Summer monsoon rainfall scenario over Bangladesh using a high-resolution AGCM

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Abstract Summer monsoon rainfall was simulated by a global 20 km-mesh atmospheric general circulation model (AGCM), focusing on the changes in the summer monsoon rainfall of Bangladesh. Calibration and validation of AGCM were performed over Bangladesh for generating summer monsoon rainfall scenarios. The model-produced summer monsoon rainfall was calibrated with a ground-based observational data in Bangladesh during the period 1979–2003. The TRMM 3B43 V6 data are also used for understanding the model performance. The AGCM output obtained through validation process made it confident to be used for near future and future summer monsoon rainfall projection in Bangladesh. In the present-day (1979–2003) climate simulations, the high-resolution AGCM produces the summer monsoon rainfall better as a spatial distribution over SAARC region in comparison with TRMM but magnitude may be different. Summer monsoon

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rainfall projection for Bangladesh was experimentally obtained for near future and future during the period 2015–2034 and 2075–2099, respectively. This work reveals that summer monsoon rainfall simulated by a high-resolution AGCM is not directly applicable to application purpose. However, acceptable performance was obtained in estimating summer monsoon rainfall over Bangladesh after calibration and validation. This study predicts that in near future, summer monsoon rainfall on an average may decrease about −0.5 % during the period 2015–2034 and future summer monsoon rainfall may increase about 0.4 % during the period 2075–2099.

1 Introduction

Bangladesh is a small country having an area about 147,570 sq. km situated in the northeastern part of South Asia within 88.02–92.68°E and 20.57–26.63°N. The land of Bangladesh is very flat: Elevation is about 1–37 m above sea level except small portions in the southeast (elevation about 200 m) which is border with Myanmar and in the northeast (elevation about 100 m) which is border with Shillong hill of India.

Bangladesh being an agricultural country, rice is the main food and the success or failure of the crops and water scarcity in any year is always viewed with the greatest concern. A major portion of annual rainfall over Bangladesh is received during summer monsoon season (June–September). Summer monsoon is also known as southwest monsoon in Bangladesh as well as in South Asia. Summer monsoon rainfall contributes around 65–70 % of its annual rainfall over Bangladesh (Rahman 2006). Seasonal prediction of southwest monsoon or summer monsoon rainfall over Bangladesh has considerable application for decision-making in agriculture and water resource sectors. In addition, the summer monsoon season in Bangladesh is characterized by the occurrence of severe floods due to heavy rainfall causing extensive damage to crops, road, livestock, and properties associated with loss of valuable lives. Any change or variation in climate and climatic scenarios affecting the summer monsoon rainfall over Bangladesh as well as South Asia is considered to be direct threat for economy of Bangladesh. Thus, long-range prediction of summer monsoon rainfall becomes very important for the interest of the Bangladeshi farmers and policy-makers of the country.

Dynamical models are useful tools to generate seasonal forecasts. They are being used at major climate prediction centers for generating operational/semi-operational global long-range forecasts. Dynamical models are based on the mathematical equations governing the physics of the atmosphere and the oceans. The advantages of dynamical models are that they are more scientific and physically based and tend to capture the events in terms of their physical causes and effects. They are also able to handle unprecedented climate events, since the basic physics would apply equally well to novel situations as to familiar situations.

Summer monsoon rainfall forecast is a high priority in India and Bangladesh. Because an accurate forecast of monsoon performance averaged over the country as a whole is also very useful for better macro-level planning of finance, power, and water resources. There are many reviews on the Indian southwest monsoon rainfall (ISMR) (Normand 1953; Jagannathan 1960; Thapliyal and Kulshreshtha 1992; Hastenrath 1995; Krishna Kumar

et al. 1995; Rajeevan 2001; Gadgil et al. 2005). A little work is done on climate change scenarios for Bangladesh using regional climate model (Islam 2009). Kusunoki et al. (2006) indicated the realistic reproduction of Baiu (Japan) rain band needs an atmospheric model with higher horizontal resolution. They investigated the future change in the Baiu rain band with a 20-km-mesh global atmospheric model, using the time-slice method (Bengtsson et al. 1996) which prescribed sea surface temperature (SST) simulated by an atmosphere–ocean general circulation model (AOGCM). It is widely recognized that global warming projections include wide range of uncertainty arising from many factors such as differences in future emission scenario, model performance, and internal natural variability of climate system. Therefore, evaluation and quantitation of uncertainty in global warming projection is strongly required to obtain more robust and reliable information on future climate changes (IPCC 2007). Despite continuous model development, atmospheric general circulation models (AGCMs) still have systematic biases in simulating the East Asian summer monsoon rainfall such as an underestimate of precipitation amount over the western Pacific (Kang et al. 2002) and inappropriate temporal characteristics between precipitation and underlying sea surface temperature (Wang and Ho 2002). Recently, a very-high-resolution AGCM with the horizontal grid size of about 20 km has been developed by the Meteorological Research Institute/Japan Meteorological Agency use in climate change studies (Mizuta et al. 2006) and has been used for climate change projection under increases in atmospheric concentrations of greenhouse gases and aerosols (Kusunoki et al. 2006: Oouchi et al. 2006). The grid size of this model is several times smaller than that previously used in climate model simulations. The global 20 km model is a unique one in terms of the horizontal resolution as well as its application to long-term integration for global change studies. Due to the very high horizontal resolution, the model has more realistic representation of land–sea distribution and topography with elevated orography than other GCMs have ever had, so it is expected to have an ability to simulate rainfall and temperature over this region more adequately. Kitoh and Kusunoki (2008) have shown a good result of a global 20-km-mesh AGCM to simulate the East Asian summer monsoon climate in comparison with its lower resolution (180 km). This opportunity is employed for the first time in generating summer monsoon rainfall scenario by using high-resolution AGCM for Bangladesh.

In this paper, summer monsoon rainfall climatology in Bangladesh derived from 20 km AGCM was calibrated with the observed data for the period 1979–2003. Then, projections for summer monsoon rainfall are made during the period 2015–2034 and 2075–2099 in Bangladesh. It is mentioned here that the period 1979–2003 is assumed for training period for calibration, and the period 2003–2006 is used for validation purposes.

2 Model description, experimental design, and methodology

2.1 Model description

The AGCM used in this study is called MRI-AGCM which is jointly developed by the Japan Meteorological Agency (JMA) and the Meteorological Research Institute (MRI). The model is based on an operational numerical weather prediction model used at JMA. Some modifications were added in radiation and land surface processes as a climate model at MRI (Mizuta et al. 2006). The time integration was accelerated by introducing a semi-Lagrangian three-dimensional advection scheme (Yoshimura and Matsumura 2005). The model has a horizontal spectral truncation of TL959 corresponding to about a 20-km

horizontal grid spacing and has 60 levels with a 0.1 hPa (altitude of about 65 km) top. TL959 means that the model has a spectral triangular truncation of spherical function at wave number 959 with a linear grid for wave-to-grid transformation. The model has 1920 grids in longitude and 960 grids in latitude. A mere increase in the horizontal resolution was found to give rise to large model biases in precipitation and temperature, much less organization of convection, and suppression of tropical cyclone generation. Therefore, MRI scientists carefully tuned the model to improve the model's present-day climatology by changing the parameters in the evaporation process, cloud water content diagnosis, vertical transport of horizontal momentum in cumulus, and gravity wave drag (Mizuta et al. 2006). Especially, overestimation of global average precipitation of the 20-km model was suppressed by decreasing the amount of detrainment of cloud water at the top of the cumulus, as well as decreasing transformation speed from cloud water to precipitation in the cloud scheme (Mizuta et al. 2006). The version of the 20-km model used in this study is slightly different from MRI-AGCM3.0 used in the previous studies (Kusunoki et al. 2006; Kusunoki and Mizuta 2008); in that, sea ice model and vegetation setting in land surface process are improved. For the cumulus parameterization, the Arakawa-Schubert scheme with prognostic closure is used (Randall and Pan 1993). The summary of the specifications of the 20-km model is given in Table 1.

2.2 Experimental design

High-resolution (20-km) AGCM experiments are conducted using the time-slice method (Bengtsson et al. 1996; IPCC 2001), which is a two-tier global warming projection using an atmosphere–ocean general circulation model (AOGCM) and an AGCM with horizontal resolution higher than that of the atmospheric part of the AOGCM. For present-day climate simulation, the 20-km model was integrated for 25 years from 1979 to 2003 (25 years) with the observed historical sea surface temperature (SST) and sea ice data of HadISST1 (Rayner et al. 2003). This simulation is equivalent to an Atmospheric Model Intercomparison Project (AMIP) type experiment for an atmospheric model, which is widely adopted in numerous modeling studies. For the near future climate simulation from 2015 to 2039 (25 years), changes in the multi-model ensemble (MME) of SSTs projected by

Table 1 The details specifications of the 20-km (AGCM) model are given below

| Items	Content
Basic equation	Hydrostatic, primitive
Horizontal structure	Spherical harmonics (latitude) and Fourier harmonics (Longitude)
Horizontal resolution	20 km, TL959
Vertical level	60, top at 0.1 hPa
Time integration	Semi-Lagrangian scheme, Yoshimura (2004)
Shortwave radiation	H_2O, O_3, CO_2, O_2, Aerosol, Shibata and Uchiyama (1992)
Longwave radiation	H_2O, O_3, CO_2, CH_4, N_2O, Shibata and Aoki (1989)
Cumulus convection	Prognostic of Arakawa-Schubert, Randal and Pan (1993)
Boundary layer	Mellor and Yamada (1974, 1982), level 2 closure
Gravity wave drag	Orographic origin, Iwasaki et al. (1989)
Cloud	Cumulus, Large-scale condensation
Precipitation process	Prognose cloud water content
Land surface	Simple Biosphere (SiB) model, Sato et al. (1989)

AOGCMs of Coupled Model Intercomparison Project 3 (CMIP3) are superposed to the detrended observed historical SST. It is mentioned here that the near future climate simulation data are used from 2015 to 2034 (20 years) due to lack of data. For the future climate simulations, the 20-km model was integrated for 25 years from 2075 to 2099 with future SSTs. The boundary SST data were prepared by superposing (a) future change in the multi-model ensemble (MME) of SST projected by Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model data set, (b) the linear trend in MME of SST projected by CMIP3 multi-model data set, and (c) the detrended observed SST anomalies for the period 1979–2003. Future change in MME of SST was evaluated by the difference between the 20th-century experiment of Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4; IPCC 2007) and future simulation under the Special Report on Emission Scenario (SRES) A1B emission scenario (IPCC 2000). Future sea ice distribution is obtained in a similar fashion. Details of the method are described in Mizuta et al. (2008).

2.3 Methodology

Observational data of Bangladesh Meteorological Department (BMD) have been used for validation of high-resolution AGCM generated summer monsoon rainfall during the period 1979–2003. Bangladesh is almost a flat country where the highest station elevation is 63 meters, located in the southeastern part of Bangladesh (Fig. 1). The BMD observation network density is very low. Many grids are found which contain no observation site when the whole Bangladesh is gridded at 20 km by 20 km in the model resolution. Since it is important to find the appropriate calibration method for the application of high-resolution AGCM for seasonal summer monsoon rainfall studies in Bangladesh, analyses have been carried out on point-to-point basis. In this procedure, observational data at a particular site are considered as the representative for that location (Islam and Uyeda 2007). Grid value of the model data is compared with the observed data representing that grid. If more than one observation site exist within a grid, the average value of all the observational sites within that grid is considered as representative value for that grid. Daily rain-gauge rainfall data collected from BMD are processed to obtain monthly and seasonal values. The model-simulated rainfall is extracted through GrADS for 28 sites of BMD (point value) and then is converted into monthly and seasonal values which are then averaged to obtain as a country average. Estimated rainfall is obtained by using a calibration method which is described in Sect. 3.3.

2.4 TRMM 3B43 rainfall

The Tropical Rainfall Measuring Mission (TRMM) is a joint U.S–Japan satellite mission to monitor tropical and subtropical precipitation and to estimate its associated latent heat. The rainfall measuring instruments on the TRMM satellite include the Precipitation Radar (PR), electronically scanning radar operating at 13.8 GHz; TRMM Microwave Imager (TMI), a nine-channel passive microwave radiometer; and Visible and Infrared Scanner (VIRS), a five-channel visible/infrared radiometer. The 3B43 algorithm is to produce the best-estimate precipitation rate and root-mean-square (RMS) error estimates at $0.25° \times 0.25°$ spatial resolution. Spatial coverage extends from 50°S to 50°N latitude. The 3B43 algorithm is to produce the TRMM and Other Data" best-estimate precipitation rate and root-mean-square (RMS) precipitation-error estimates. These gridded estimates are on a calendar month temporal resolution and a $0.25° \times 0.25°$ spatial resolution global band
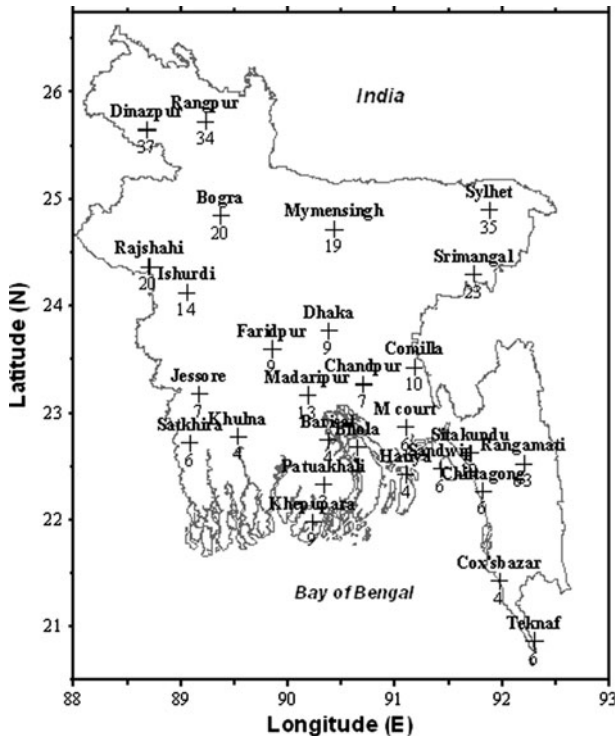
Fig. 1 *Plus marks* represents Bangladesh Meteorological Department rain-gauge locations and below *plus marks* represents elevation in meters

extending from 50°S to 50°N latitude. The 3B43 algorithm is executed once per calendar month to produce the single, best-estimate precipitation rate, and RMS precipitation-error estimate field (3B43) by combining the 3-hourly merged high-quality/IR estimates with the monthly accumulated Climate Assessment and Monitoring System (CAMS) or Global Precipitation Climatology Centre (GPCC) rain-gauge analysis (3A45).

3 Results and discussion

3.1 Simulation of summer monsoon rainfall over SAARC region

Summer monsoon rainfall is very much important for the SAARC region as it is used for agriculture and water management purposes in Bangladesh, India, Nepal, Bhutan, etc., where SAARC stands for South Asia Association for Regional Cooperation. Summer monsoon rainfall (mm/day) derived from high-resolution AGCM over the SAARC region is compared with TRMM V6 3B43 rainfall as shown in Fig. 2a, b. High-resolution AGCM-simulated summer monsoon rainfall (mm/d) averaged from June to September (JJAS) for the period 1979–2003 and TRMM 3B43 V6 (0.25° × 0.25°.) summer monsoon rainfall (mm/d) averaged from June to September for the period 1998–2010 are presented in Fig. 2a, b. Summer monsoon rainfall (mm/day) simulated by AGCM is found to be much more consistent with TRMM-observed rainfall. It is observed that most part of the
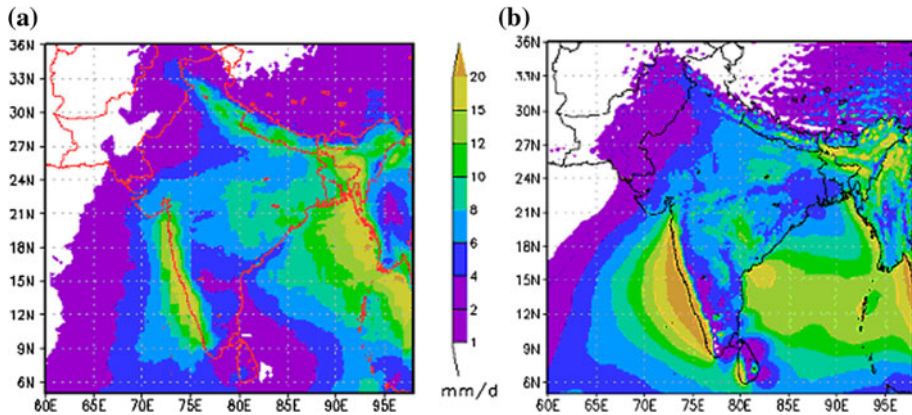
Fig. 2 a Summer monsoon rainfall (mm/day) obtained from TRMM V6 during the period 1998–2010.
b Summer monsoon rainfall (mm/day) obtained from high-resolution AGCM during the period 1979–2003

Afghanistan is below 1 mm/day rainfall, and western part of Pakistan showed zero rainfall and northwestern part of Pakistan showed 1–2 mm/day rainfall for summer monsoon season which are well captured by the AGCM. It is also indicated that heavy rainfall in the Western Ghat and less rainfall in the Eastern Ghat of India, southern part of Nepal, and northeastern part of Bangladesh are well simulated by the AGCM. But, amount is underestimated in some places over the region and overestimated around the Bay of Bengal. Model's high horizontal resolution enables us to simulate orographic rainfall as a maximum to the west of the Western Ghats in southern India and a southern periphery of the Himalaya range (Yatagai et al. 2005).

3.2 Inter-annual variation of summer monsoon rainfall over Bangladesh

The 20-km high horizontal resolution AGCM simulation in summer monsoon rainfall has been studied to evaluate the model skills in representing temporal variation during the period 1979–2003. It is seen that the summer monsoon rainfall (mm) of AGCM has underestimated for all years for the same period. The high-resolution AGCM summer monsoon rainfall (mm) has also shown constant bias during the period 1979–2003 (Fig. 3).

The average summer monsoon rainfall (JJAS) during the period 1979–2003 simulated by high-resolution AGCM is 1,033 mm with a standard deviation of 125 mm as shown in Table 2, whereas all-Bangladesh summer monsoon rainfall based on 28 rain-gauge stations averaged during the period 1979–2003 is 1,756 mm with a standard deviation of 207 mm. The model-simulated summer monsoon rainfall is underestimated with the all-Bangladesh summer monsoon rainfall; its variability is almost half with the observed values. During the month of June, July, August, and September, the AGCM-simulated rainfall is 365, 246, 212, and 210 mm with a standard deviation 101, 35, 28, and 36 mm, respectively. Similarly, observed summer monsoon rainfall is 484, 525, 427, and 321 mm with a standard deviation of 137, 113, 112, and 64 mm for June, July, August, and September, respectively (Table 2).

A summary of correlation and root-mean-square error (RMSE) between observed and model-simulated average summer monsoon rainfall in Bangladesh is shown in Table 2. During the month of June, July, August, and September, correlation between observed and model-simulated summer monsoon rainfall is found to be poor, which is not statistically
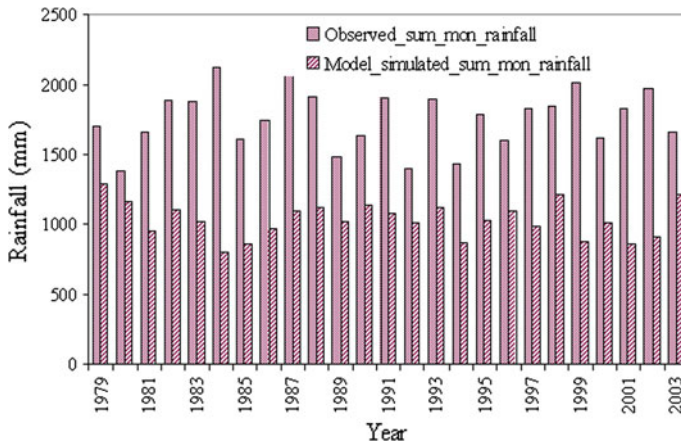
Fig. 3 Comparison between observed and model-simulated (uncalibrated) summer monsoon rainfall (mm) during the period 1979–2003

Table 2 Statistical characteristics of observed and model-simulated (uncalibrated) summer monsoon rainfall (mm) over Bangladesh during the period 1979–2003

	June	July	August	September	Monsoon (JJAS)
Model-uncalibrated summer monsoon rainfall (mm)					
Observed	484	525	427	321	1,756
Model	365	246	212	210	1,033
Model bias	120	279	214	110	723
Correlations	−0.25	0.19	−0.07	−0.17	−0.14
RMSE	221	299	243	135	765
Standard deviations					
Observed	137	113	112	64	207
Model	101	35	28	36	125

significance with RMSE of 221, 299, 243, and 135 mm for June, July, August, and September, respectively.

3.3 Calibration process of summer monsoon rainfall over Bangladesh

The 20-km high-resolution AGCM-simulated summer monsoon rainfall may have systematic bias and needs to be calibrated with the observed rainfall data; otherwise, model output is not directly useful for application purpose. In this study, 28 rain-gauge stations average summer monsoon rainfall data of Bangladesh are utilized for calibration. Model-simulated monthly and seasonal (JJAS) rainfall (mm) is compared with rain-gauge rainfall. It is observed that the model underestimated summer monsoon rainfall as an amount. The similar result is reported by Islam and Uyeda (2008), Islam (2009). The bias correction method of the World Climate Research Programme (WCRP) is used in this study as described in WCRP (2011). To find out the estimated rainfall, the following equation is used:

$$\mathrm{RF}_{\mathrm{estimated}} = <X> + \left(Y_{\mathrm{jr}} - <Y>\right) \tag{1}$$

where RF$_{estimated}$ is the rainfall that will be projected for future, $<X>$ and $<Y>$ are the long-term climatological averages derived from the observed and model variable (for the observed period 1979–2003), and j identifies the initial times and r the forecast range. This estimated rainfall is useful for validation of high-resolution AGCM in Bangladesh.

3.4 Calibration of summer monsoon rainfall over Bangladesh

For calibration, Eq. (1) is used at each station for different months and at different observational places in Bangladesh. After calibration, it is found that the high-resolution AGCM summer monsoon rainfall (mm) is reasonably consistent with observed summer monsoon rainfall during the period 1979–2003 as shown in Fig 4. In general, there is a good agreement between the model calibrations and observed summer monsoon rainfall (mm) except in the years 1979, 1980, 1984, 1989, 1992, 1996, 1999, 2002, and 2003 in which the model shows little bit underestimation by −18.1, −36.8, −17.6, −24.2 −14.3, and −17.1 % for 1979, 1980, 1989, 1992, 1996, 2003 and overestimation shows by 27.7, 20.4 and 16.7 % for 1984, 1999, and 2002, respectively.

The high-resolution AGCM calibrated average summer monsoon rainfall (JJAS) during the period 1979–2003 is 1,762 mm with a standard deviation of 125 mm is shown in Table 3, whereas all-Bangladesh summer monsoon rainfall based on 28 rain-gauge stations averaged during the period 1979–2003 is 1,756 mm with a standard deviation of 207 mm. After calibration, the model summer monsoon rainfall is compared with the all-Bangladesh summer monsoon rainfall, where it is found to be very close to observed value. During the month of June, July, August, and September, the AGCM calibrated summer monsoon rainfall is 487, 525, 428, and 323 mm with a standard deviation 101, 35, 28, and 36 mm, respectively. Similarly, observed summer monsoon rainfall is 484, 525, 427, and 321 mm with a standard deviation of 137, 113, 112, and 64 mm for June, July, August, and September, respectively (Table 3).

A summary of correlation and root-mean-square error (RMSE) between observed and model-calibrated average summer monsoon rainfall in Bangladesh is also shown in Table 3. During the month of July and August, a better correlation is found which is highly statistically significant. In the month of June and September, correlation between observed and model-calibrated summer monsoon rainfall is also found which is statistically
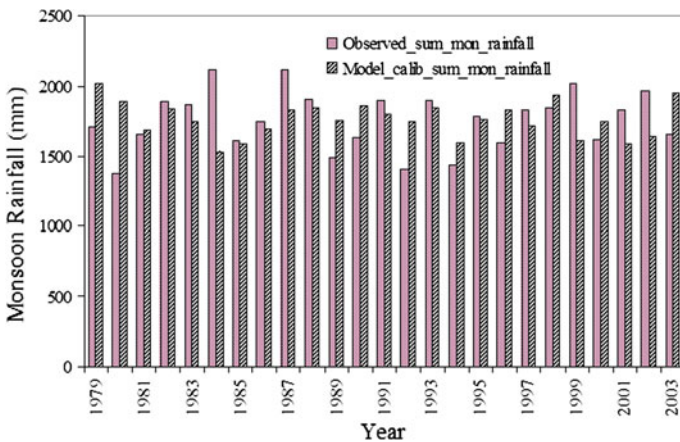
Fig. 4 Comparison between observed and model-calibrated summer monsoon rainfall (mm) during the period 1979–2003

Table 3 Statistical characteristics of observed and model-calibrated summer monsoon rainfall (mm) over Bangladesh during the period 1979–2003

	June	July	August	September	Monsoon (JJAS)
Model-calibrated summer monsoon rainfall (mm)					
Observed	484	525	427	321	1,756
Model	487	525	428	323	1,762
Model bias	−3	0	−1	−2	−6
Correlations	−0.25	0.19	−0.07	−0.17	−0.14
RMSE	186.0	109.0	115.0	77.4	251.2
Standard deviations					
Observed	137	113	112	64	207
Model	101	35	28	36	125

significant with RMSE of 186.0, 109.0, 115.0, and 77.4 mm for June, July, August, and September, respectively (Table 3).

4 Validation of summer monsoon rainfall over Bangladesh

The high-resolution AGCM-simulated area averaged summer monsoon rainfall (mm/day) over Bangladesh is compared with the observed (rain-gauge) rainfall during the period 1979–2003 as shown is Fig. 5a, b. Spatial distribution of model-simulated summer monsoon rainfall (mm/day) and the observed rainfall over Bangladesh is found to be almost similar except in the southeastern part of Bangladesh. Less rainfall is also observed over western part of Bangladesh. High-resolution AGCM does not capture rainfall well over the southeastern part, but rainfall in the northeastern and western part of Bangladesh is well captured by the high-resolution model (AGCM). It is clear that heavy rainfall belt over northeastern part of Bangladesh is located in hilly region on the slope of Shillong hill of Meghalaya in India, and western part is located in large landmass area over Bangladesh and India. It indicates that high-resolution AGCM can simulate the seasonal rainfall with a better spatial distribution. High-resolution model validation is performed against observed (rain-gauge) rainfall with the help of Eq. (1). Hence, calibration value improved a lot and made it to be very close to observed value by using a calibration method which was described in Sect. 3.3. Without calibration, model-generated summer monsoon rainfall scenarios do not match directly with the observed rainfall. The average model-calibrated rainfall coincided with observed summer monsoon rainfall (mm). It is indicated that calibrated summer monsoon rainfall (mm) is quite well captured by AGCM (Fig. 6).

High-resolution AGCM model-calibrated summer monsoon rainfall is compared with observed summer monsoon rainfall (mm) during the period 2004–2006 as shown in Fig 6. Model underestimated summer monsoon rainfall by 17.6, 6.8 % in 2004 and 2005, whereas model overestimated −6.6 % in 2006, respectively. On an average, model-calibrated summer monsoon rainfall underestimated about −6.9 % during the period 2004–2006. It is found that the model-calibrated summer monsoon rainfall is very close to observed rainfall. It is assumed that the high-resolution AGCM performance is quite reasonable because about −6.9 % biases may be considerable in long-range forecasting by using a high-resolution climate model. It is also indicated that this type of information may be helpful
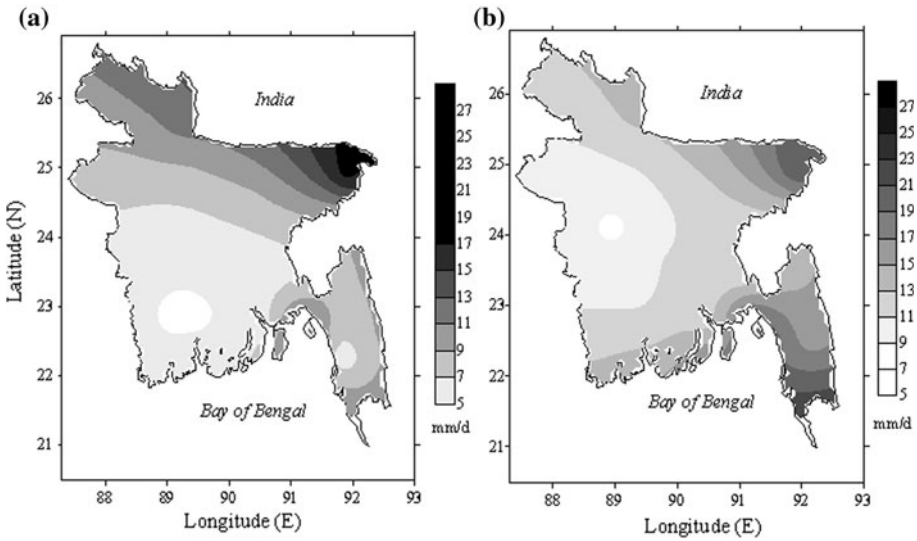
Fig. 5 **a** Model-simulated summer monsoon rainfall (mm/day) over Bangladesh during the period 1979–2003. **b** Observed summer monsoon rainfall (mm/day) over Bangladesh during the period 1979–2003
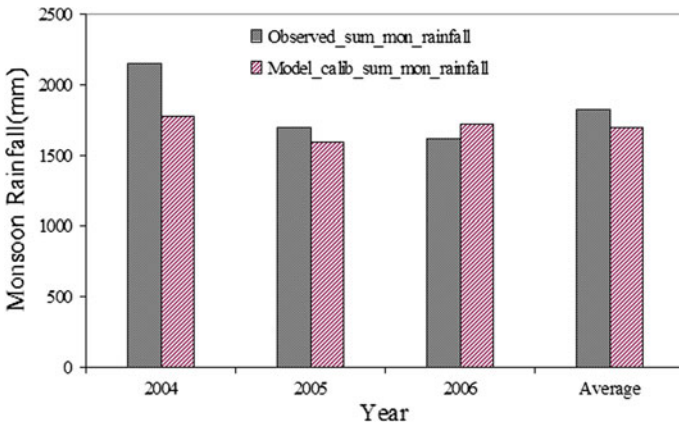
Fig. 6 Comparison between observed and model-calibrated summer monsoon rainfall (mm) during the period 2004–2006 and averaged summer monsoon rainfall at the same period

for farmers and planners of the country to mitigate water-related disaster like land slide, flood and water scarcity, etc.

5 Projection of summer monsoon rainfall over Bangladesh

5.1 Projections of summer monsoon rainfall for the near future (2015–2034)

The model-calibrated summer monsoon rainfall may change by −1.2, −23.5, −8.5, 14.9, 12.1, 12.9, −20.8, 7.4, 13.0, 18.1, −16.8, −9.1, 9.0, −14.7, 24.7, −27.6, −6.0, −2.4, 6.1,

and 3.4 % for 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027, 2028, 2029, 2030, 2031, 2032, 2033, and 2034, respectively. It is found that the change lies between −27.6 and 24.7 % during the above mentioned period. On an average, summer monsoon rainfall may decrease by −0.5 % over Bangladesh for near future during the period 2015–2034. However, the idea may be helpful about for long-range forecast is the goal of this study which is needed to the planners and stakeholders of the country.
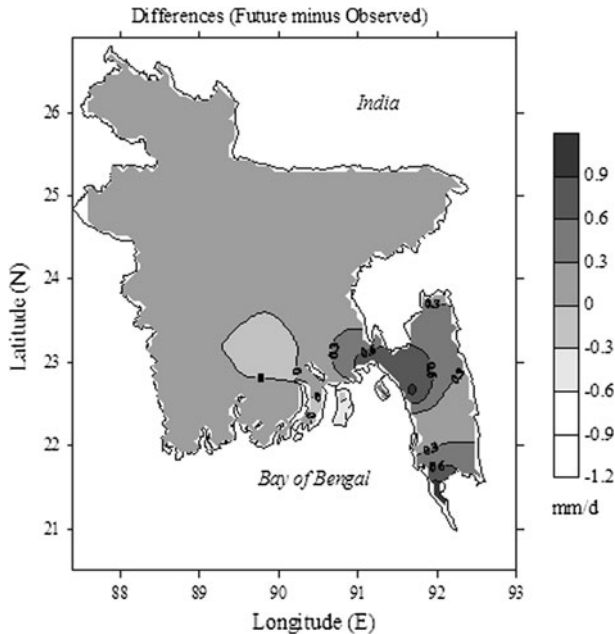
Figure 7 shows the spatial distribution of differences between model-calibrated near future and observed summer monsoon rainfall (mm/day) during the period 2015–2034 and base period (1979–2003), respectively. From the figure, it is seen that the change of highest summer monsoon rainfall is observed in the northeastern part and next to highest is seen in the northwestern part, whereas less summer monsoon rainfall is found in the southwestern part of Bangladesh.

6 Summer monsoon rainfall projections for the future (2075–2099)

The change of summer monsoon rainfall was found to be 7.3, −29.1, −6.5, 4.2, 29.9, 20.9, −11.7, −16.3, 16.3, 24.6, −27.3, −4.4, 14.6, −22.9, 21.7, −24.3, 4.9, −14.1, 3.1, 6.3, 21.9, −27.2, −1.8, 13.3, and 6.7 % for 2075, 2076, 2077, 2078, 2079, 2080, 2081, 2082, 2083, 2084, 2085, 2086, 2087, 2088, 2089, 2090, 2091, 2092, 2093, 2094, 2095, 2096, 2097, 2098, and 2099, respectively. It is observed that the change lies between −29.1 and 29.6 for the period 2075–2099, and on an average, summer monsoon rainfall may increase 0.4 % over Bangladesh for future for the same period.
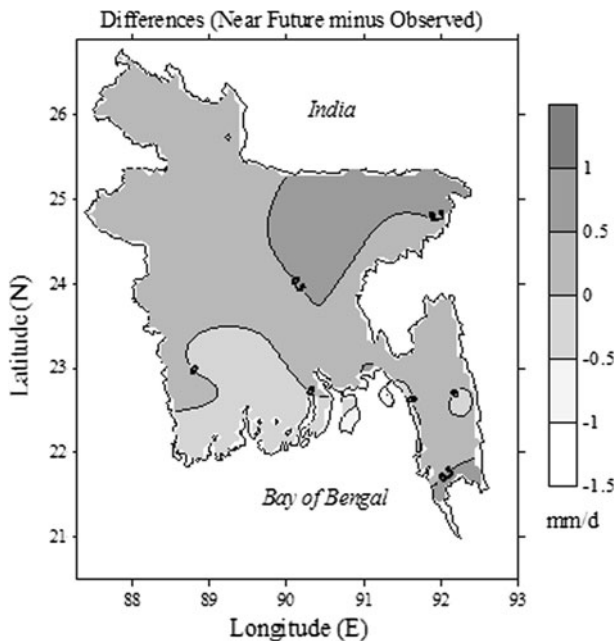
Fig. 7 The spatial distribution of summer monsoon rainfall anomaly (mm/day) over Bangladesh averaged during the period 2015–2034 and base period (1979–2003)

Fig. 8 The spatial distribution of summer monsoon rainfall anomaly (mm/day) over Bangladesh averaged during the period 2075–2099 and base period (1979–2003)

Figure 8 shows the differences between spatial distributions of model-calibrated future and observed summer monsoon rainfall (mm/day) during the period 2075–2099 and base period (1979–2003), respectively. The average summer monsoon rainfall throughout the country is all most similar except southeastern part of Bangladesh. Southeastern part rainfall may increase little bit in Bangladesh during the period 2075–2099.

7 Conclusions

A high-resolution (20 km) climate model named MRI-AGCM is employed in generating summer monsoon rainfall for Bangladesh. High-resolution AGCM generated summer monsoon rainfall scenario is calibrated with observed (rain-gauge) data during the period 1979–2003. The bias correction method of the World Climate Research Programme is utilized for validation of AGCM generated summer monsoon rainfall during the period 2004–2006. Better performance of AGCM through validation encourages utilizing it in summer monsoon rainfall forecast for Bangladesh. The TRMM 3B43 V6 data are also used for understanding the model performance. On an average, near future and future summer monsoon rainfall may change by −0.5 and 0.4 % during the period 2015–2034 and 2075–2099, respectively. This study find that high-resolution AGCM-simulated summer monsoon rainfall is not directly useful for application purposes. Without calibration with ground base data, the model outputs are very risky in using for long-term summer monsoon rainfall forecasting. However, these results may be utilized by stakeholders, policy, and decision-makers for multi-purpose uses including water-related disasters and agricultural planning for the country.

References

Bengtsson L, Botzet M, Esch M (1996) Will greenhouse gas-induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes? Telllus 48A:57–73

Gadgil S, Rajeevan M, Nanjundiah R (2005) Monsoon prediction: why yet another failure? Curr Sci 88:1389–1400

Hastenrath S (1995) Recent advances in tropical climate prediction. J Clim 8:1519–1532

IPCC (2000) In: Nakic′enovic′ N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Yong Jung T, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z (eds) Special report on emissions scenarios. A special report of working group III of the intergovernmental panel on climate change. Cambridge University Press, Cambridge,p 595

IPCC (2001) Climate change 2001: the scientific basis. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, vander Linden PJ, Dai X, Maskell K, Johnson CA (eds) Contribution of working group I to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

IPCC (2007) Climate change 2007: the physical science basis. In: Solomon SD Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignol and HL Miller (eds) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, 996 pp

Islam MN (2009) Rainfall and temperature scenario for Bangladesh. Open Atmospheric Sci J Bentham Open 3:93–103

Islam MN, Uyeda H (2007) Use of TRMM in determining the climatic characteristics of rainfall over Bangladesh. Remote Sens Environ Elsevier Inc 108(3):264–276. doi:10.1016/j.rse.2006.11.011

Islam MN, Uyeda H (2008) Vertical variations of rain intensity in different rainy periods in and around Bangladesh derived from TRMM observations. Int J Climatol 28:273–279. doi:10.1002/joc.1585

Jagannathan P (1960) Seasonal forecasting in India: a review. FMU: 1–80, India Meteorological Department, Pune, India

Kang IS, Jin K, Wang B, Lau KM, Shukla J, Krishnamurthy V, Schubert SD, Wailser DE, Stern WF, Kitoh A, Meehl GA, Kanamitsu M, Galin VY, Satyan V, Park CK, Liu Y (2002) Intercomparison of the climatological variations of Asian summer monsoon precipitation simulated by 10 GCMs. Clim Dyn 19:383–395

Kitoh A, Kusunoki S (2008) East Asian summer monsoon simulation by a 20-km mesh AGCM. Clim Dyn 31:389–401. doi:10.1007/s00382-007-0285-2

Kumar KK, Soman MK, Kumar KR (1995) Seasonal forecasting of Indian summer monsoon rainfall. Weather 50:449–467

Kusunoki S, Mizuta R (2008) Future changes in the Baiu rain rand projected by a 20-km mesh global atmospheric model: sea surface temperature dependence. SOLA 4:85–88. doi:10.2151/sola 2008-022

Kusunoki S, Yoshimura J, Yoshimura H, Noda A, Oouchi K, Mizuta R (2006) Change of Baiu rain band in global warming projection by an atmospheric general circulation model with a 20 km grid size. J Meteor Soc Jpn 84:581–611

Mizuta R, Oouchi K, Yoshimura H, Noda A, Katayama K, Yukimoto S, Hosaka M, Kusunoki S, Kawai H, Nakagawa M (2006) 20 km-mesh global climate simulations using JMA-GSM model-mean climate states. J Meteor Soc Jpn 84:165–185

Mizuta R, Adachi Y, Yukimoto S, Kusunoki S (2008) Estimation of the future distribution of sea surface temperature and sea ice using the CMIP3 multi-model ensemble mean. Technical report Meteorol Res Inst 56:28 pp http://www.mri-jma.go.jp/Publish/Technical/DATA/VOL_56/tec_rep_mri_56.pdf#page=5. Accessed 11 Nov 2010

Normand C (1953) Monsoon seasonal forecasting. Q J R Meteorol Soc 79:463–473

Oouchi K, Yoshimura J, Yoshimura H, Mizuta R, Kusunoki S, Noda A (2006) Tropical cyclone climatology in a global warming climate as simulated in a 20 km mesh global atmospheric model frequency and wind intensity analyses. J Meteor Soc Jpn 84:259–276

Rahman MM (2006) A validation of regional climate model simulation with observational data over Bangladesh: M. Phil. thesis, Bangladesh University of Engineering & Technology (BUET) Library, Dhaka, Bangladesh

Rajeevan M (2001) Prediction of Indian summer monsoon: status, problems and prospects. Curr Sci 11:1451–1457

Randall D, Pan DM (1993) Implementation of the Arakawa-Schubert cumulus parameterization with a prognostic closure. Meteorol Monoger 46:145–150

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. J Geophys Res 108:4407. doi:10.1029/2002JD002670

Thapliyal V, Kulshreshtha S (1992) Recent models for long range forecasting of southwest monsoon rainfall over India. J Arid Environ 43:239–248

Wang B, Ho L (2002) Rainy season of the Asian-Pacific summer monsoon. J. Climate 15:386–398

WCRP (2011) Data and bias correction for decadal climate predictions. World Climate Research Programme report, International CLIVAR Project Office, CLIVAR Publication Series No 150

Yatagai A, Xie P, Kitoh A (2005) Utilization of a new gauge-based daily precipitation dataset over monsoon Asia for validation of the daily precipitation climatology simulated by the MRI/JMA 20-km mesh AGCM. SOLA 1:193–196

Yoshimura H, Matsumura T (2005) A two-time-level vertically conservative semi-Lagrangian semiimplicit double Fourier series AGCM. CAS/JSC WGNE Res Activities Atmos Ocean Model 35:3.27–3.28