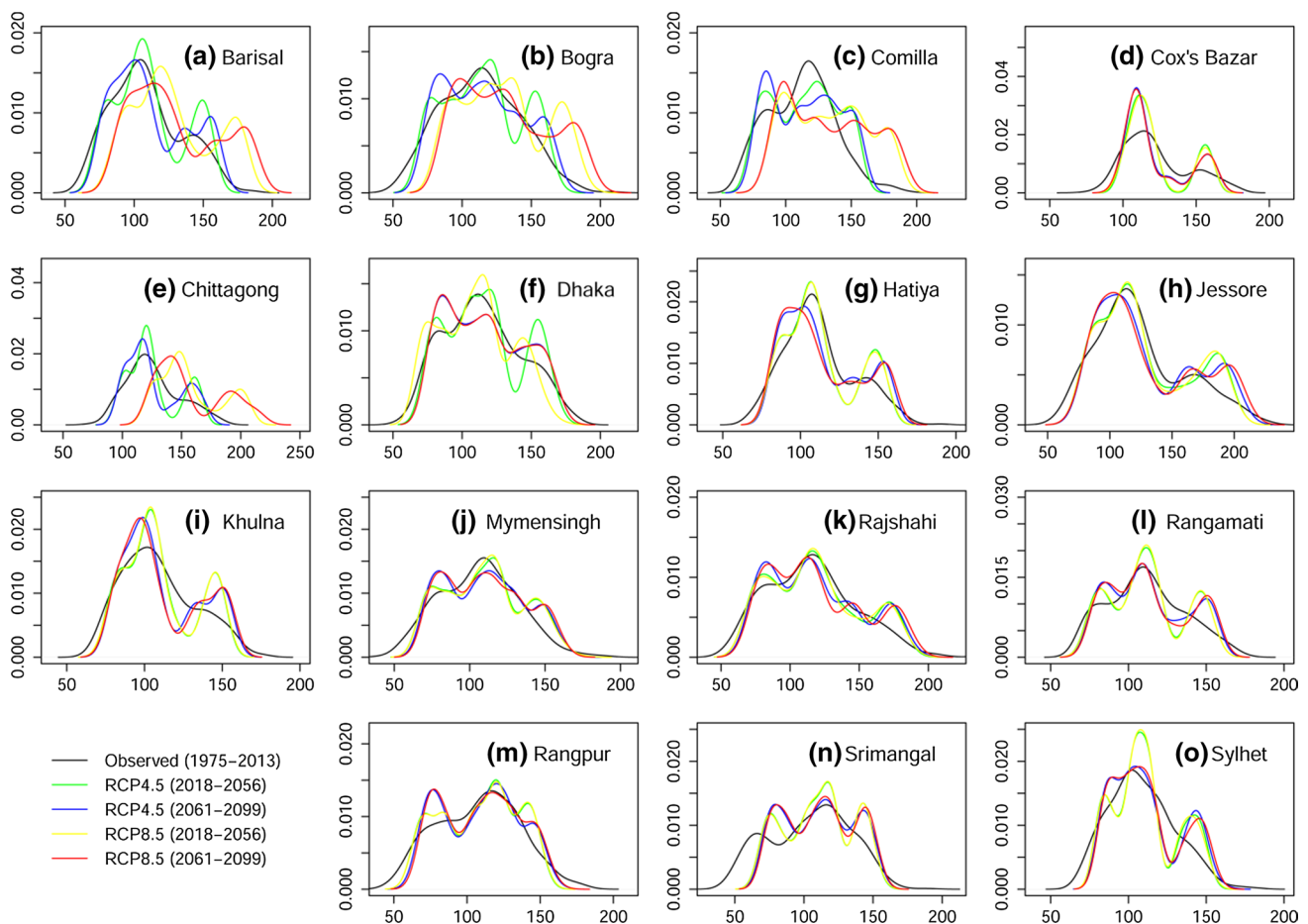


Fig. 5 Density plots of ET₀ for observed, RCP 4.5 (F1, F2) and RCP 8.5 (F1, F2) scenarios

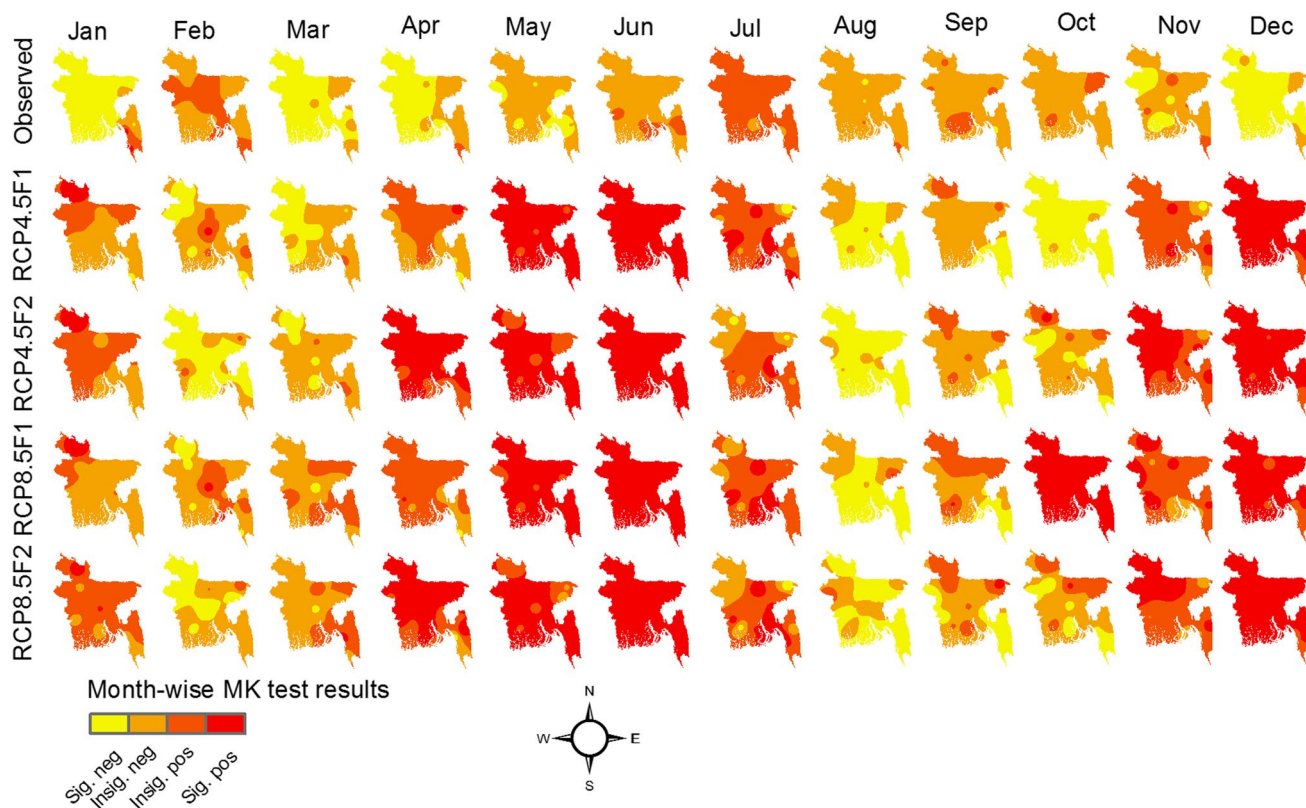


Fig. 6 Month-wise ET_0 trends of all the stations from modified MK test for observed, RCP 4.5 (F1, F2) and RCP 8.5 (F1, F2) scenarios

insignificant positive ET_0 trend and the same type of trend is observed in the middle parts of the country in February. In other months (May, June, August, September, October, and November), observed trends from historical data are dominated by insignificant negative trends. From the RCPs' modelled data, it is found that the trends of month-wise ET_0 have turned to positive from negative (both for significant and insignificant levels). A significant positive trend is evident in the months of May, June and December from RCP4.5F1 scenario. August and October mainly represent decreasing trend, whereas the remaining months (January, February, March, April, July, and September) of the year are captured by both negative and positive trends of insignificant category for the same scenario. During the month of August, all scenarios revealed significant decreasing trends for almost the whole country. More or less similar trends are observed in other future scenarios for different months of year except in October of RCP8.5F1. The month of October represents a significant trend in RCP4.5F1, but it is almost opposite in RCP8.5F1 (significant positive). However, the generalized picture found from the month-wise trend analysis is that the summer and winter seasons are showing increasing trends of different levels and spring or autumn seasons are representing mixed pattern of ET_0 trends for the country in all the scenarios.

3.3 Annual trends

As mentioned in Sect. 3.1, for the same time span, the highest total of ET_0 is calculated for RCP8.5F2 scenario, whereas the lowest total is calculated for historical period from 1975 to 2013. However, the rising ET_0 is not distributed evenly in every year for the stations. By applying two methods; MK test and Theil–Sen estimation, annual trends were checked. From MK test results (Fig. 7), it is evident that major part of the country is experiencing significant level of decreasing trend of ET_0 change for historical period. Only exception is seen in southern Cox's Bazar district, which has a mixed pattern of insignificant negative and insignificant positive trends. It is also noticeable that western part of the country is captured by higher MK test Z values than other parts during the historical period. From RCP4.5F1, the annual ET_0 trends are taking turns to positive for maximum parts of the country. The northern, central and southern parts of the country revealed significant levels of increasing trend, whereas western, southeastern and northeastern parts depict insignificant increasing trends for RCP4.5F1 scenario. Except for the southeast part, the whole country revealed significant increasing trend for RCP4.5F2 scenario. Though the MK test Z values decreased a bit in RCP8.5F1 or F2 scenarios in comparison to RCP4.5F2, the major parts are occupied by

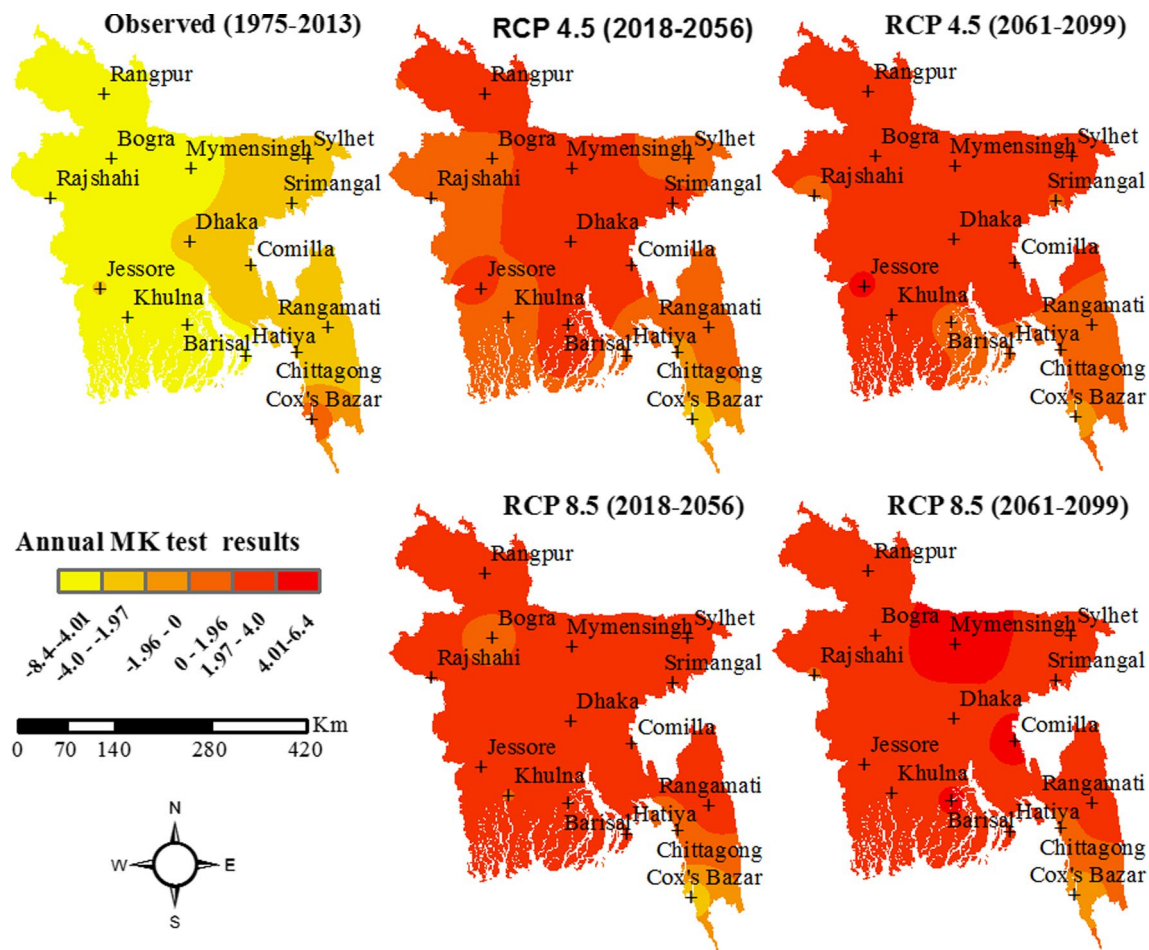


Fig. 7 Long-term annual ET_0 trends of all the stations from modified MK test for observed, RCP 4.5 (F1, F2) and RCP 8.5 (F1, F2) scenarios

significant levels of increasing trends for RCP8.5. However, Cox’s Bazar area of southeastern part is representing lower MK Z values than other parts of the country for all the RCP scenarios in the study.

It is anticipated that the identified long-term annual trends from modified MK test would not be same for the entire period. The changes in trends were checked in historical ET_0 data and potential trend turning points were identified using sequential MK test in the study for all the stations. Among the 15 stations, only 6 stations (Cox’s Bazar, Chittagong, Dhaka, Khulna, Srimangal, and Sylhet) depicted clear trend turning points and for other 9 stations, the trend signal was mixed. Sequential MK test results for all the stations are displayed in Fig. 8. For Cox’s Bazar station, potential trend turning points are identified around the years of 1976, 1981 and 2001. Only one potential trend turning point is found for Chittagong station that is around 1991. For Dhaka station, the only trend turning point is observed around 1993 but Khulna station depicts at least two trend turning points in the years 1980 and 1993. Srimangal station ET_0 data represent two trend turning points at around 1985 and 1993. In

the case of Sylhet station, at least 3 trend turning points in between 1934 and 1991 are observed. However, the absence of trend turning points in other stations does not indicate the absence of trend in reality but it was not recognized by the method. The reason of such failure to show exact trend turning/changing points by the method is illustrated by Nalley et al. (2013).

Detected ET_0 changes over time using Theil–Sen estimation for historical and RCP scenarios in the study are presented in Fig. 9. Using historical data for the period 1975–2013, it is evident that northwest (Rangpur), north-east (Sylhet) and eastern hilly (Rangamati) areas are experiencing the highest decreasing trends of ET_0 , which is from 3.6 to 7.2 mm decade⁻¹. Rajshahi, Bogra, Mymensingh and Srimnagal belts are depicting a stumpy type (0–3.6 mm decade⁻¹) of decreasing trends of ET_0 along with Khulna, Barisal and Chittagong regions. Jessore, Dhaka, Comilla and Cox’s bazaar areas are enjoying low (0–3.6 mm decade⁻¹) to medium (3.61–7.2 mm decade⁻¹) levels of increasing ET_0 trends from the historical climate. For RCP4.5F1, northwest and southern most areas are portraying decreasing trends of

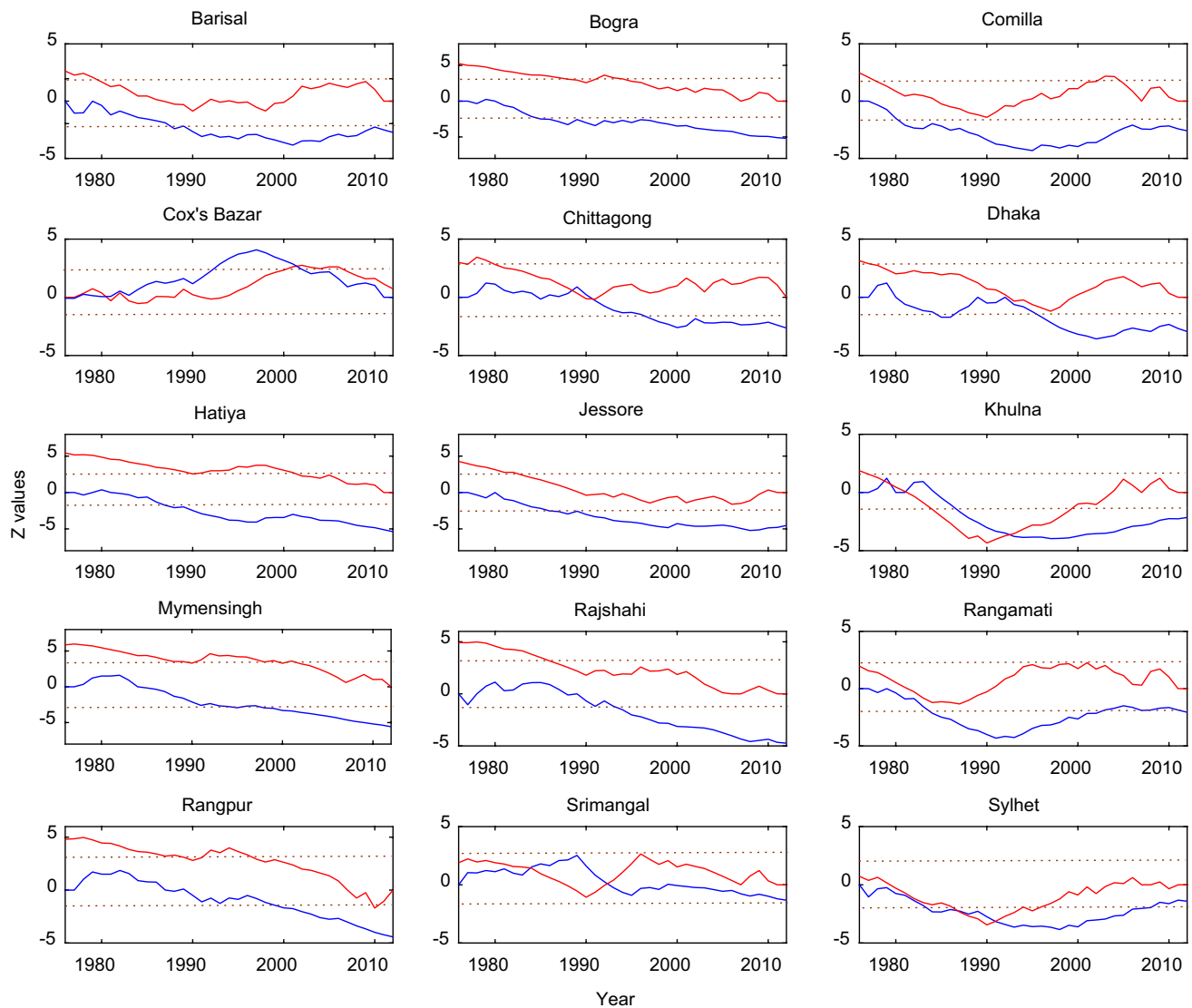


Fig. 8 Sequential MK test results for ET_0 from observed climate of the stations. Red and blue lines are indicating forward and backward trends, respectively. The dotted lines are indicating the upper and

lower boundary of the Z values; if the forward and backward lines cross each other outside the dotted lines then it indicates the presence of significant trend

moderate to high levels but other parts are showing increasing trends up to $7.2 \text{ mm decade}^{-1}$. In the case of RCP4.5F2, the whole country reveals the increase of ET_0 from low ($0\text{--}3.6 \text{ mm decade}^{-1}$) to high levels ($7.21\text{--}10.9 \text{ mm decade}^{-1}$) except for the southern parts of Chittagong and Cox's Bazar districts. In 2018–2058 period for RCP8.5, major area of the country will experience medium level of ET_0 rise except Bogra and Cox's Bazar areas. For RCP8.5 during the period 2061–2099, Cox's Bazar area will continue with decreasing trend of moderate level, but Sylhet and Mymensingh areas will experience the highest change of ET_0 ($7.21\text{--}10.9 \text{ mm decade}^{-1}$). However, all other parts of the country will enjoy a rise of moderate to high levels of ET_0 during 2061–2099 period for RCP8.5 scenario.

4 Discussion

To know the possible changes of ET_0 under climate change condition was the main objective of the present study. However, the main challenge was to ensure quality climate data to calculate ET_0 for both historical and future periods from observed and global circulation models' output. Regarding the historical climate data, the main obstacle was the considerable amount of missing data for longer periods. It was found that maximum stations have good quality of temperature and precipitation data, but other climatic parameters (wind speed, sunshine), were found having missing values for significant number of years. Though the selected 15 stations are with minimum missing data, a few stations among

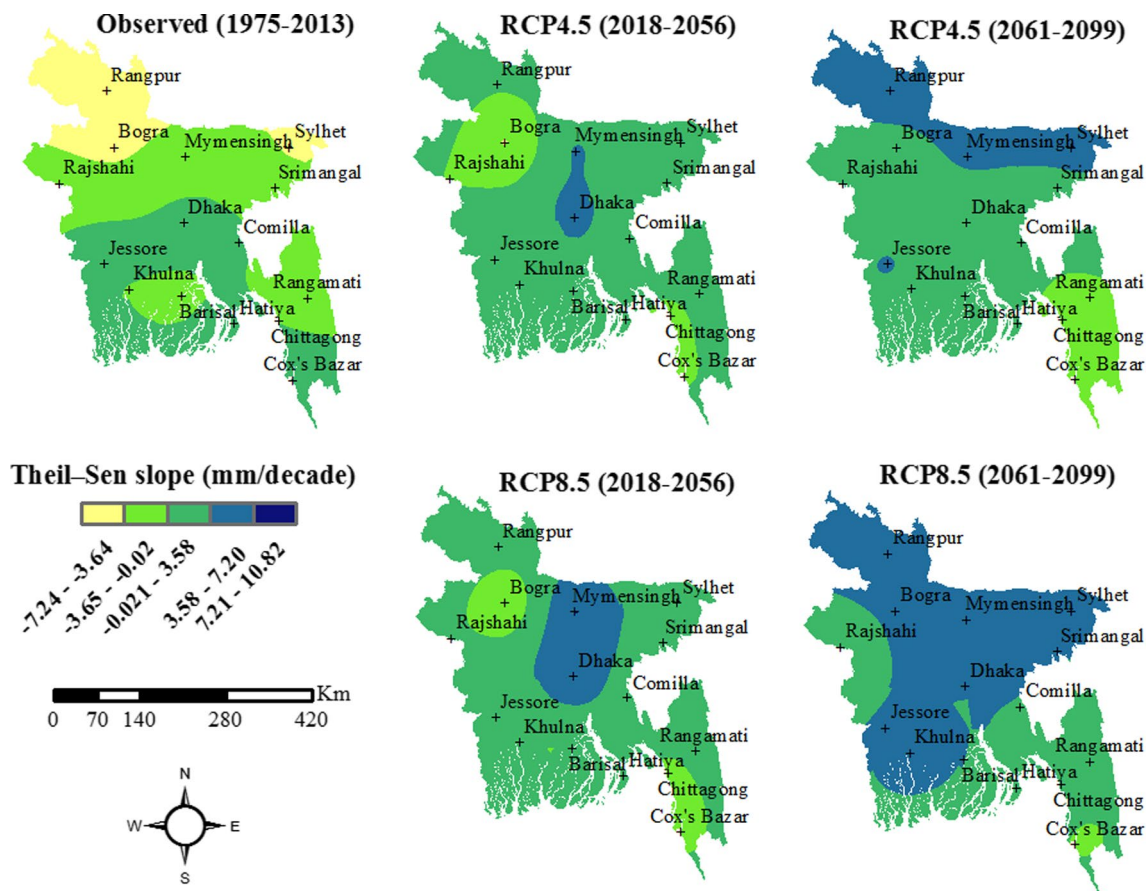


Fig. 9 Long-term annual ET_0 change rates (mm decade⁻¹) of all the stations from Theil-Sen slope estimation at 95% confidence level for observed, RCP 4.5 (F1, F2) and RCP 8.5 (F1, F2) scenarios

them still have missing values for some parameters as mentioned. In those cases, missing data were filled-up by taking data from the nearest neighbouring stations. It is also well known that downscaling climatic data with expected quality is a tedious exercise, especially for rainfall and wind speed data. However, the downscaling part was done using SDSM, and it is evident from the validation that the data quality is within the useful category for this study. During the model calibration, in some cases, more than one predictor variable were chosen and all the variables did not give significant results in statistical tests like R^2 , SE or Durbin-Watson tests for every months of year. However, the predictor variables were selected based on the correlation results and analysing the scatter plots of the residuals through variables screening in SDSM. Finally, the correlation between observed data and modelled outputs was checked and it was found that the model outputs are strongly correlated with the observed data (correlation coefficients are above 0.9 for all the parameters of all stations). Thus, it is concluded that the modelled data from SDSM are in useful category. Spearman correlation between ET_0 and climatic parameters, and within the climatic parameters of Barisal station, is presented in Table 3,

which depicts that temperature, sunshine and wind speed are strongly related with ET_0 . Similar relation was also observed between ET_0 and other climatic parameters by Mojid et al. (2015) in a study for the northern part of Bangladesh. So, any insignificant deviation for the climatic parameters data other than temperature from SDSM may not affect the final calculation of ET_0 .

In general, total ET_0 will increase in future for almost the whole study area as it was found from the present study (Fig. 4). However, decreasing ET_0 trend within the observed period found in the study seemed to be unusual, but similar result was observed for Bogra and Rangpur (northern districts) areas in previous study (Mojid et al. 2015). It is anticipated that increasing use of groundwater for dry season rice cultivation in the whole country has played important role in increasing air moisture during the past four decades. The increased air moisture negatively affected the ET_0 formation during the historical period. Further studies may help to get a better insight into the matter considering land cover change, groundwater extraction and comparative analysis of temperature, cloud covers, wind speed, humidity and precipitation trends, which influence ET_0 . However, the

Table 3 Spearman correlation between ET_0 and climatic parameters, and among the climatic parameters

Parameters	ET_0	Max. temp	Min. temp	Mean temp	Rainfall	Humidity	Wind Sp.	Sunshine
ET_0	1	0.43	0.75	0.59	-0.12	-0.34	0.31	0.58
Max. temp.	0.43	1	0.72	0.96	0.18	0.43	0.25	-0.34
Min. temp.	0.75	0.72	1	0.88	-0.04	-0.01	0.12	0.17
Mean temp.	0.59	0.96	0.88	1	0.10	0.28	0.22	-0.16
Rainfall	-0.12	0.18	-0.04	0.10	1	0.26	0.14	-0.34
Humidity	-0.34	0.43	-0.01	0.28	0.26	1	0.09	-0.54
Wind Speed	0.31	0.25	0.12	0.22	0.14	0.09	1	-0.13
Sunshine	0.58	-0.34	0.17	-0.16	-0.34	-0.54	-0.13	1

changing ET_0 trend from negative to positive in future is also conventional because there is less to no possibility of increasing total irrigated area in future for the country. The increasing ET_0 trends for future scenarios in Bangladesh are also consistent with the findings of other researchers (Ayub and Miah 2011; Shahid 2011). Ayub and Miah (2011) calculated the rise of ET_0 of about 1.14% by 2030 and about 2% by 2050 using Providing Regional Climates for Impact Studies (PRECIS) model for Rajshahi (north-western district) region. Shahid (2011) also found that daily evapotranspiration will increase up to twenty-first century in different levels in northwest Bangladesh by applying MAGICC/SCENGEN to project the future climate. ET_0 is a calculated parameter used in this study. It is calculated from the other climatic parameters; maximum and minimum temperature, precipitation, wind speed and sunshine hours. So there is no doubt that any change in the climatic parameters will ultimately affect the calculated ET_0 . However, all climatic parameters do not influence the ET_0 equally. Figure 3 presents the relationship between ET_0 and other climatic parameters. ET_0 is positively correlated with temperature, solar radiation and wind speed. So, rising temperature of the country, as predicted by different studies (CDMP II 2012; Rahman and Lateh 2015; Rabby et al. 2015) will cause more ET_0 formation and will increase the irrigation demand for agricultural purposes. On the other hand, relative humidity and rainfall are negatively related with the ET_0 . Increasing temperature will cause more evaporation from the sea and will increase the rainfall in the area. So, calculating reference evapotranspiration is a complex process. However, overall increase in ET_0 for twenty-first century implies that climate change will affect it and will require more water for irrigation purposes. Examining the relationships of ET_0 with elevation and land use change was not within the major scopes of this study. However, in general significant change or influence was not observed in ET_0 due to elevation or land use change in the study area. Though it is assumed that land use change or elevation of a large area should have significant roles on the ET_0 formation, further studies are required to establish that.

Spatially, the variation in ET_0 trends is seen all over the country from scenario to scenario in the study. During the

historical period (1975–2013), western part of the country depicted higher decreasing trend than the eastern part. It is known that agricultural practices in the western part are more intensive than the eastern part because population density is higher in western part than the eastern part, which is a hilly area. Moreover, western part has a flat topography, whereas the eastern part is occupied by Pleistocene hills, which might have some roles in wind speed as well as on albedo. All these factors cumulatively affected the ET_0 trends of the regions. The ET_0 trend turning points during the historical period were found from sequential MK test, but further studies are also required to correlate the reasons of trend changes with other climatic and environmental variables. Except the southern most areas of the country (Chittagong and Cox's Bazar), the whole country depicts a rising ET_0 trends for the RCPs in the study, which indicates significant impacts of climate change on it.

Rising ET_0 trends in the upcoming years will adversely affect the agricultural production of the country. Main source of food grains for the huge population of the country is dry season rice (*Boro rice*), which requires huge amount of water in its different growth stages. The crop is cultivated all over the country and irrigation is required from land preparation to grain formation period (November to April). During the mentioned dry period, Bangladesh experiences little or no rainfall. Moreover, the rising ET_0 trend will create a complex situation for all other water demanding sectors. From the past experiences, farmers may try to cope with the changing situation by extracting more water from underground sources. Unfortunately, groundwater level is declining rapidly since the 1980s. Though all the projections showed increasing rainfall for the country in twenty-first century, replenishing groundwater does not solely depend on rainfall. Trans-boundary water issue is also important in regards to groundwater recharging, irrigation, fisheries and navigation of the country. Thus rising ET_0 will increase the irrigation cost of the farmers and will ultimately affect the production. Cost of other water using sectors will also increase along with the rising environmental and public health issues. Creating options for using surface water for irrigation, making reservoir to store water during monsoon

and developing efficient irrigation system would be some strategies to cope with the changing climatic condition of the country.

5 Conclusion

Possible changes of ET₀ trend in Bangladesh due to expected change in climate in twenty-first century are investigated in the study using observed and CMIP5 modelled climatic data. The study shows that on an average, the trend of ET₀ is changing from negative in the most recent historical past to positive in upcoming years, which is a prediction of a major change in ET₀ trends patterns in the next few years. Summer season (May, June, July) depicted the common increasing trends for both the historical and modelled data, but only winter season (November, December, January) revealed increasing trends from RCPs. Annual increasing trends of ET₀ for RCPs is found up to 10.9 mm decade⁻¹ in the century. Increasing temperature will increase the atmospheric moisture holding capacity, which would be considered as the main reason of such increasing trends in ET₀. Statistical downscaling method, applied in the study to get localized climatic data from GCMs, is identified as a useful method, and SDSM would be a handy tool in this purpose. However, reliable quality observed data, which is a pre-requisite to calibrate the SDSM and downscale from GCMs was a drawback in the study, especially for the climatic parameters other than temperature and precipitation. Taking cautions in selecting the appropriate predictor variables during calibration of SDSM is also vital for finer localized data from coarse GCM outputs. Mann–Kendall method and Theil–Sen estimations were found in good agreement in the whole study. Considering land use change and cropping pattern, groundwater extraction along with the microclimate of any area is strongly suggested in future studies for ET₀ trends. The possible problems that may arise from increasing ET₀ are over extraction of groundwater and thus water level declining, increasing irrigation expenditure and crop production cost, some environmental, and public health exertions like increasing soil salinity level in coastal areas, intensifying the already existing arsenic problem in groundwater, etc. Using surface water for irrigation, changing the land use and cropping patterns to maintain soil moistures, increasing surface water reservoirs along with negotiations on trans-boundary issues with neighbouring countries are recommended to cope with changing ET₀ trends of the country under the climate change hiatus.

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