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Assessing the Potential Impacts of Climate Changes on Rainfall and Evapotranspiration in the Northwest Region of Bangladesh

Fazlul Karim [1,*], Mohammed Mainuddin [1], Masud Hasan [2] and Mac Kirby [1]

1 CSIRO Land and Water, Commonwealth Scientific and Industrial Research Organisation, Canberra, ACT 2601, Australia; Mohammed.Mainuddin@csiro.au (M.M.); Mac.Kirby@csiro.au (M.K.)
2 Crawford School of Public Policy, ANU College of Asia and the Pacific, The Australian National University, Canberra, ACT 2601, Australia; Masud.Hasan@anu.edu.au
* Correspondence: Fazlul.Karim@csiro.au; Tel.: +61-2-6246-4526

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Abstract: Changes in the natural climate is a major concern for food security across the world, including Bangladesh. This paper presents results from an analysis on quantitative assessment of changes in rainfall and potential evapotranspiration (PET) in the northwest region of Bangladesh, which is a major agricultural hub in the country. The study was conducted using results from 28 global climate models (GCMs), based on IPCC's 5th assessment report (AR5) for two emission scenarios. Projections were made over the period of 2045 to 2075 for 16 administrative districts in the study area, and the changes were estimated at annual, seasonal and monthly time scale. More projections result in an increase in rainfall than decrease, while almost all projections show an increase in PET. Although annual rainfall is generally projected to increase, some projections show a decrease in some months, especially in December and January. Across the region, the average change projected by the 28 GCMs for the moderate emission was an increase of 235 mm (12.4%) and 44 mm (3.4%) for rainfall and PET, respectively. Increases in rainfall and PET are slightly higher (0.6% and 0.2%, respectively) under high emission scenarios. Increases in both rainfall and PET were projected for two major cropping seasons, Kharif (May-Oct) and Rabi (Nov-Apr). Projections of rainfall show increase in the range of 160 to 250 mm (with an average of 200 mm) during the Kharif season. Although an increase is projected in the Rabi season, the amount is very small (~10mm). It is important to note that rainfall increases mostly in the Kharif season, but PET increases for both Kharif and Rabi seasons. Contrary to rainfall, increase in PET is higher during Rabi season. This information is crucial for better adaptation under increased water demand for agricultural and domestic use.

Keywords: agriculture; climate change; GCM; scaling factor; PET; RCP

1. Introduction

Over the last several decades, global warming has been observed on local, regional and global scales. According to the Intergovernmental Panel on Climate Change (IPCC) global averaged combined land and ocean surface temperature show a warming of 0.85 °C (ranging from 0.65 to 1.06 °C) over the period 1880 to 2012 [1]. Similar to other parts of the world, Bangladesh has experienced an increase in average temperature in all parts of the country [2–4], including the northwest region [5,6]. This observed trend is also generally true for other climate variables, such as maximum and minimum temperatures. However, the studies on rainfall do not yield a consistent picture, with some studies showing an increase in rainfall over recent decades [7–9], whereas others show a decrease [10–12]. Several studies agree that rainfall has increased in the southern coastal regions, and possibly also in the north, but may have declined in the central parts of the country [13,14]. The differences in the observed rainfall trends may result from the substantial variability of rainfall, coupled with differences in the periods and areas studied.

The impacts of global climate change on agricultural production is very large across the world [15–17] and the impacts have already begun to be visible in Bangladesh [18,19], which is a small south Asian nation with a land area of approximately 147,570 km^2, and home to about 160 million people. The country greatly relies on an agriculture-based economy, where water resources are highly critical. It is ranked sixth among 170 countries in the Global Climate Risk Index for the period 1996–2015 [20]. The Asian Development Bank estimated that Bangladesh may experience a 2% GDP loss (annually) by 2050 because of climate change [21]. As water impacts practically all sectors (people, agriculture, industries and ecosystems), there have been considerable research efforts into predicting or projecting water availability under future climates [22–24] to inform the development of effective adaptation options. Therefore, it is important to understand the changes in rainfall that determine variations in water resources. It is anticipated that food and water security in Bangladesh will be under increasing pressure due to socio-economic growth and global climate change. As per recent estimates, the population in Bangladesh will be more than 230 million by 2050 [25]. The growth of population and expanding economy will result in an increase in water demand. Moreover, the warmer future climate will increase evapotranspiration and hence increase demand for water in irrigated agriculture, urban centers and water-dependent ecosystems. The northwest region of Bangladesh is one of the major food hubs in the country. Therefore, any change in future rainfall and potential evapotranspiration (PET) could have significant implications for socio-economic and agricultural perspectives [5,6,26].

Presently, global climate models (GCMs) are one of the most used tools for projecting future climates and potential changes in precipitation and PET. The Coupled Model Intercomparison Project (CMIPs) of IPCC has made available GCM outputs for the Program for Climate Model Diagnosis and Intercomparison (PCMDI), and these products are freely available for research. The climate model outputs from Phase 3 of the CMIP (CMIP3) were broadly used in IPCC's 4th Assessment Report (AR4). In 2013, IPCC released its 5th Assessment Report (AR5), which was based on climate models from Phase 5 of the CMIP (CMIP5), along with greenhouse gas concentration scenarios termed as representative concentration pathways (RCPs). The models from CMIP5 joined with the RCP scenarios have delivered more precise representations of climate outputs than the CMIP3 model results, because corrections were made in regard to some key assumptions of climate that were previously overlooked by the model developers. The CMIP5 models are considered more competent for capturing numerous features of the Asian monsoon climate than the CMIP3 models [27].

It is important to note that GCMS are typically run at coarse resolutions (250 to 600 km). Therefore, the GCM outputs are inherently unable to represent regional or local climate features and dynamics at the necessary spatial resolutions for detailed analyses [28]. Therefore, a hydrological response to climate change is generally projected, using downscaled future climate projections to drive a hydrological model [29–31]. One of the key challenges in factoring climate change into water resources management lies in the uncertainty in the projections [32,33]. The sources of the projection uncertainties could be from the GCMs, the downscaling approaches, or the hydrological models [34,35]. The performance of GCMs over the South Asia region, including Bangladesh, have been investigated by many researchers [36–40]. For example, Saha et al. [38] found that the majority of the CMIP5 GCMs fail to simulate the post-1950 decreasing trend of Indian summer monsoon rainfall, as they did not capture the weakening monsoon associated with the warming of southern Indian Ocean and strengthening of cyclonic formation in the tropical western Pacific Ocean. Some studies have suggested placing more weight on or using only projections from the better performing GCMs. However, it is challenging to select better performing GCMs for a region or country as none of GCMs can reproduce all salient features of global climate [40]. The uncertainty in climate projections from GCMs and from downscaling approaches must be adequately represented within the specific context and objectives of any water resources management study.

In the past few years, several studies have estimated the changes in precipitation and/or evapotranspiration for Bangladesh [9,12,41,42], and the majority of the studies suggested an overall increase in monsoon rainfall and decrease in post-monsoon rainfall [41,43]. However, these studies used the climate model output from CMIP3 and were driven by the IPCC AR4 scenarios. In recent years, some studies [44–47] estimated the future climate and associated extremes for Bangladesh based on the IPCC's AR5 report. These studies revealed that overall precipitation and temperature are likely to increase in the future over this region. However, these studies are not specific to the northwest region and uncertainties in GCMs projections were not considered. Moreover, neither study examined projected changes in potential evapotranspiration (PET), which is an important input for irrigation demand estimation.

This paper aims to estimate the changes in future rainfall and PET based on IPCC's AR5 under RCP4.5 and RCP8.5 emission scenarios [1]. The novelty of this study is that we aimed to examine rainfall and PET jointly, and to encompass the range of projections to capture the full range of uncertainty. At the same time, this avoids artificially inflating the uncertainties by treating the uncertainties in rainfall and PET projections as independent. This was best done by identifying the two GCMs that best showed the highest and lowest projected rainfall, the two that showed the highest and lowest projected PET, and then using the rainfall and PET projections for those GCMs. We also used the projections for the GCM which was closest to the average rainfall and PET, making five sets of projections in all. We used the GCMs which satisfied the criteria across the region, rather than per grid cell, which could potentially introduce discontinuities in projections.

2. Data and Methods

2.1. Study Area

This study focused on the northwest region of Bangladesh, which is bounded by the Jamuna River to the East, the Ganges to the south and India to the north and west (Figure 1). It consists of 16 administrative districts covering an area of approximately 32,600 km^2 and population of 38 million [48]. Bangladesh has a tropical monsoon climate, characterized by wide seasonal variations in rainfall, moderately warm temperatures and high humidity. An integral part of the region's climate lies in the seasonal reversal of atmospheric circulation between the winter and summer months. There are four distinct seasons in Bangladesh, which include the dry winter season from December to February (DJF), the pre-monsoon hot summer season from March to May (MAM), the rainy monsoon season from June to September (JJA) and the post-monsoon autumn season, which lasts from September to November (SON). The average temperature of the country ranges from 18.5 to 21.0 °C during winter and 27.8 to 29.0 °C during summer. The average relative humidity for the whole year ranges from 70.5 to 78.1%, with the maximum in September and minimum in March [4,49]. The hottest month is May, when the average temperature varies from 27 °C in the east and south to 31 °C in the west-central part of the country, whereas the temperature sometimes increases up to 40 °C in the western regions [50]. The cold winter air of northwestern India passes through the country, which loses much of its intensity and reaches the northwestern corner of the country in January, making it the coldest month wherein the temperature varies from 17 °C in the northern parts to 20–21 °C in the coastal area. However, in late December to early January, the minimum temperature in the extreme north-western and northeastern part of the country can fall to the 4 °C point. Across the six meteorological stations in the northwest region, average maximum temperature varies from 24 °C in January to 34 °C in June. Between November and February average maximum temperature stays below 27 °C, but crosses 32 °C between April and October [6].

Rainfall in Bangladesh is strongly seasonal and mostly occurs during monsoon, caused by weak tropical depressions that are brought from the Bay of Bengal into Bangladesh by the wet monsoon winds. Annual rainfall varies from approximately 1400 mm in the west to over 4300 mm in the east [44]. Higher rainfall in the northeast is caused by the additional uplifting effect of the Meghalaya plateau.

Like other parts of the country, rainfall in the northwest region varies both spatially as well as seasonally. In general, the northern part (e.g., Kurigram) receives more rain than the south (e.g., Pabna). The PET in the northwest region varies seasonally but is less variable spatially. In general, PET is high during March to May and low during December and January (Figure 2). Between six meteorological stations, annual PET varies from 1220 mm (Dinajpur) to 1362 mm (Ishurdi). The mean reference PET is 1290 mm annually and 580 mm during the dry season [26].

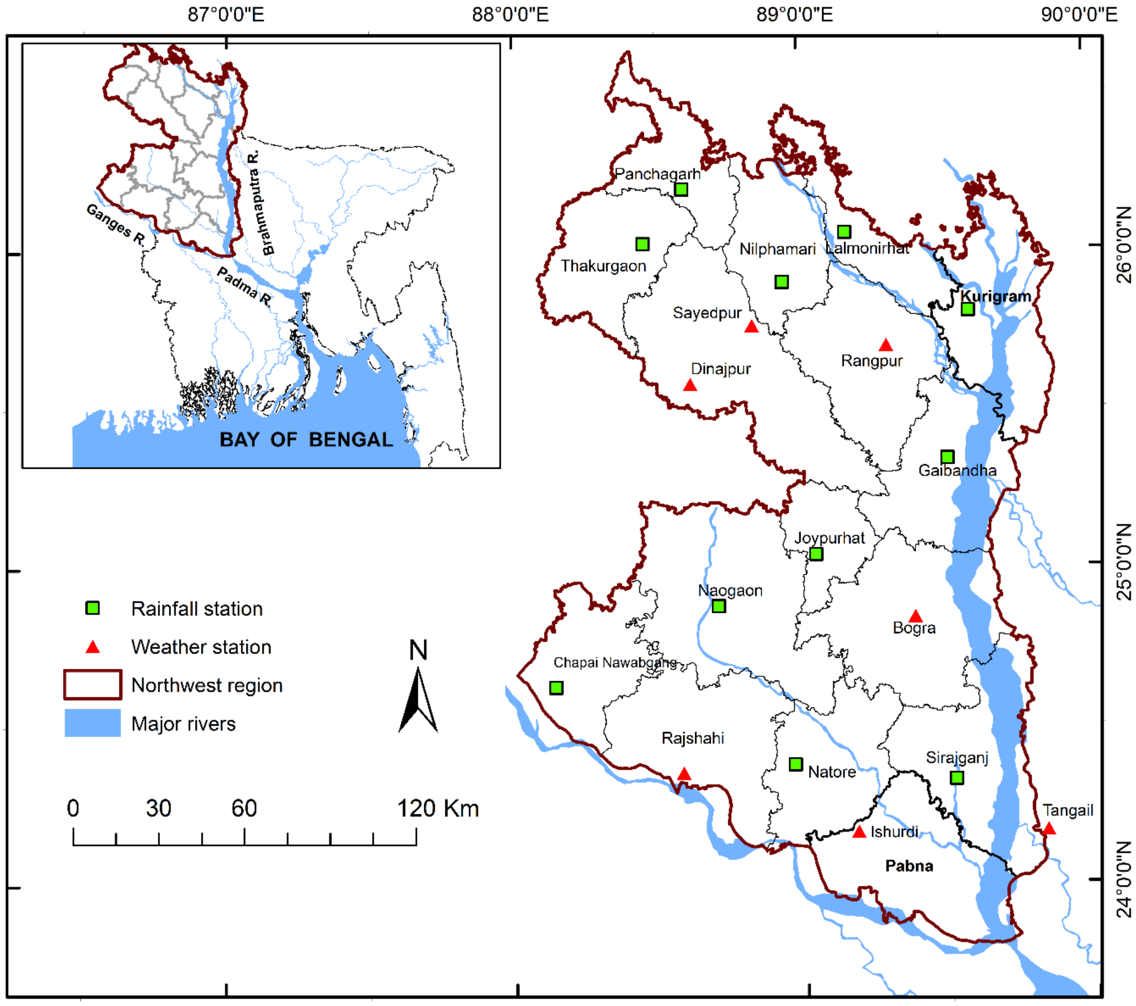

Figure 1. Study area map showing administrative districts and locations of meteorological stations in the northwest region of Bangladesh.

2.2. Data Sources for Present and Future Climate

There are six weather stations in the northwest region of Bangladesh monitored by the Bangladesh Meteorological Department (BMD). In addition, there are 10 rainfall measuring stations monitored by the Bangladesh Water Development Board (BWDB). Daily temperature, rainfall and PET data for all stations in the northwest region and one neighboring station (Tangail, Figure 1) were obtained from the BMD and BWDB. The rainfall stations are spatially distributed across the region and there is at least one rainfall station in all 16 districts monitored either by the BMD or BWDB. The majority of these stations have been operational since 1970. However, considering the quality of measurement and continuity of records, data from 1985 to 2015 were used in the characterization of the observed temperature and rainfall.

The annual mean rainfall for the 16 districts in the northwest region varies spatially, ranging from 1428 mm in Rajshahi to 2543 mm in Kurigram with a mean of 1895 mm. Monthly rainfall in the northwest region varies from just 6 mm in December to 394 mm in July (Figure 2). About 93% rainfall occurs in the months of May to October, with 56% during the rainy season (June to September). On average only 1.6% rainfall occurs during the winter (December to February).

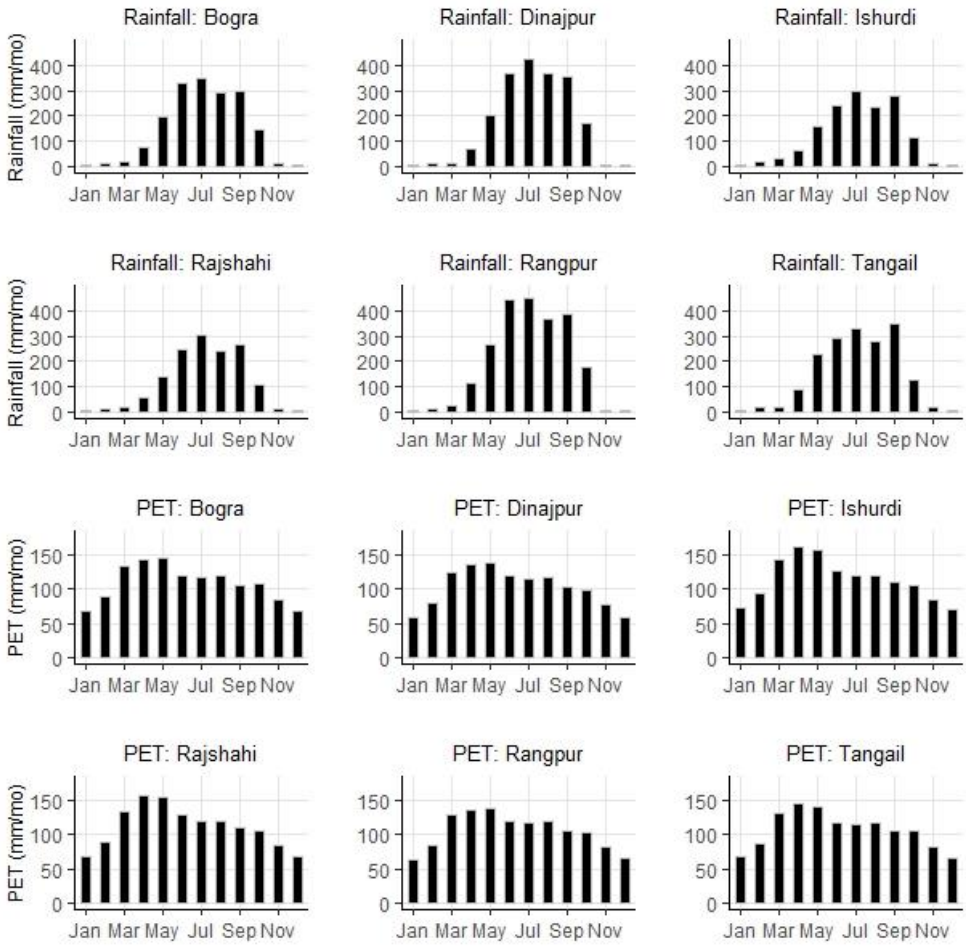

Figure 2. Monthly mean rainfall and potential evapotranspiration (PET) (based on data from 1985 to 2015) at six meteorological stations in the northwest region of Bangladesh (refer to Figure 1 for location).

The future of anthropogenic greenhouse gas and aerosol emissions is uncertain, encompassing substantial unknowns in population and economic growth, technological developments and transfer and political and social changes. The CMIP5 database allows access to variables from each individual model. Currently, GCM results are available for RCP2.6, RCP4.5, RCP6.0 and RCP8.5, and the outputs are available at daily, monthly and yearly time steps for the period of 2006 to 2100. The RCPs are named after the target energy forcing by 2100. Each RCP contains the same categories of input data but the values can vary based on different emission scenarios over time, as determined by the underlying socioeconomic assumptions which are unique to each RCP [51].

IPCC's AR5 presents the global temperature rise under different RCPs (Table 1). A high RCP indicates a larger temperature rise. Results are presented for the mid (2046–2065) and late-century (2081–2100) for the 4 RCPs [1]. The projections are relative to historical global temperature in the period of 1976 to 2005. However, temperature projections can be converted to a reference period of 1850 to 1900 or 1980 to 1999 by adding 0.61 °C or 0.11 °C, respectively [1]. In this study, we have chosen the RCP4.5 and RCP8.5 scenarios as per previous studies [44,46,47].

Table 1. Global warming scenarios under the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5) for different emission scenarios (source: IPCC AR5).

Emission Scenario	Temperature Increase (°C) by 2046–2065		Temperature Increase (°C) by 2081–2100	
	Mean	Likely Range	Mean	Likely Range
RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8

2.3. Downscaling of GCM Results

Downscaling is a process of transferring GCM outputs at a local scale (e.g., catchment) for climate impact assessment. Three downscaling methods are commonly used. These include: (i) empirical downscaling, which perturbs the baseline observations to reflect a future climate based on the change informed by GCMs (for a future period relative to a baseline period); (ii) statistical downscaling, which develops a statistical relationship between GCM atmospheric variables and observed climate variables, and then use this relationship to derive future climate variables from future GCM variables; and (iii) dynamical downscaling, where regional climate models (RCMs) are used [52] to model the physical atmospheric and land surface processes at a smaller spatial scale, informed or constrained by a larger scale GCM. Every method has advantages and limitations, and studies generally conclude that no single downscaling method is better, because different downscaling methods are developed for different applications [34]. Chiew et al. [53] found that the results from empirical downscaling typically lie within the range of other regionally available statistical and dynamical downscaling methods. Frost et al. [54] recommend using empirical downscaling methods for regional water resource planning applications. Based on these key advantages of empirical scaling methods, Zheng et al. [30] estimated the scaling factors (SF) for Southeast Asia, including Bangladesh, in a companion study. This study therefore uses the SFs derived by Zheng et al. [30] that are relevant to the northwest region of Bangladesh. For the empirical downscaling, the scaling factor is estimated as SF = Xf/Xb, where Xf and Xb are the GCM simulation for the future (2046–2075) and baseline (1976–2005) periods respectively. The scaling factor is then used to produce a future climate time series by multiplying baseline observed climate data with the SF. While there are 18 points in the SF grids produced by Zheng et al. [30], only 6 grids that are close to a weather station are selected (Figure 3).

2.4. Selection of Climate Models

There are 28 GCMs for which rainfall and PET data are readily available for Bangladesh. Table 2 presents the list of climate models, founding institution and their spatial resolution. Future climate projections from all 28 GCMs were investigated, and a GCM was considered best for the northwest region of Bangladesh that projected closest rainfall and PET to the average value of all GCMs.

To represent a wide range of projections from 28 GCMs (Table 2), five scenarios were considered, one as average of all models, two for rainfall extremes (low and high) and two for PET extremes (low and high). It is important to note that GCMs were selected considering the combined impacts on rainfall and PET, rather than considering each variable independently. As noted in the introduction, this avoids artificially inflating the uncertainties by treating the uncertainties in rainfall and PET projections as independent. The concept of selecting best GCMs is schematically represented in Figure 4. To reduce uncertainty in future projections, results from 28 GCMs were evaluated, and their spatial and seasonal variabilities were assessed. While estimating low and high values for rainfall, the average value for PET was considered. Similarly, for estimating low and high value for the PET, the average value of rainfall was considered. However, rather than evaluating the GCMs in terms of rainfall and PET themselves, we evaluated them in terms of the scaling factors. It is important to note that each GCM is sensitive to parameterization, and it is assumed that none of the models is better than others [55]. Five scenarios are named as follows: (i) low rainfall and average PET (S1); (ii) high rainfall and average PET (S2); (iii) average rainfall and average PET (S3); (iv) average rainfall and low PET (S4); and (v) average rainfall and high PET (S5). It is important to note that outliers (i.e., exceptionally low or high values) were excluded from the analysis.

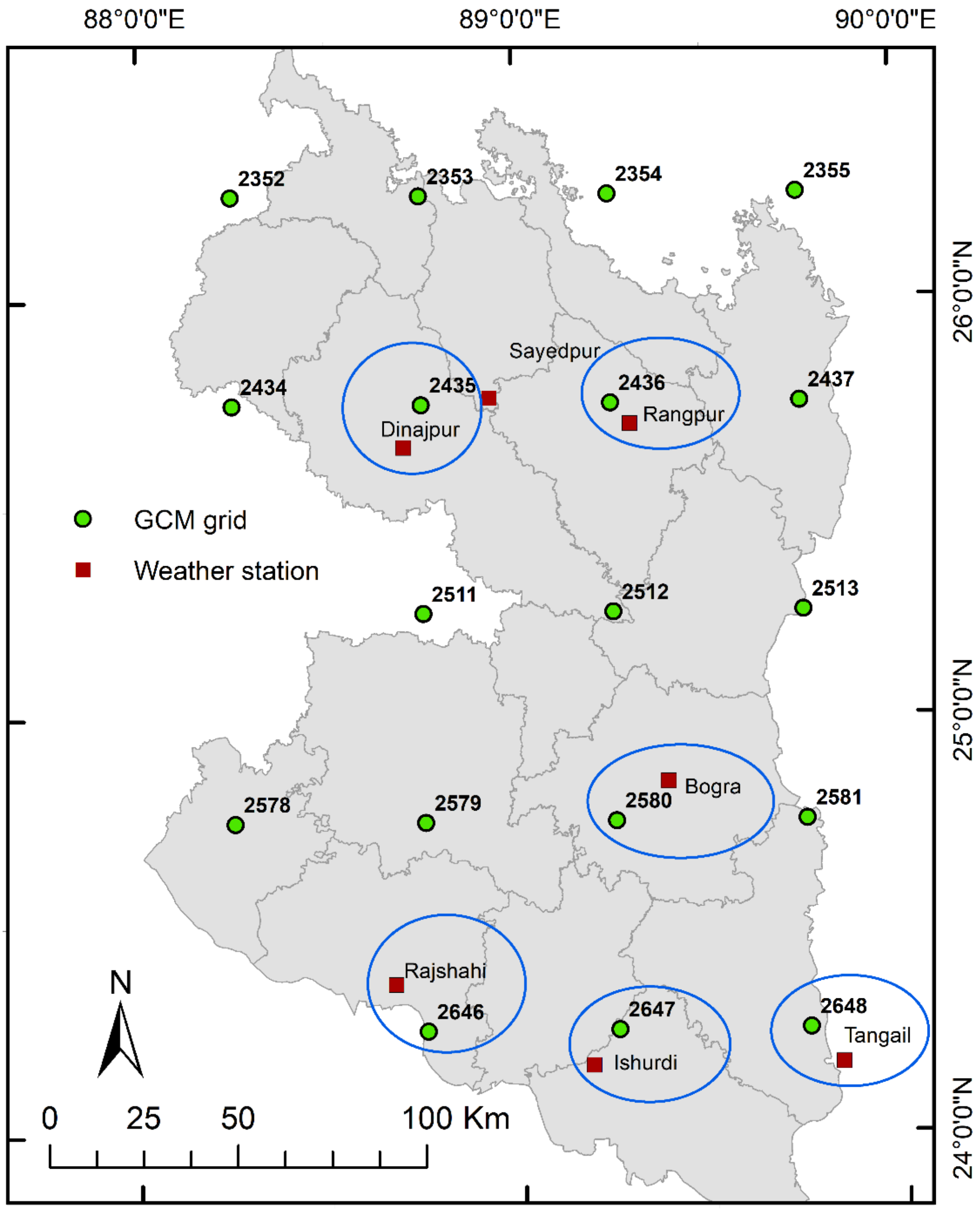

Figure 3. Global climate model (GCM) grids (green dot) and metrological stations (red square) in the northwest region of Bangladesh. Selected GCM grids are circled blue, along with nearest meteorological station. The numbers show the grid point numbers in the Zheng et al. [30] scaling factor set.

Table 2. List of global climate models their founding institution and spatial resolution.

CMIP5 Model ID	Institution and Country of Origin	Atmospheric Horizontal Resolution (°lat × °long)
Access-1.0	CSIRO-BOM, Australia	1.9 × 1.2
Access-1.3	CSIRO-BOM, Australia	1.9 × 1.2
BCC-CSM1-1	Beijing Climate Center, China	2.8 × 2.8
BCC-CSM1-M	Beijing Climate Center, China	1.1 × 1.1
CanESM2	Canadian Centre for Climate Modelling and Analysis	2.8 × 2.8
CCSM4	National Center for Atmospheric Research, USA	1.2 × 0.9
CESM1-BGC	National Center for Atmospheric Research, USA	1.2 × 0.9
CESM1-CAM5	National Center for Atmospheric Research, USA	1.2 × 0.9
CNRM CM5	National Centre for Meteorological Research, France	1.4 × 1.4
CSIRO MK3-6	Commonwealth Scientific and Industrial Research Organisation, Australia	1.9 × 1.9
GFDL-CM3	Geophysical Fluid Dynamics Laboratory, USA	2.5 × 2.0
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory, USA	2.5 × 2.0
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory, USA	2.5 × 2.0
GISS-E2-H	NASA/Goddard Institute for Space Studies, USA	2.5 × 2.0
GISS-E2-H-CC	NASA/Goddard Institute for Space Studies, USA	1.0 × 1.0
GISS-E2-R	NASA/Goddard Institute for Space Studies, USA	2.5 × 2.0
GISS-E2-R-CC	NASA/Goddard Institute for Space Studies, USA	1.0 × 1.0
HadGEM2-AO	National Institute of Meteorological Research and Korea Meteorological Administration (NIMR-KMA), Korea	1.9 × 1.2
HadGEM2-CC	Met Office Hadley Centre, UK	1.9 × 1.2
HadGEM2-ES	Met Office Hadley Centre, UK	1.9 × 1.2
INMCM4	Institute of Numerical Mathematics, Russia	2.0 × 1.5
IPSL-CM5A-LR	Institute Pierre Simon Laplace, France	3.7 × 1.9
IPSL-CM5A-MR	Institute Pierre Simon Laplace, France	2.5 × 1.3
MIROC5	Japan Agency for Marine-Earth Science and Technology, Japan	1.4 × 1.4
MIROC-ESM	JAMSTEC, Japan	2.8 × 2.8
MIROC-ESM-CHEM	JAMSTEC, Japan	2.8 × 2.8
MRI-CGCM3	Meteorological Research Institute, Japan	1.1 × 1.1
NorESM1-M	Norwegian Climate Centre, Norway	2.5 × 1.9

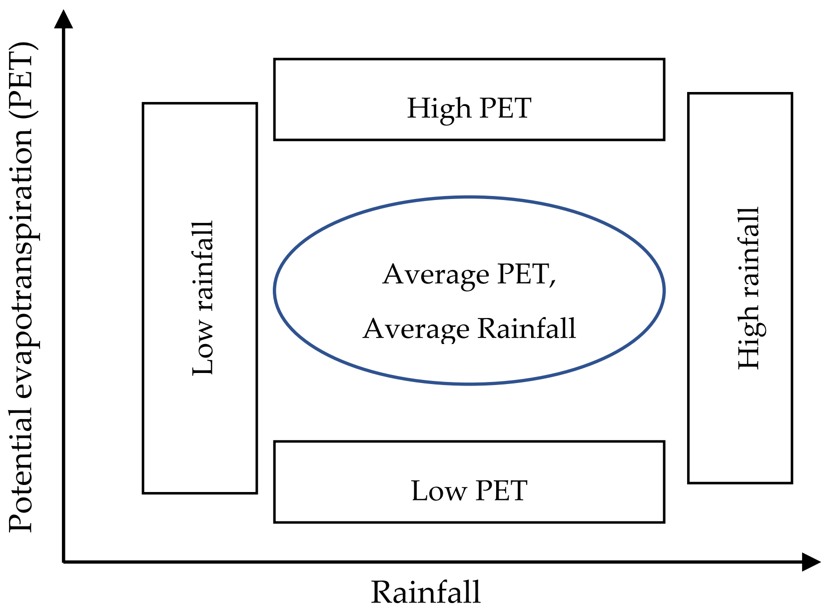

Figure 4. Conceptual diagram of selecting five future climate scenarios by combining the low, medium and high PET with low, average and high rainfall.

The conceptual diagram in Figure 4 is implemented in Figure 5, using rainfall and PET scaling factor outputs from 28 GCMs. The green dots represent the average of individual GCM projections for six grids and the error bars show the spatial variability between grids in the northwest region. Some green dots can be seen without any error bar, which indicates the same projected value for all six grids. The orange dot shows the mean projected value by 28 GCMs. A GCM that projected rainfall and PET close to scenario S1 (low rainfall and average PET) was considered as the best model for that scenario. Similarly, best GCMs for other four scenarios (S2 to S5) were selected, as shown in Figure 5.

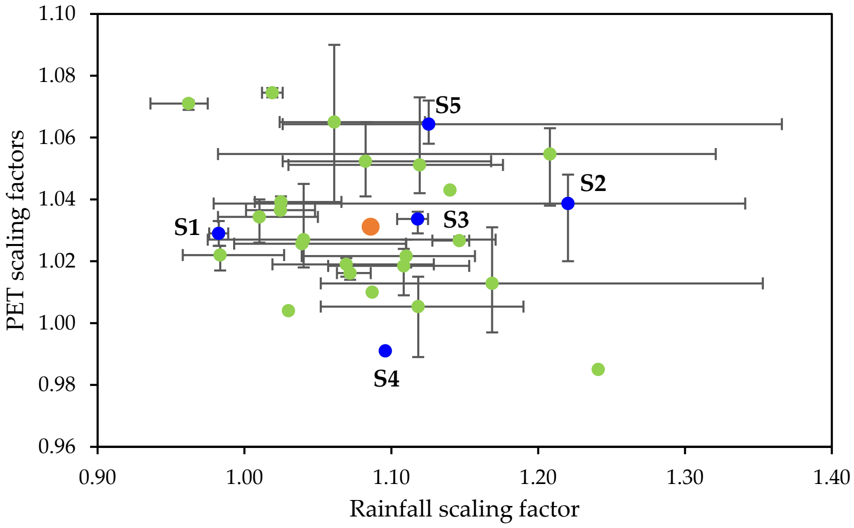

Figure 5. Method of selecting best GCMs for five scenarios (S1 to S5). Green, blue and orange dots represent 28 GCMs, five selected GCMs for S1 to S5 and average of 28 GCMs respectively. The error bar shows the spatial variability between six grids.

In this study, rainfall and PET are projected based on scaling factors derived from GCM results. Historical data for the period of 1985 to 2015 were used as the baseline condition. Scaling factors and subsequent rainfall and PET time series were derived for a period over 2046–2075 for the RCP4.5 and RCP8.5 emission scenarios. Spatial variability between the meteorological stations and temporal variability at monthly, seasonal and annual timescale were investigated. A single set of scaling factors were used for all 16 districts in the study area, to reduce uncertainty in local variations. Three sets of time series data for rainfall and PET were constructed based on monthly, seasonal and annual scaling factors. Four seasons, each representing 3 calendar months (DJF, MAM, JJA and SON) were considered to capture intra-annual variability in climate. In addition, two main crop seasons in Bangladesh, Rabi (November to April) and Kharif (May to October) were investigated. In the case of monthly and seasonal scaling, daily time series were readjusted to match the annual total that were derived from annual scaling factors.

3. Results

3.1. Variability in GCM Predictions

Scatter plots of rainfall and PET from 28 GCMs for the six grids in the northwest region of Bangladesh show a large variation between models (Figure 6). The majority of the GCMs projected increases in rainfall and PET for all six locations. While overall GCM projections are within a sensible range, some outliers (circled in red on Figure 6) show very high increases in rainfall. These outliers were excluded from subsequent analysis. The majority of the models projected higher increases for rainfall than PET. The results indicate that increases in both rainfall and PET are almost always projected, although the amount of increase could vary based on the RCP emission scenarios. Projections for rainfall is less certain (SF varies from 0.94 to 1.37) compared to PET (SF varies 0.99 to 1.09).

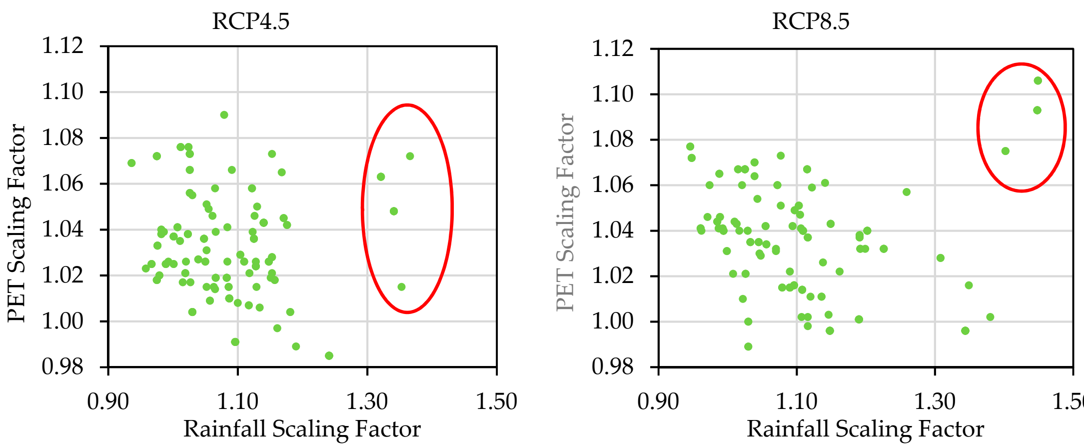

Figure 6. Scatter plot of modelled scaling factors for rainfall and PET for 28 GCMs for the six GCM grids. Red circles show the outliers in model projections.

A detailed analysis shows that variations between GCM results are quite large (up to 43% for rainfall and 11% for PET) (Figure 7). Although absolute values are slightly higher for RCP8.5 compared to RCP4.5, the pattern of inter-model variability is similar for both RCP4.5 and RCP8.5. Excluding the outliers, the projected 25th, 50th (median) and 75th quartile values are similar between six GCM grids, with small variations between them. The highest median increases in rainfall and PET were found for the Grid 2580 (Bogra district, refer to Figure 3 for location).

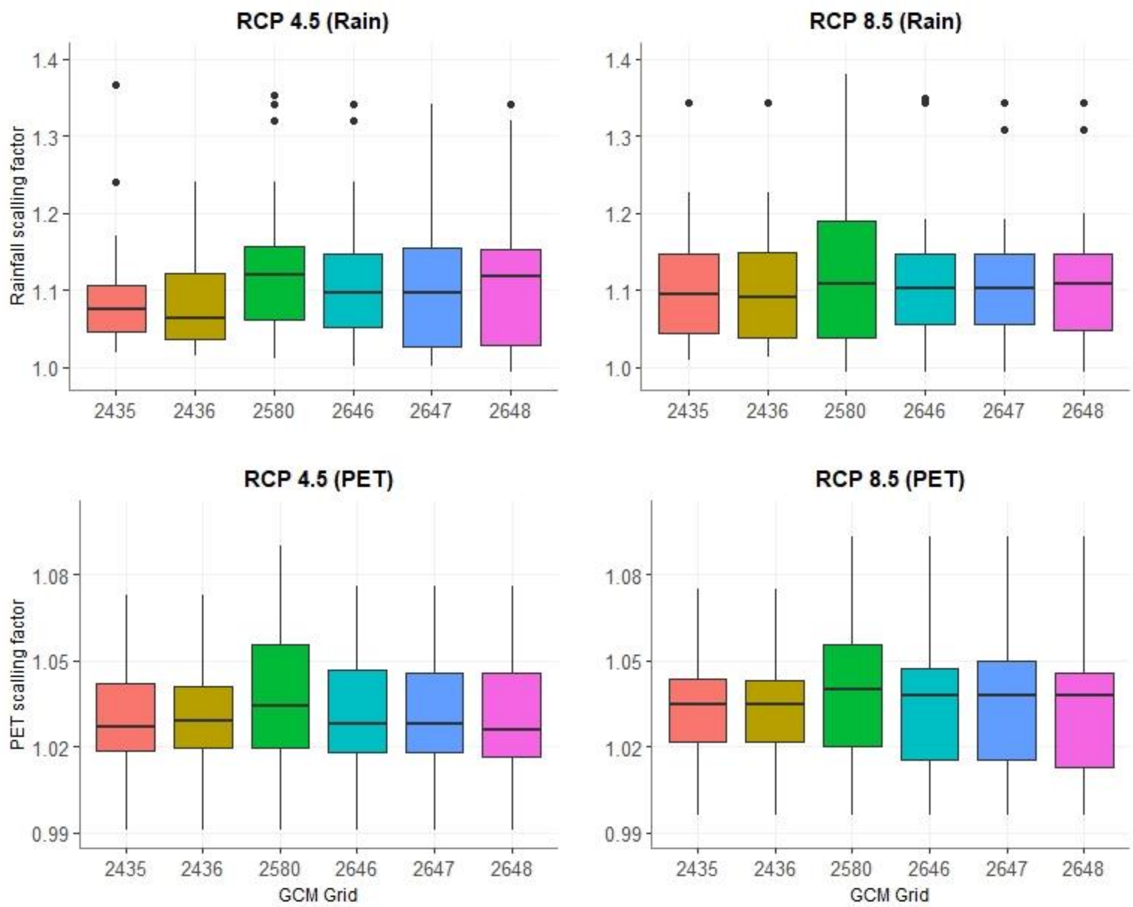

Figure 7. Quantile plots of scaling factors for the six GCM grids in the northwest region of Bangladesh.

For the entire data set, an average increase of 8.6% and 3.1% for rainfall and PET respectively for the RCP4.5 scenario and 11.7% and 3.6%, respectively, for the RCP8.5 are found (Table 3). Without the outliers, increases in rainfall and PET are slightly less (reduced by 1~2% for rainfall and <1% for PET). Seven models (out of 28) projected decreases in rainfall, and only three models projected decreases in PET. The maximum reduction for rainfall and PET are 6.6% and 1.5%, respectively, for the RCP4.5 scenario. Similar reductions are projected for the RCP8.5 scenario. The maximum rainfall increase is much higher (up to 36.6% for RCP4.5 and 38% for RCP 8.5) than the maximum reduction (6.4% for RCP4.5 and 5.4% for RCP 8.5).

Table 3. Summary of scaling factors for 28 model projections for the six GCM grids in the northwest region of Bangladesh.

Climate Index	RCP 4.5				RCP 8.5			
	All Data		Excluding Outlier		All Data		Excluding Outlier	
	Rainfall	PET	Rainfall	PET	Rainfall	PET	Rainfall	PET
Minimum	0.936	0.985	0.936	0.985	0.946	0.969	0.946	0.969
25th percentile	1.019	1.017	1.014	1.015	1.027	1.015	1.025	1.015
Mean	**1.086**	**1.031**	**1.070**	**1.030**	**1.117**	**1.036**	**1.097**	**1.033**
Median	1.081	1.027	1.065	1.026	1.097	1.039	1.092	1.037
75th Percentile	1.133	1.045	1.125	1.042	1.183	1.049	1.148	1.044
Maximum	1.366	1.090	1.241	1.090	1.449	1.106	1.380	1.077

Similar to the historical climate, the projected changes in rainfall and PET also vary spatially and seasonally. Figure 8 shows a comparison of average increase in rainfall and PET between six GCM grids in the study area. The changes for RCP4.5 (red bars) and RCP8.5 (light blue bars) are similar, although the absolute values for RCP8.5 are slightly higher. The increase in rainfall varies from 6.4 to 8.0% for the RCP4.5 and 8.7 to 11.9% for the RCP8.5 and the highest increase (8.0 and 11.9% for the RCP4.5 and RCP8.5 respectively) was found for the grid 2580 (corresponding to Bogra district, refer to Figure 1 for location). The increases in PET varies from 2.8 to 3.2% for the RCP4.5 and 3.1 to 3.5% for the RCP8.5 and the highest increase was found for the grid 2580 for RCP4.5 and grid 2647 for RCP8.5. For all six GCM grids, changes in rainfall are higher than changes in PET. The results indicate that both rainfall and PET are projected to increase at all locations in the northwest region, and the increase in rainfall is greater than the increase in PET.

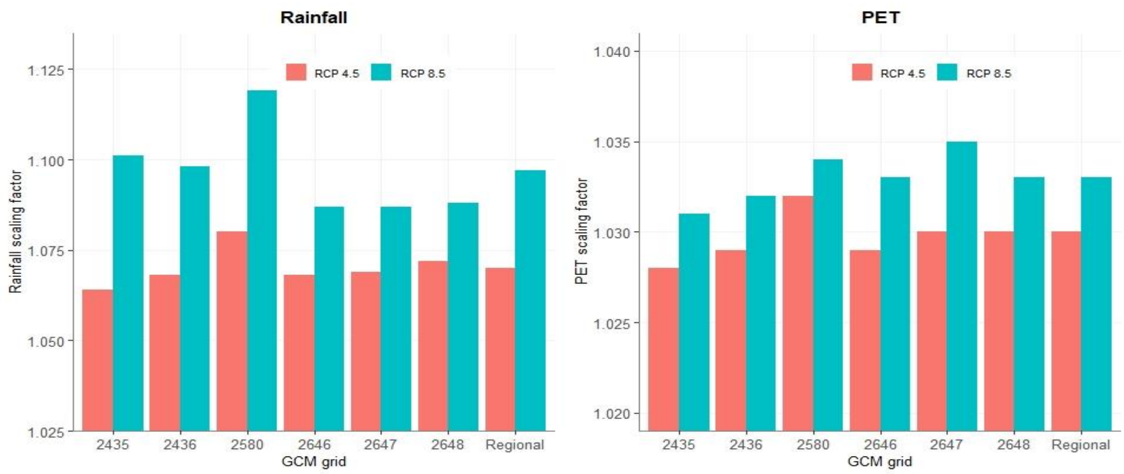

Figure 8. Spatial variations of annual rainfall and PET between six GCM grids in the northwest region of Bangladesh for the RCP 4.5 (red bars) and RCP8.5 (light blue bars) emission scenarios.

While it is evident that future rainfall and PET are projected to increase in the northwest region of Bangladesh, this increase is not uniform at monthly or seasonal time scales (Figures 9 and 10, respectively). Most of the models projected rainfall increase from February to November and decrease in December and January (Figure 9). Similar patterns of monthly increase/decrease were found for RCP4.5 and RCP8.5 scenarios. Across the region, the maximum monthly increase of 19.7% (for the grid 2435) was projected in May, and the maximum decrease of 11.5% (for the grid 2436) was projected in December for the RCP4.5. These values are 26.4% and 10.8%, respectively, for the RCP8.5. A decrease in rainfall is projected in December for all six grids but only for two grids (2435 and 2436) in January. A rainfall increase is projected for all other months. It is important to note that rainfall in December is very small (<1%). Therefore, any increase or decrease in December does not impact total rainfall.

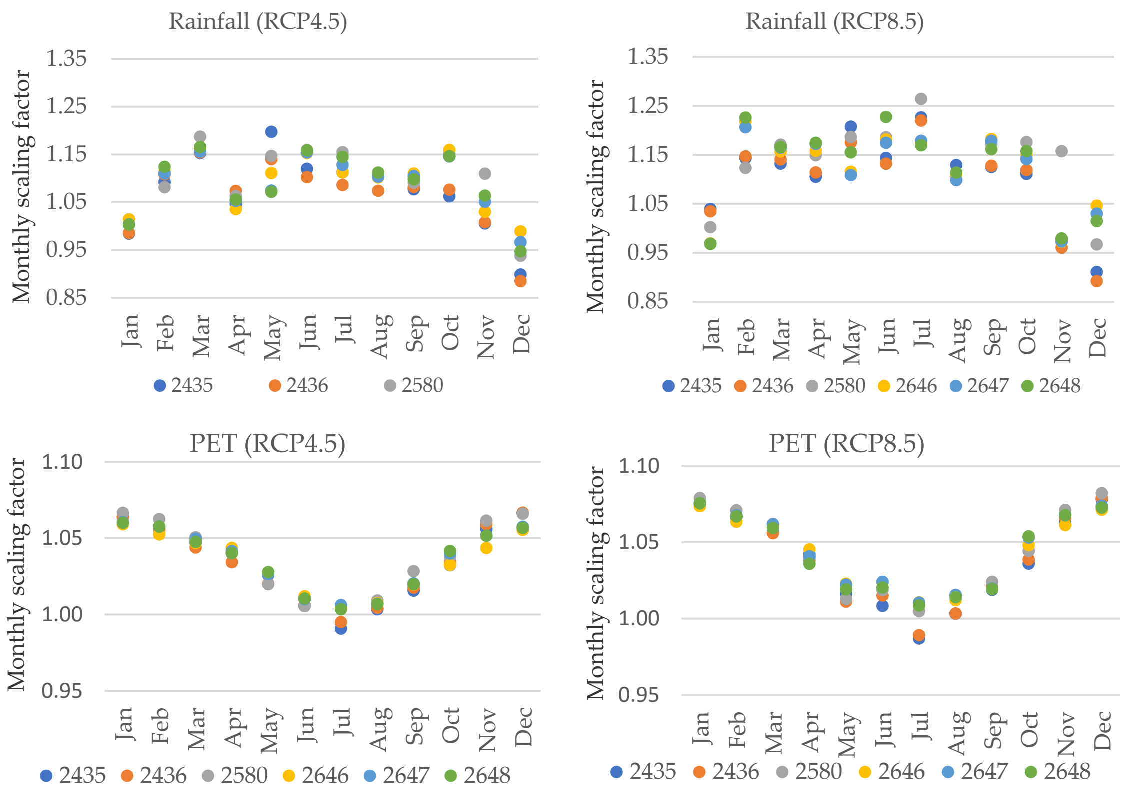

Figure 9. Variations of monthly scaling factor of rainfall (**upper panels**) and PET (**lower panels**) across the northwest region for the six GCM grids (refer to Figure 3 for location).

Monthly variations were also projected for PET. However, the changes are opposite to rainfall. For example, the maximum PET increase was projected for the months of December and January while decreases in rainfall were projected for those two months. Between months, increase in PET varies from 0 to 6.7% and decrease from 0 to 0.9 %. The minimum PET was projected for the month of July. The patterns of increase and decrease are similar for RCP4.5 and RCP8.5.

Changes in rainfall and PET vary between seasons as seen in monthly data (Figure 10). For three seasons (out of four), increases in rainfall were projected for both RCP4.5 and RCP8.5. For the DJF season, decrease in rainfall were projected for three GCM grids (2435, 2436 and 2648, refer to Figure 3 for location). Seasonal change in rainfall varies from −3.9 to 12.8% for the RCP4.5, compared to an annual mean of 8.6%. For the RCP8.5, these changes are −1.2 to 16.5% for an annual mean of 12.8%. It is important to note that rainfall in Dec-Jan-Feb is only 1.4% (equivalent to 26 mm) of annual rainfall, indicating minimal impact on total rainfall under future climate.

Changes in PET varies from 0 to 6.5% between seasons, compared to the annual mean of 3.1% for the RCP4.5, and 0 to 7.7%, compared to the annual mean of 3.6% for the RCP8.5. It indicates that there is a larger projected increase in PET for the RCP8.5 than for RCP4.5, which is consistent with the rainfall increase. It is interesting to note that none of the models projected a decrease in PET at a seasonal timescale, although some models projected no change. The maximum increase in PET was projected for the Dec-Jan-Feb season and minimum for the Jun-Jul-Aug season, which is opposite to the rainfall increase.

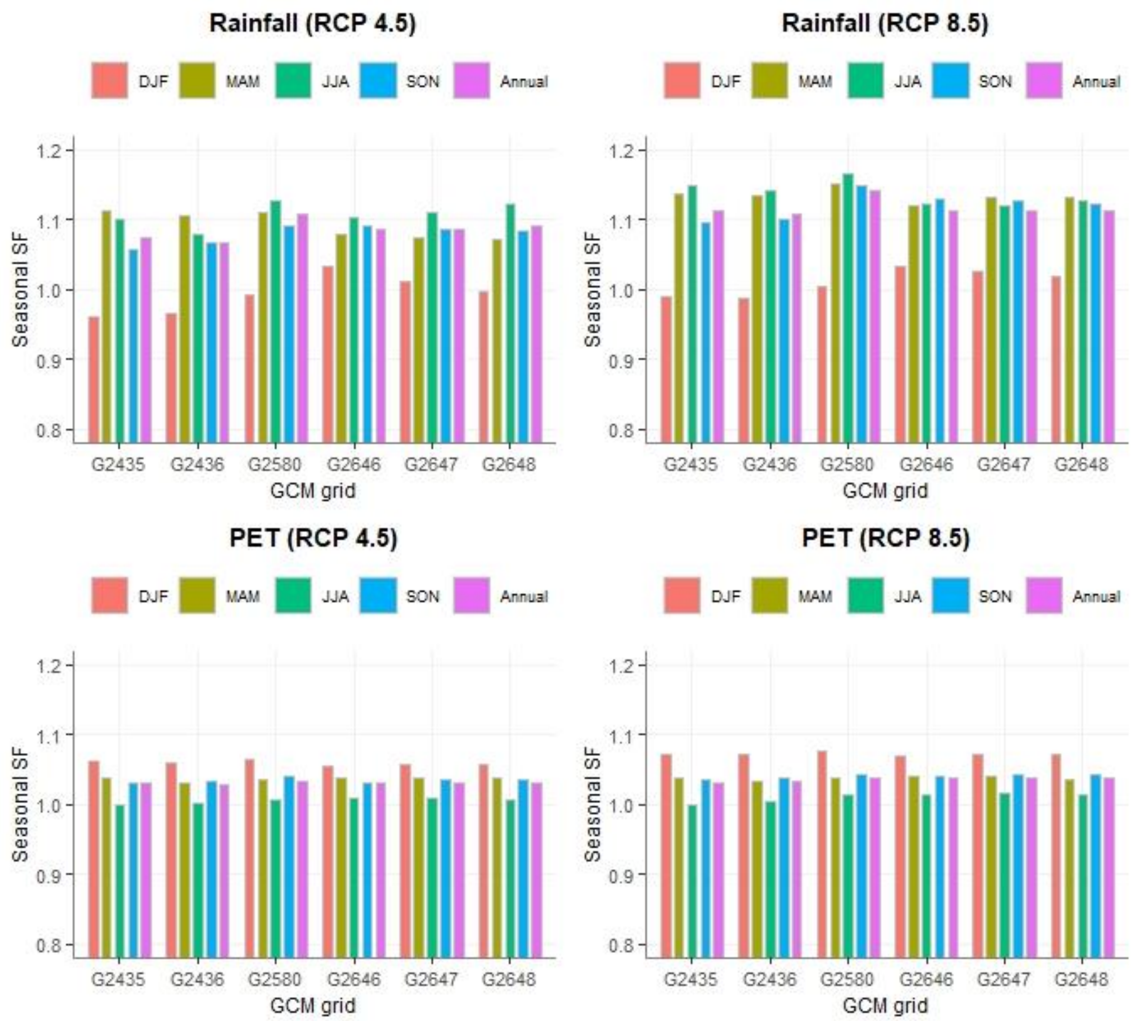

Figure 10. Variations of seasonal scaling factor of rainfall (**upper panels**) and PET (**lower panels**) across the northwest region (DJF: Dec-Jan-Feb, MAM: Mar-Apr-May, JJA: Jun-Jul-Aug, SON: Sep-Oct-Nov).

3.2. *Projection of Future Change*

3.2.1. Changes at Annual Scale

Given the difficulty of making firm projections about future climate, this study investigated five alternative scenarios of future climate that span a reasonable range of potential future climates. The scenarios are labelled as S1 to S5, as described in Section 2.4 and Figure 5. Annual scaling factors for the best GCMs for five scenarios are presented in Table 4. For the low rainfall and average PET (S1) scenario, the GFDL-ESM2G was found to be the best for the RCP 4.5 and RCP8.5 (Table 4). For the scenarios S3 and S5, the same model but different sub-modules were found to be the best for the RCP 4.5 and 8.5 (Table 4). For scenarios 2 and 4, different models were identified as best performing for RCP4.5 and RCP8.5. The results show that for an average change scenario (S3), rainfall could be increase by 11.8% for the RCP4.5 and 12.4% for the RCP8.5. For the low rainfall scenario (S1), a small reduction in rainfall (1 to 2%) is predicted, while for the low PET scenario, the reduction is negligible (<1%). While an increase in mean annual rainfall is generally projected for the entire northwest region of Bangladesh, there is a possibility of decrease in rainfall in some months, as seen in the previous section (Figure 11).

Table 4. Best performing GCMs and scaling factors (SFs) for the northwest region of Bangladesh.

Scen.	Description	Selected GCM		SF for Rainfall		SF for PET	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
S1	Low rainfall, Average PET	GFDL-ESM2G	GFDL-ESM2G	0.983	0.997	1.029	1.038
S2	High rainfall, Average PET,	MIROC-ESM	HADGEM2-CC	1.220	1.238	1.039	1.041
S3	Average rainfall, Average PET	BCC-CSM1-1	BCC-CSM1-1M	1.118	1.124	1.034	1.036
S4	Average rainfall, Low PET	GISS-E2-H-CC	ACCESS1.3	1.096	1.098	0.991	0.997
S5	Average rainfall, High PET,	IPSL-CM5A-LR	IPSL-CM5A-MR	1.126	1.130	1.064	1.071

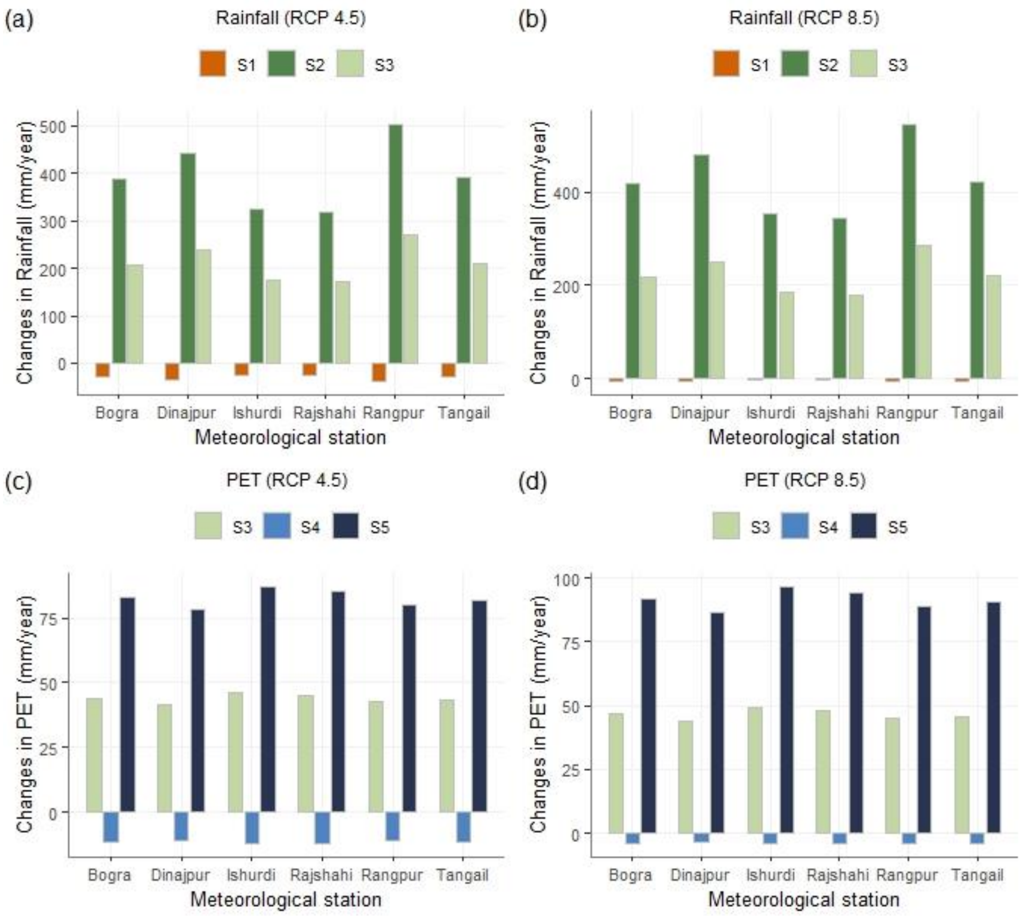

Figure 11. Projected changes in rainfall (**a**,**b**) and PET (**c**,**d**) at six meteorological stations in the northwest region of Bangladesh for the five scenarios (S1 to S5).

By the 2060s, rainfall in the northwest region is projected to rise between 10 to 22% on average for different scenarios, except for the scenario S1, for which about a 1.7% reduction is projected. Figure 11 shows an example of projected changes in annual rainfall at six meteorological stations for low, medium and high rainfall scenarios (S1, S2 and S3). Annual rainfall increases by 33 to 385 mm for scenarios S2 to S5, while it decreases by 30 mm for S1 (low rainfall scenario), compared to the historical mean annual rainfall of 1750 mm.

Four out of five scenarios (S1, S2, S3 and S5) showed an increase in PET, while the S4 scenario showed very small decrease (<1%) in PET (Table 4). On an annual basis, the increase could be up to 8% or about 100 mm for the S5 scenario (high PET). While an increase in mean annual PET is generally projected for the entire northwest region of Bangladesh, there is a possibility of a decrease in

PET in some months, such as June, July and August (Figure 10). Changes in PET for three scenarios (S3, S4, S5) representing medium, low and high increases are shown in Figure 11 for the RCP4.5 and RCP8.5. For an average condition (S3), the increase in PET varies between 41 to 46 mm between six stations. For the low PET scenario (S4), the decrease is between 10 to 12 mm between the stations, while the maximum increase could be up to 102 mm at Ishurdi for the RCP4.5. The changes are very similar for the RCP8.5.

3.2.2. Changes at Crop Growing Seasons

The two major crop seasons in Bangladesh are broadly classified as Kharif (May to October) and Rabi (November to April). For the S3 scenario (i.e., average of all projections), the changes in rainfall and PET are positive (i.e., increase) for both Kharif and Rabi seasons (Figure 12). While, at monthly scale, reduction in rainfall (e.g., in December and January) and PET (in July) are projected (Figure 9), no reduction is projected for the Kharif or Rabi season (Figure 12). An analysis based on six meteorological stations in the northwest region shows that there is a possibility of rainfall increase in the range of 160 to 250 mm (with an average of 200 mm) with respect to historical rainfall of 1320 (Ishurdi) to 2060 mm (Rangpur) during the Kharif season for the RCP4.5 scenario. Although there is an increase in the Rabi season, the amount is very small (~10mm) compared to historical average rainfall of 140 mm. It is important to note that about 92% rainfall occurs during the Kharif season. While rainfall increases mostly in Kharif season, PET increases for both Kharif and Rabi seasons. Contrary to rainfall, the increase in PET is higher during the Rabi season.

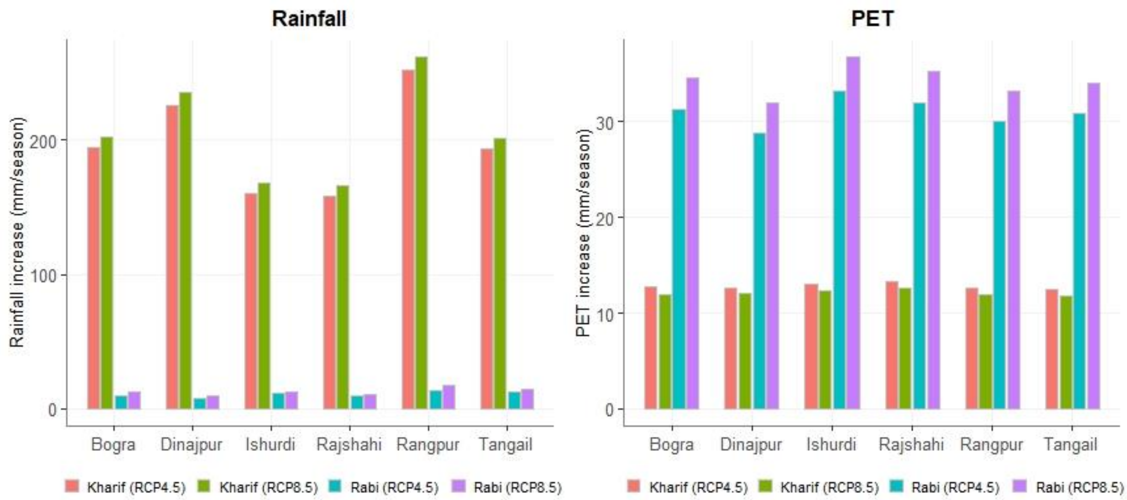

Figure 12. Projected changes in rainfall (**left panel**) and PET (**right panel**) during the Kharif and Rabi seasons in the northwest region of Bangladesh.

4. Discussion

This study demonstrates that projected rainfall change varies from a small decrease to a large increase across the northwest region of Bangladesh. Mean annual rainfall could increase by 11.8% with ±1% across the region, which is positive for the agricultural productions. Increase in rainfall during the Rabi season creates positive impacts, as it reduces the demand for groundwater feed irrigation. Results are consistent with recent studies (e.g., [44,46,47]) on future climate projections where an increase in rainfall, especially for the northwest region, is reported. Based on 17 GCMs, Caesar et al. [44] projected precipitation changes in the range of −1.25 to 10.28% over the period of 2041–2060 and 11.75 to 23.66% over 2080–2099. Similarly, based on results from five regional climate models, Hasan et al. [46] reported mean increase of 4 to 35% over Bangladesh and up to 26% in the northwest region over the period of 2050s. However, increase in rainfall may not always produce positive impacts, because there is a possibility of more extreme events, such as floods with harmful impacts on agriculture [17,46].

Increase in rainfall during the Kharif season is not positive because there is no shortage of water. An increase in PET is projected by most GCMs. This implies a higher irrigation demand for agricultural production which produces negative impact to threatened groundwater resource.

It is important to note there is a large variability between month and seasons. Although annual rainfall and PET may increase in the northwest region, there is a possibility of a decrease in some months. The changes in rainfall and PET during the Kharif and Rabi seasons may have significant implications for agricultural productions in the region. As reported by Kamruzzaman et al. [47], increase in future precipitation may reduce the drought occurrence, which is good news for agricultural productions. However, an annual increase in rainfall could be accompanied by a dry season decrease, thus deepening the dry season drought despite the overall increase. There is also a possibility of increasing extreme events such as flood, which has noticeable adverse effects on crop production [46]. Increased frequency of precipitation ensures regular supplies of water for growing plants and is, therefore, a good outcome from an agricultural perspective. Another important factor that can affect the crop yield is the duration and frequency of wet and dry periods. Therefore, increase in rainfall may not always be advantageous for agricultural production. It is important to note that Kharif season is mostly rainfed and directly impacted by any changes in rainfall and PET. Therefore, increase in rainfall during Kharif season may not be advantageous for agricultural production. As the Rabi season is mostly irrigated agriculture, changes in rainfall and PET could impact production indirectly. For example, increase in PET during the Rabi season indicates that irrigation demand is generally projected to be higher under future climate [18].

5. Conclusions

This study provides an assessment of future changes on rainfall and PET in the northwest region of Bangladesh over the period of 2045–2075 for the RCP4.5 and RCP8.5 emission scenarios. The study was conducted using results from 28 GCMs, based on IPCC's 5th assessment report. It describes a step by step procedure to regionalize best performing GCMs instead of selecting a different GCM for individual grids. The scenario modelling combining rainfall and PET is an efficient way to capture the uncertainty in future climate projections particularly for agricultural impact assessment. The method captures the uncertainties in projections in a consistent way across the region. The algorithm developed here is applicable to any region. However, if the area is very large and hydroclimate varies largely across the region, it is recommended to divide the area into several sub-zones instead of a single zone.

Increases in rainfall are generally projected in the northwest region of Bangladesh, with some projections showing decreases. Almost all projections show increases in PET. Although increases in annual rainfall and PET are projected, there may be decreases in some months. Therefore, it is recommended to use monthly scaling factors for the studies on extreme events, such as floods and droughts, while annual scaling factor may suffice for long term impact assessment. This study also investigated the impacts on rainfall and PET during two major cropping seasons in Bangladesh (Kharif and Rabi), and found an increase in rainfall and PET for both seasons. At annual scale, the increase in rainfall is greater than the increase in PET for the Kharif season, but less for the Rabi season. While, at monthly scale, a reduction in rainfall was projected for December and January and in PET for July, no reduction was found at a seasonal scale (i.e., Kharif/Rabi). The findings are useful to quantify the impacts on streamflow and its subsequent impact on groundwater, which is the major source of water for irrigated crops. This information is crucial for better adaptation under increased water demand for agricultural and domestic use.

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