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Climate Change Analysis for Bangladesh Using CMIP5 Models

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ABSTRACT: Using the Coupled Model Inter-comparison Project phase 5 (CMIP5) global climate modeling predictions, the study analyzes the distribution of rainfall and temperature in Bangladesh in recent years (1981–2005) and in three future periods (2025–2049, 2050–2074 and 2075–2099) considering RCP 4.5 and RCP 8.5 scenarios. In the historical period, all three CMIP5 models (MPI-ESM-LR, MPI-ESM-MR and NorESM1-M) mostly underestimated the observed mean rainfall data collected from Bangladesh Meteorological Department (BMD), but for temperature the result is found almost similar between models and observation. The CMIP5 models simulation reveal biases in monthly mean rainfall and temperature over Bangladesh in the past, so bias-correction is performed for future data. Quantile mapping bias-correction reduces significant amount of biases from the projection data of rainfall and temperature. By the end of the twenty-first century, the multi-model ensemble annual mean rainfall averaged over Bangladesh is projected to change between -2% to 9% and -3% to 15% under RCP 4.5 and RCP 8.5, respectively. The changes in spatial patterns of annual rainfall indicate a decrease in rainfall over a major portion in the west and the northwestern and an increase in the southeast, east, and the northeastern part of the country. The multi-model ensemble projection reveals a continuous increase in the annual mean temperature and shows a larger increase over the northwestern part and west-central part of Bangladesh. By the end of the twenty-first century, the annual mean temperature over Bangladesh is projected to increase by 1.9 (0.9-2.8) °C and 4 (2.8-4.6) °C under the RCP 4.5 and RCP 8.5 scenarios respectively, relative to the reference climate (1981-2005).

Keywords: Climate change, Rainfall, Temperature, CMIP5, RCP

INTRODUCTION

Bangladesh is counted as one of the top most nations vulnerable to the impacts of climate change (Harmeling, 2008). The Intergovernmental Panel on Climate Change (IPCC) has also termed Bangladesh as one of the most vulnerable countries in the world because of climate change (IPCC, 2007). It has been predicted that because of climate change, there will be a gradual increase of temperature and change in rainfall pattern in Bangladesh which might have variety of implications in agriculture, water resources and public health (Karim et al., 1999; Fung et al., 2006; Shahid, 2009). In Bangladesh, due to lack of detailed study on climate projections and the variability of climate changes, its impact on natural disasters and economy is poorly understood.

The study of global climate change has been ongoing for several decades already. Climate change studies can be analyzed from different aspects such as causes and effects of global warming, variations of temperatures and rainfall, and the earth atmosphere system. Currently some of the climatic parameters and their potential future changes are evaluated in an ensemble of the 5th Phase of Coupled Model Inter-comparison Project. Though the Coupled Model Inter-comparison Project Phase 6 (CMIP6) is the most current and extensive of the CMIPs but because of the availability of data the Coupled Model Inter-comparison Project Phase 5 (CMIP5) is used widely till now. The 5th Phase of Coupled Model Inter-comparison Project which is known as CMIP5 is a widely used standard experimental protocol for analyzing the output of coupled atmosphere-ocean general circulation models (AOGCMs). The CMIP5 which is coordinated by the World Climate Research Program (WCRP) has produced a multi-model dataset designed to develop our knowledge of climate, its variability and change through the application of the models of global climate system (Taylor et al. 2012). The CMIP5 GCMs provide simulations of the longer term climate forced with various scenarios for “radiative forcing”, or the energy imbalance of the climate system due to changing greenhouse gas and aerosol concentrations in the atmosphere. These scenarios are called Representative Concentration Pathways (RCPs) (Moss et al. 2010; Van Vuuren et al. 2014).

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RCP is a set of greenhouse gas concentration and emissions pathways designed to support research on impacts and potential policy responses to global climate change (Moss et al., 2010; Van Vuuren et al., 2011). In the 5th Assessment Report (AR5) of IPCC, four RCPs are normally used as a basis for future climate modeling: (i) RCP 2.6, (ii) RCP 4.5, (iii) RCP 6 and (iv) RCP 8.5. RCP 2.6 is a mitigated scenario and it is a "very stringent" pathway. In RCP 2.6 radiative forcing reaches a value around 3 Wm^{-2} in mid-century, returning to 2.6 Wm^{-2} by 2100 (Van Vuuren et al., 2007). RCP 4.5 is known as a medium stabilization scenarios and emissions in RCP 4.5 peak around 2040, then decline. In RCP 4.5 radiative forcing is stabilized at approximately 4.5 Wm^{-2} before 2100 (Clarke et al., 2007; Wise et al., 2009; Smith and Wigley, 2006). RCP 6 is also a medium stabilization scenarios and emissions in RCP 6 peak around 2060, then decline. In RCP 6 radiative forcing is stabilized at approximately 6.0 Wm^{-2} after 2100 (Hijioka et al., 2008; Fujino et al., 2006). RCP 8.5 is a very high baseline emission scenario in which radiative forcing reaches greater than 8.5 Wm^{-2} by 2100 and emissions in RCP 8.5 continues to rise throughout the 21st century (Riahi et al., 2007).

In this research, an attempt has been taken to build an algorithm for future climate projections using Coupled Model Inter-comparison Project Phase 5 under different RCP scenarios for analyzing the climate change of Bangladesh. The main aim of this study is to determine and correct the bias of the CMIP5 GCM models output through suitable methods and to analyze the changing behaviour of rainfall and temperature over Bangladesh up to twenty-first century using CMIP5 GCM models.

DATA, MODEL AND METHODOLOGY

Data and Model

This research investigation has been carried based on observational and secondary data collected from different sources. Observational data are given huge importance in the research. Observed data of temperature and rainfall are collected from Bangladesh Meteorological Department (BMD). For this study purpose, data of temperature and rainfall are being collected for 34 stations of BMD during the period 1981-2019. The downscaled CMIP5 GCM models data are downloaded from CCCR-(Centre for Climate Change Research) FTP Server (ftp:// cccr.tropmet. res.in/ FTP Server/ NEX-INDOUS_ Data/) which is regional data portals for CORDEX (Coordinated Regional Downscaling Experiment) South Asia. This dataset are also known as NEX-GDDP India. The format of the dataset is NetCDF and the spatial resolution of the dataset downloaded from CCCR is 0.25 degrees (~25 km x 25 km). Data are downloaded for both historical (1950-2005) and future (different RCPs, 2006-2099) simulations.

Among the four RCPs adopted by IPCC, high adaptation measures is the key assumptions of RCP 2.6 (van Vuuren et al., 2010). As robust, realistic climate change scenarios need to be developed to facilitate the planning of adaptation measures, RCP 2.6 is not included for the climate model ensemble. This leaves the selection between RCP 4.5, RCP 6 and RCP 8.5. The best choice in that case is to include RCP 4.5 and RCP 8.5, thus including one medium stabilization scenario and the high emission scenario, and covering the entire range of radiative forcing resulting from RCP 4.5, RCP 6 and RCP 8.5. For this reason only RCP 4.5 and RCP 8.5 are included in this research. In this research on the basis of same ensemble member from the models available at CORDEX for South Asia first 3 models are selected. All the GCM runs for the ensemble member r1i1p1. These 3 models are: (i) MPI-ESM-LR (ii) MPI-ESM-MR and (iii) NorESM1-M.

Methodology

This study was conducted on 34 meteorological stations in Bangladesh. These 34 stations are divided into six regions (Figure 1) for the study purpose.

At first the differences between model and observed averages and trends are compared and the performance of the CMIP5 models over Bangladesh are examined in the past climate (1981–2005) against the BMD observations. For this purpose, the temperature and rainfall biases are also computed for the 3 CMIP5 models. In the analysis of historical period monthly, seasonal and annual model averages and trends are compared with observed averages and trends for temperature and rainfall during the same period of 1981-2005, as consistence observation are available during this period. For better understanding analysis period has been divided into two time slices as follows- (i) the period of 1950-2005 has been defined as P1 and (ii) the period of 1981-2005 has been defined as P2.

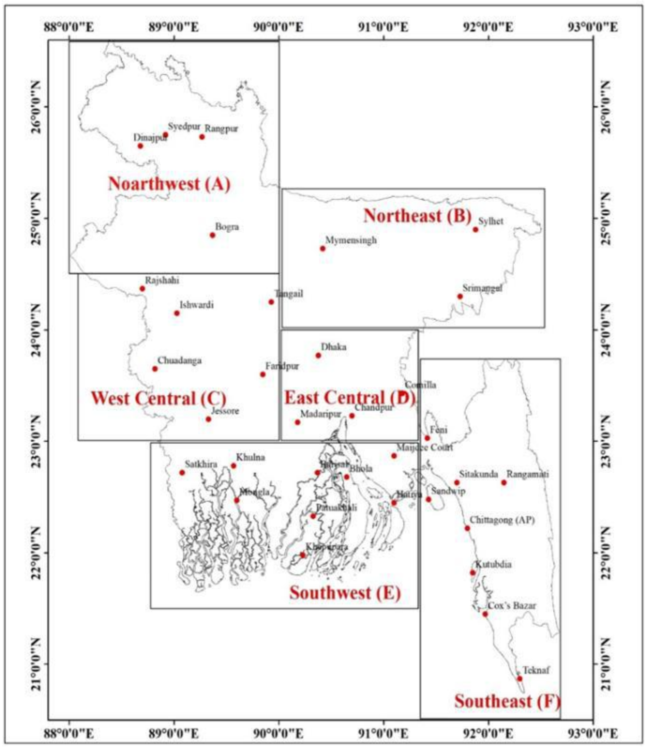


Figure 1: Map of the Study Area Showing Different Regions Along with BMD Stations

Source: Bangladesh Meteorological Department (BMD)

Then bias of the historical GCM outputs are calculated and the bias of the future GCM outputs are corrected. RMSE of historical GCM outputs are also calculated to indicate the absolute fit of the model to the data that means how close the observed data are to the model's predicted values. Lower values of RMSE indicate better fit. Bias and RMSE are calculated using "R" programming and "Python" programming is used for bias correction. Bias and RMSE are calculated using the equations-

$$Bias = \frac{\sum_{i=1}^{n}(Oi-Pi)}{n} \quad \text{......................................} (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Pi-Oi)^2}{n}} \quad \text{...............................} (2)$$

Where, Pi and Oi are the simulation and observed data, respectively, and n is the length of the distribution of the data point being analyzed.

Furthermore, based on the baseline period (1981–2005), both area to area and grid to grid bias correction is attempted for the future period (2006-2099). From the different methods of bias correction the common Simple Quantile Mapping (SQM) method is used for both rainfall and temperature. The differences between the observed and simulated cumulative distribution functions (CDFs) for the historical period were quantified and then applied to the future simulations for a given percentile. The following equation (3) (Kamruzzaman et al., 2019) is used for bias-correction-

$$X'_p(t) = Xp(t) + F^{-1}_{obs}\left(F_{p.sim}\left(X_p(t)\right)\right) - F^{-1}_{r.sim}(F_{p.sim}\left(X_p(t)\right)) \quad \text{......................................} (3)$$

Where $X'_p(t)$ and $Xp(t)$ denote the bias-corrected and raw future projections on month t, and F (θ) and $F^{-1}(\theta)$ are a CDF of the monthly data θ and its inverse, respectively. The subscripts p.sim, r.sim, and obs indicate the future projection, retrospective simulation, and observed monthly data, respectively.

The future data of temperature and rainfall are analyzed over three distinct time periods with respect to the baseline period (1981-2005) which are: (i) the near-future period: 2025–2049; (ii) the mid-future period: 2050–2074 and (iii) the far-future period: 2075–2099.

In the analysis part all the three models are also analyzed individually besides the multi-model ensemble and conclusions are made based on the multi-model ensemble. The reason behind that is to make a comparison between the results of those three CMIP5 GCM models.

RESULTS AND ANALYSIS

Historical Behavior of Rainfall and Temperature of Bangladesh

Multi-model Ensemble Monthly, Seasonal and Annual Rainfall over Bangladesh

Model average annual rainfall during 1950-2005 (defined as P1) over Bangladesh was 2237.5 mm and its trend was +0.79 mm/10yr. But it was 2230.6 mm during 1981-2005 (defined as P2) and its trend was -1.81 mm/10yr which was below the station average during the same period. The station average during P2 was 2489.7 mm and its trend was -1.85 mm/10yr. The monthly and seasonal variation of multi-model ensemble rainfall over Bangladesh is depicted in Figure 2.

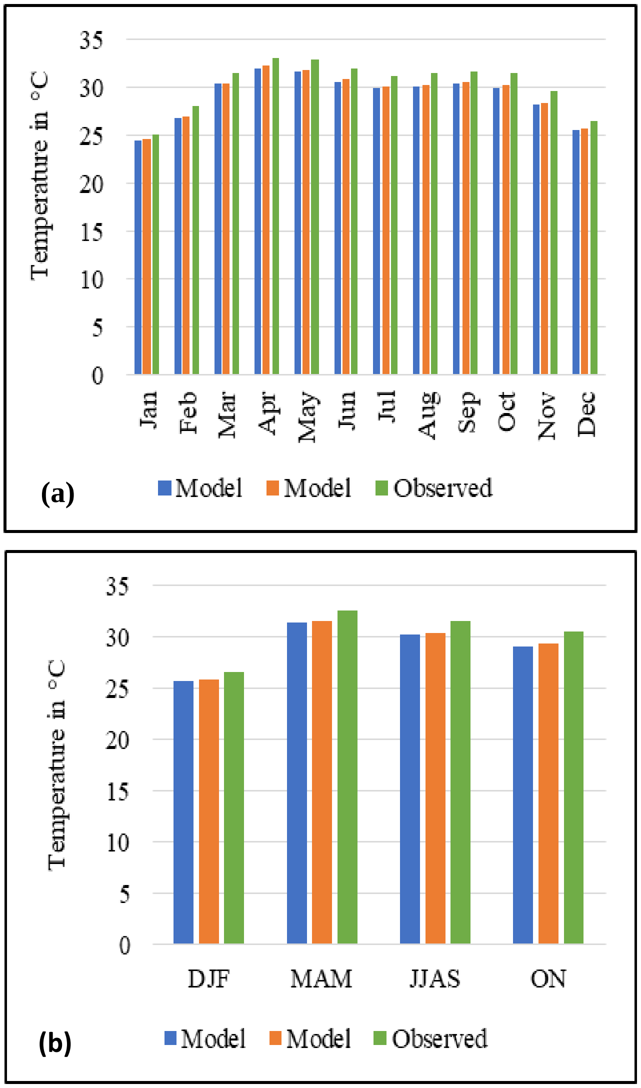


Figure 2: Multi-model Ensemble Variation of (a) Monthly Average and (b) Seasonal Average Rainfall over Bangladesh

Multi-model Ensemble Monthly, Seasonal and Annual Maximum Temperature over Bangladesh

Model average annual maximum temperature during 1950-2005 (defined as P1) over Bangladesh was 29.2 °C and its trend was +0.08 °C /10yr. But it was 29.4 °C during 1981-2005 (defined as P2) and its trend was +0.17 °C /10 yr which was below the station average during the same period. The station average during P2 was 30.5 °C and its trend was +0.25 °C /10yr. The monthly and seasonal variation of multi-model ensemble maximum temperature over Bangladesh is depicted in Figure 3.

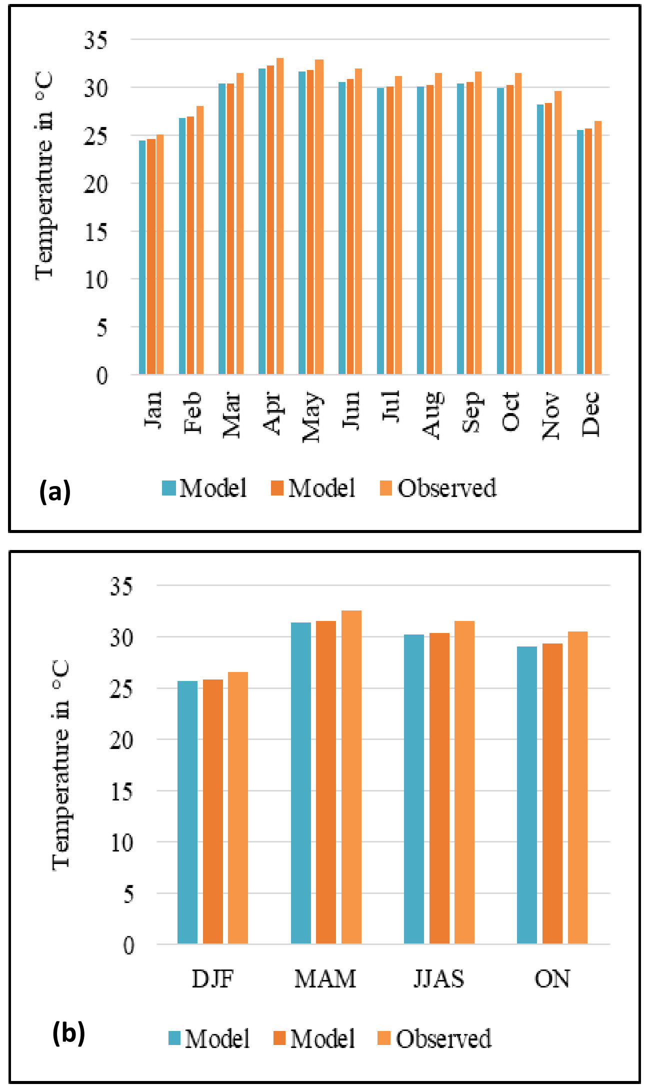


Figure 3: Multi-model Ensemble Variation of (a) Monthly Average and (b) Seasonal Average Maximum Temperature over Bangladesh

Multi-model Ensemble Monthly, Seasonal and Annual Minimum Temperature over Bangladesh

Model average annual minimum temperature during 1950-2005 (defined as P1) over Bangladesh was 20.5 °C and its trend was +0.11 °C /10yr. But it was 20.7 °C during 1981-2005 (defined as P2) and its trend was +0.21 °C /10yr which was below the station average during the same period. The station average during P2 was 21.2 °C and its trend was +0.18 °C/10yr. The monthly and seasonal variation of multi-model ensemble minimum temperature over Bangladesh is depicted in Figure 4.

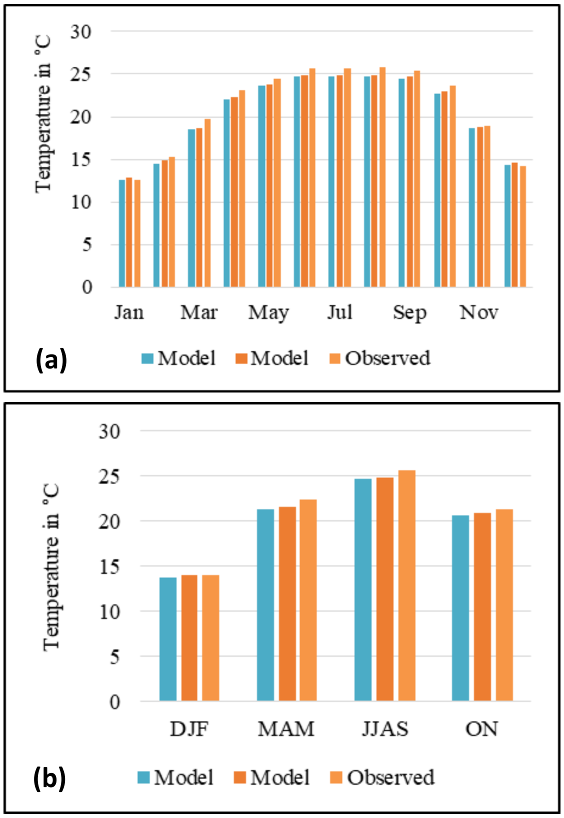


Figure 4: Multi-model Ensemble Variation of (a) Monthly Average and (b) Seasonal Average Minimum Temperature over Bangladesh

Model Performance and Bias-Correction

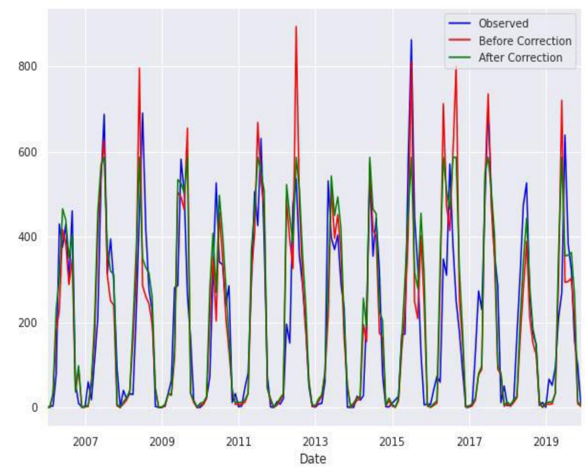
Before starting the bias-correction process the bias and RMSE of the models data are calculated to estimate the models accuracy. The values are depicted in Table 1.

Table 1: Bias and RMSE of the Monthly data of the Selected Models

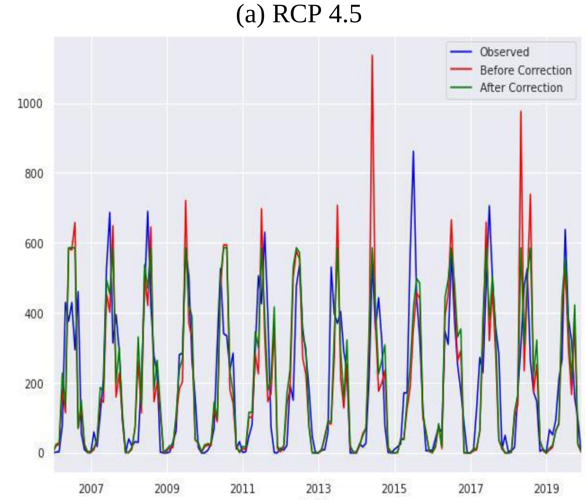
Variable	Model	RMSE	Bias
Rainfall (pr)	MPI-ESM-LR	142.43 mm	20.05 mm
Rainfall (pr)	MPI-ESM-MR	144.23 mm	21.17 mm
Rainfall (pr)	NorESM1-M	145.14 mm	23.56 mm
Maximum Temperature (tasmax)	MPI-ESM-LR	1.58 °C	1.02 °C
Maximum Temperature (tasmax)	MPI-ESM-MR	1.50 °C	0.99 °C
Maximum Temperature (tasmax)	NorESM1-M	1.68 °C	1.17 °C
Minimum Temperature (tasmin)	MPI-ESM-LR	1.15 °C	0.48 °C
Minimum Temperature (tasmin)	MPI-ESM-MR	1.13 °C	0.51 °C
Minimum Temperature (tasmin)	NorESM1-M	1.18 °C	0.65 °C

Table 1 shows that significant biases exist in the data and RMSE values indicate lower fit as well. Also from the previous section of historical period analysis, this study found that there are major differences in some cases in the trend analysis between observed and model data. For all these reasons attempt has been taken to bias-correct the future data.

Simple Quantile Mapping technique is used in this research that works thorough Empirical Quantile Mapping. In this process based on the baseline period (1981–2005), bias correction was applied for the future period (2006-2099). Here the evaluation of bias-correction is shown for the period during 2006-2019 as the projection data of GCM models start from 2006 and observed data are available till 2019 at the time of this research.



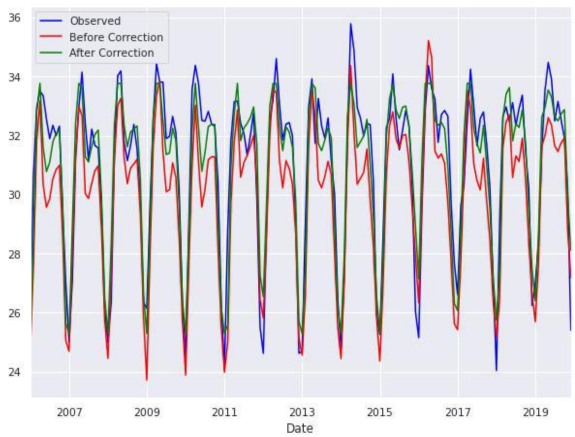
(a) RCP 4.5



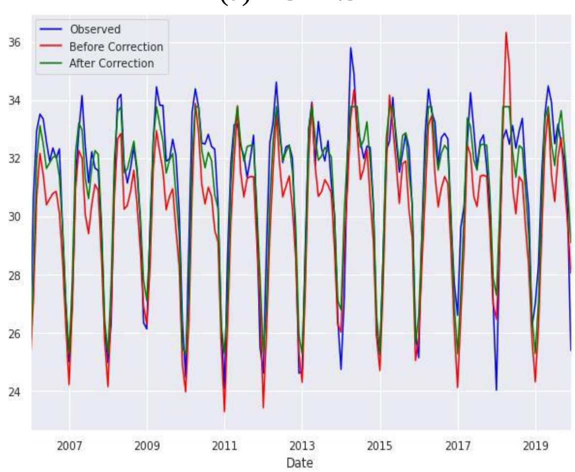
(b) RCP 8.5

Figure 5: Evaluation of Bias-corrected Monthly Rainfall

Figure 5 shows that Quantile Mapping bias-correction reduces significant amount of biases from all the models for rainfall. The correction is highly visible in the rainfall data as the values of bias and RMSE were higher for rainfall (Table 1). The lines between the observation and the after correction are much closer than the observation and the before correction in almost all the cases.

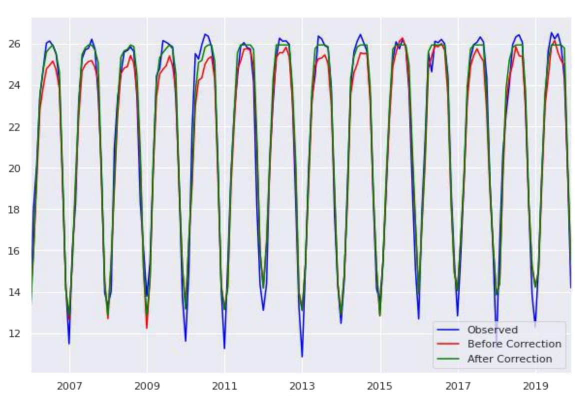


(a) RCP 4.5

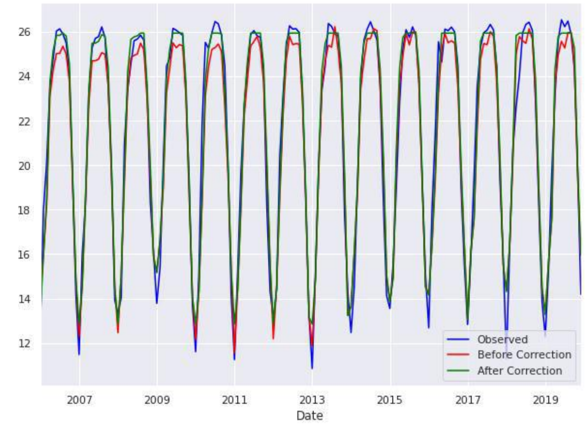


(b) RCP 8.5

Figure 6: Evaluation of Bias-corrected Monthly Maximum Temperature



(a) RCP 4.5



(b) RCP 8.5

Figure 7: Evaluation of Bias-corrected Monthly Minimum Temperature

Though the amount of biases are lower for temperature but the lines between the observation and the after correction are closer than the observation and the before correction (Figure 6 and 7). So, Quantile Mapping bias-correction also reduces biases from all the models for temperature data.

FUTURE CLIMATE SCENARIOS FOR BANGLADESH

Projected Annual Rainfall

The spatial distribution of multi-model ensemble projected annual mean rainfall for three future time slices under two RCP is shown in Figure 8. The spatial pattern of projected rainfall is highest in the northeastern part of Bangladesh under all future scenarios. For the near-future period, the annual mean rainfall averaged over Bangladesh is projected 2585 mm and 2811 mm under RCP 4.5 and RCP 8.5 respectively (Figure 8, left panels). For the mid-future period, the annual mean rainfall is projected 2638 mm and 2548 mm under RCP 4.5 and RCP 8.5 respectively (Figure 8, middle panels). The projected rainfall is highest over the southeastern part and lowest over west-central part of Bangladesh. For the far-future period, the annual mean rainfall over Bangladesh is projected 2400 mm and 2702 mm under RCP 4.5 and RCP 8.5 respectively (Figure 8, right panels). The projected rainfall is lowest over the west-central part of Bangladesh. The projected rainfall shows rapid decrease with time over Bangladesh under both the two different future scenarios (Figure 8).

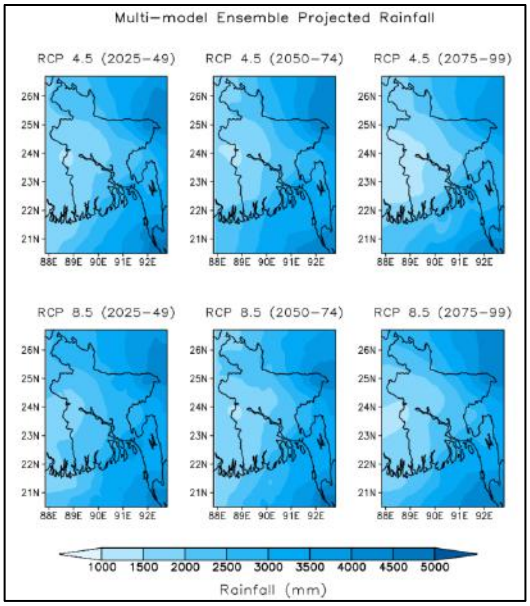


Figure 8: Multi-model Ensemble Projected Annual Mean Rainfall for three Future Periods (2025–49), (2050–74) and (2075-99) Under the Two RCP Scenarios (RCP 4.5 and RCP 8.5) Over Bangladesh

The projected annual rainfall shows a slightly increasing trend with time over under both the two different future scenarios and all the models shows highest amount rainfall over the northeastern and southeastern parts and lowest rainfall over west-central and northwestern parts of Bangladesh while analyzed individually.

Projected Annual Maximum Temperature

The spatial distribution of multi-model ensemble projected annual mean maximum temperature for three future time slices under two RCP is shown in figure 9. The spatial pattern of projected temperature shows a larger increase in the western part of Bangladesh under all future scenarios. For the near-future period, the annual mean maximum temperature averaged over Bangladesh is projected 29.9 °C and 30.2 °C under RCP 4.5 and RCP 8.5 respectively (Figure 9, left panels). The projected temperature is highest over the western part and lowest over the northeastern and southeastern parts of Bangladesh. The projected annual mean temperature over the region increases as the time progresses. For the mid-future period, the annual mean maximum temperature is projected 30.9 °C and 31 °C under RCP 4.5 and RCP 8.5 respectively (Figure 9, middle panels). For the far-future period, the annual mean maximum temperature over Bangladesh is projected 31.9 °C and 32.6 °C under RCP 4.5 and RCP 8.5 respectively (Figure 9, right panels). The projected temperature is highest over the west-central part of Bangladesh. The projected temperature shows a continuous increase with time over Bangladesh under both the two different future scenarios (Figure 9).

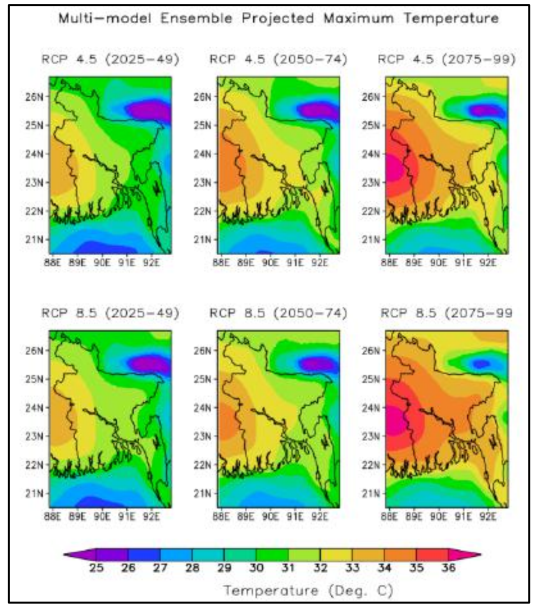


Figure 9: Multi-model Ensemble Projected Annual Mean Maximum Temperature for Three Future Periods (2025–49), (2050–74) and (2075-99) Under the Two RCP Scenarios (RCP 4.5 and RCP 8.5) Over Bangladesh

Projected Annual Minimum Temperature

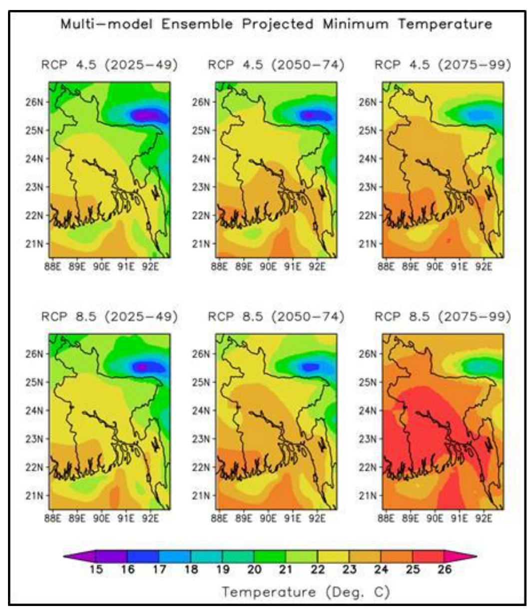


Figure 10: Multi-model Ensemble Projected Annual Mean Minimum Temperature for Three Future Periods (2025–49), (2050–74) and (2075-99) Under the Two RCP Scenarios (RCP 4.5 and RCP 8.5) Over Bangladesh

The spatial distribution multi-model ensemble projected annual mean maximum temperature for three future time slices under two RCP is shown in Figure 10. The spatial pattern of projected temperature shows a larger increase in the western part of Bangladesh under all future scenarios. For the near-future period, the annual mean minimum temperature averaged over Bangladesh is projected 21.5 °C and 21.8 °C under RCP 4.5 and RCP 8.5 respectively (Figure 10, left panels). For the mid-future period, the annual mean minimum temperature is projected 22.1 °C and 22.5 °C under RCP 4.5 and RCP 8.5 respectively (Figure 10, middle panels). The projected temperature is highest over the southern part of Bangladesh. For the far-future period, the annual mean minimum temperature over Bangladesh is projected 22.9 °C and 24.1 °C under RCP 4.5 and RCP 8.5 respectively (Figure 10, right panels). The projected temperature is highest over the southern and central part of Bangladesh.

The projected annual temperature also shows a continuous increase with time over Bangladesh while analyzed individually and temperatures under RCP 8.5 are much warmer than RCP 4.5 for all the models under both the two different future scenarios.

Future Changes in Rainfall on the Annual Scale

The spatial distribution of multi-model ensemble projected changes in annual mean rainfall for three future time slices under two RCP scenarios is shown in Figure 11. For the near-future period, the projected annual mean rainfall over Bangladesh shows changes between -2% to 7% and 0% to 8% under RCP 4.5 and RCP 8.5 respectively (Figure 11, left panels). For the mid-future period, the projected annual mean rainfall shows changes between 0% to 8% and -3% to 9% over Bangladesh under RCP 4.5 and RCP 8.5 respectively (Figure 11, middle panels). The projected rainfall decreases mostly over the northwestern part of Bangladesh. The rest of the regions shows a consistent change during the mid-future period under all the two scenarios. On the other hand, during the far-future period, the annual mean rainfall shows changes between 0% to 9% and -1% to 15% under RCP 4.5 and RCP 8.5 respectively, with respect to the reference period (Figure 11, right panels). The largest changes in annual mean rainfall is projected in the far-future period under RCP 8.5.

So, the projected annual rainfall can increase up to 15% and can decrease up to 3% in different regions compared to present climate and by the end of the twenty-first century, the area-averaged annual mean rainfall over Bangladesh is projected to increase up to 9% and 15% under RCP 4.5 and RCP 8.5, respectively.

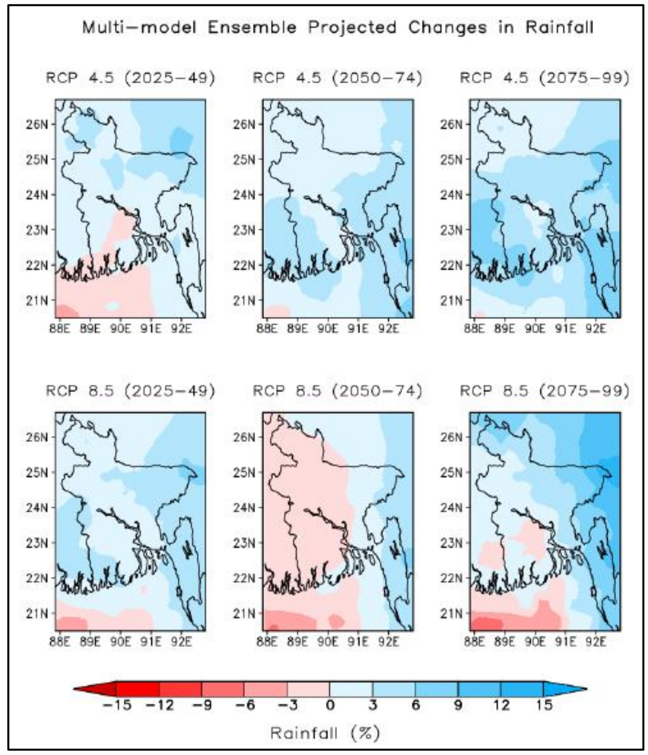


Figure 11: Multi-model Ensemble Projected Changes in Rainfall (%) in Relation to the Reference Period (1981–2005) for Three Future Periods (2025–49), (2050–74) and (2075-99) under the two RCP Scenarios (RCP 4.5 and RCP 8.5) Over Bangladesh.

Future Changes in Maximum Temperature on the Annual Scale

The spatial distribution of multi-model ensemble projected changes in annual mean maximum temperature for three future time slices under two RCP scenarios is shown in Figure 12. The spatial pattern of projected temperature shows a larger increase in the northern parts of Bangladesh under all future scenarios. For the near-future period, the annual mean maximum temperature averaged over Bangladesh is projected to increase by 1.3 °C and 1.4 °C under RCP 4.5 and RCP 8.5 respectively (Figure 12, left panels). The projected temperature changes are largest over the northwestern part of Bangladesh. The projected annual mean temperature over the region increases as the time progresses. For the mid-future period, the annual mean maximum temperature is projected to increase by 1.9 °C and 2.8 °C under RCP 4.5 and RCP 8.5 respectively

(Figure 12, middle panels). In the case of the far-future period, the annual mean maximum temperature over Bangladesh is projected to increase by 2.1 °C and 4.0 °C under RCP 4.5 and RCP 8.5 respectively (Figure 15, right panels). The projected temperature shows a continuous increase under both the two different future scenarios (Figure 12).

So, the projected annual maximum temperature shows continuous increase in all the parts of Bangladesh and this increase can be up to 5 °C (varying from 0.5°C to 6°C for individual models) compared to the reference period.

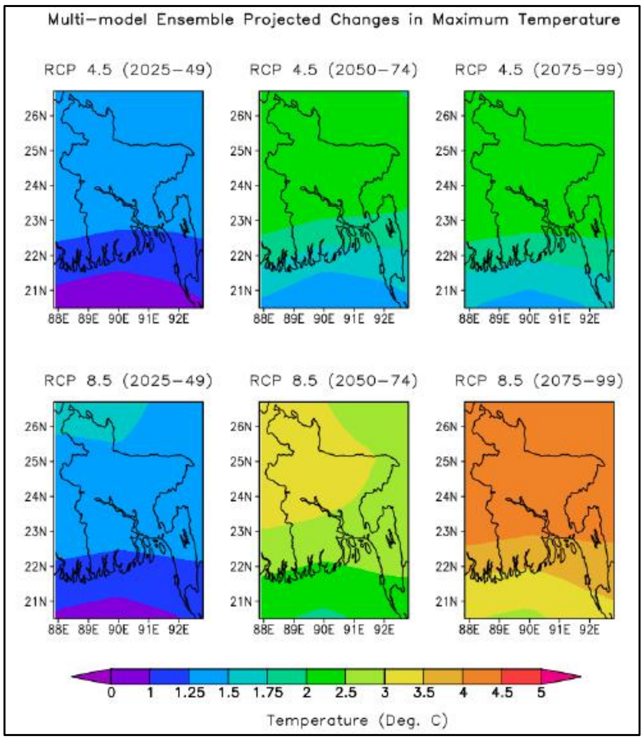


Figure 12: Multi-model Ensemble Projected Changes in Maximum Temperature (°C) in Relation to the Reference Period (1981–2005) for Three Future Periods (2025–49), (2050–74) and (2075-99) Under the Two RCP Scenarios (RCP 4.5 and RCP 8.5) Over Bangladesh

Future Changes in Minimum Temperature on the Annual Scale

The spatial distribution of multi-model ensemble projected changes in annual mean minimum temperature for three future time slices under two RCP scenarios is shown in Figure 13. For the near-future period, the annual mean minimum temperature averaged over Bangladesh is projected to increase by 1.3 °C and 1.4 °C under RCP 4.5 and RCP 8.5 respectively (Figure 13, left panels). The projected annual mean temperature over the region increases as the time progresses. For the mid-future period, the annual mean minimum temperature is projected to increase by 1.7 °C and 2.8 °C under RCP 4.5 and RCP 8.5 respectively (Figure 13, middle panels). In the case of the far-future period, the annual mean minimum temperature over Bangladesh is projected to increase by 1.9 °C and 4.0 °C under RCP 4.5, and RCP 8.5 respectively (Figure 13, right panels). The projected temperature shows a continuous increase over Bangladesh under both the two different future scenarios (Figure 13). The projected temperature changes are largest over the northwestern part of Bangladesh under RCP 8.5.

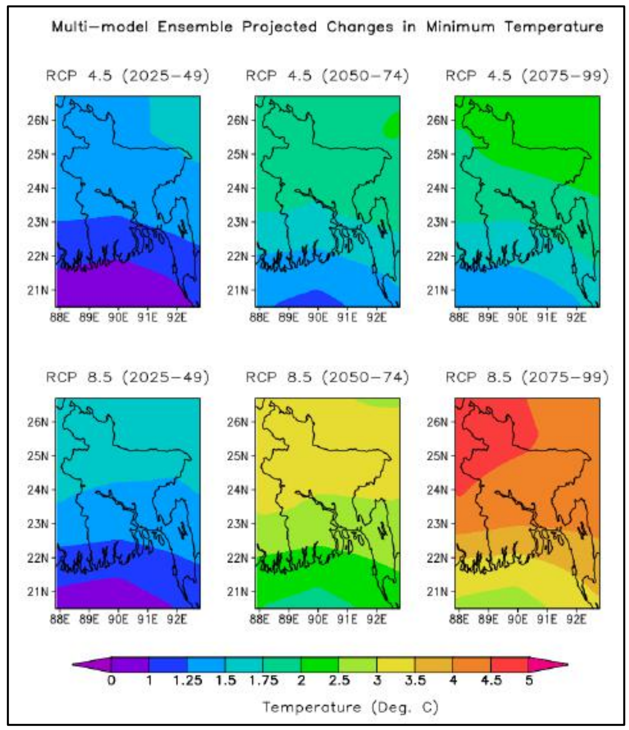


Figure 13: Multi-model ensemble projected changes in minimum temperature (°C) in relation to the reference period (1981–2005) for three future periods (2025–49), (2050–74) and (2075-99) under the two RCP scenarios (RCP 4.5 and RCP 8.5) over Bangladesh.

So, the projected annual minimum temperature also shows continuous increase in all the parts of Bangladesh and this increase can be up to 5 °C (varying from 0.5°C to 6°C for individual models) compared to the reference period.

DISCUSSION AND CONCLUSION

This study assessed the performance of three GCMs from CMIP5 to reproduce the current temperature and rainfall and analyze the future changes based on different RCP scenarios in six different parts of Bangladesh.

The results of the analysis of historical period mostly show underestimation with observed data especially during the monsoon months in terms of rainfall, but for temperature the result is found almost similar between models and observation. From this differences in historical period attempt has been taken for bias-correction of future data using quantile mapping method and the results of bias-correction are quite satisfactory. Quantile mapping bias-correction reduces significant amount of biases from the projection data of rainfall and temperature. The correction is highly noticeable in the rainfall data as the values of bias and RMSE were higher for rainfall (Table 1) and the analysis of historical period also shows major dissimilarity between model and observation for rainfall. These findings were almost similarly discussed in the previous studies by Kamruzzaman et al. (2019) and Shahid (2010).

This research finds that annual rainfall in Bangladesh would change in the range of -20% to 20% for different models. The rainfall over the country is expected to increase during 2075–2099 for all the scenarios. By the end of the twenty-first century, the multi-model ensemble annual mean rainfall averaged over Bangladesh is projected to change between -2% to 9% and -3% to 15% under RCP 4.5 and RCP 8.5, respectively. The changes in spatial patterns of annual rainfall indicate a decrease in rainfall over a major portion in the west and the northwestern, and an increase in the southeast, east, and the northeastern of the country. With slight variations in the projected magnitudes, the results of this research are generally in agreement with some previous studies (e.g. Chaturvedi et al. 2012 Caesar et al. 2015; Fahad et al. 2018; NCHM, 2019; MoFE, 2019).

The multi-model ensemble from three CMIP5 models reveals a continuous increase in the annual mean temperature over Bangladesh during the twenty-first century under two RCP scenarios (i.e., RCP 4.5 and RCP 8.5). The northwestern parts and the west central parts of Bangladesh are projected to experience the largest increase in future temperature (exceeding 5 °C; Figure 15-22) by the end of the twenty-first century under RCP 8.5 relative to the reference climate (1981–2005). By the end of the twenty-first century, the annual mean maximum temperature averaged over Bangladesh is projected to increase by 1.9 °C and 4.0 °C under RCP 4.5, and RCP 8.5 scenarios, respectively. Similarly, the annual mean minimum temperature averaged over Bangladesh is projected to increase by 2.1 °C and 4.0 °C under RCP 4.5, and RCP 8.5 scenarios, respectively by the end of the century. The country-averaged annual mean temperatures also show a robust increases relative to the reference climate under all emission scenarios (Figure 12 and 13).

In the case of the far-future period, the results of this research finds that the annual mean temperature over Bangladesh will increase by 2.8 to 4.6 °C under RCP 8.5 which is quite similar with some previous studies. Though the climate change projections based on a multi-model ensemble from global climate models are almost missing over Bangladesh, a few previous studies used climate models to describe the rainfall and temperature changes over Bangladesh. In the study of Caesar et al., (2015), 17-member perturbed physics ensemble of projections was used from a global climate model to drive their regional climate model over South Asia from 1971 to 2099. This study found an increase in annual mean temperature from 2.6 to 4.8 °C by 2100, relative to the reference period. Alamgir et al. (2019) used eight CMIP5 GCMs to statistically downscale over Bangladesh and reported an increase in temperature by 2.7 to 4.7 °C under RCP 8.5 at the end of this century.

The results of this study indicate that the northwestern part of Bangladesh is highly vulnerable to climate change due to the large increase in the projected annual mean temperature. The enhanced future warming is likely to severely impact the irrigation patterns (Chaturvedi et al., 2014) and irregular rainfall may cause extreme summer flash floods over this region in the future. The results presented in this study should be useful for climate adaptation strategies for the different regions of Bangladesh. In addition to this, the results of the study can be useful for conducting climatological studies and climate change impact assessment over Bangladesh.

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