

# Validation of General Climate Models (GCMs) over Upper Blue Nile River Basin, Ethiopia

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## Abstract

Potential of climate change impact assessment on hydrology and water resources of rivers is increasing from time to time due to its importance for water resources planning and management in the future. In order to carry out climate change impact studies, using General Climate Models (GCM) is a common practice and before using any of these models, it is essential to validate the models for the selected study area. Blue Nile River is one of the most sensitive rivers towards climate change impacts. The main source of Blue Nile River is Lake Tana where the two adjacent tributary rivers, Ribb & Gumera, are located and the main object of this paper is validation of current 15 GCM outputs (IPCC-AR5) over these two rivers using empirical quantile perturbation downscaling technique. The performance of the downscaled outputs of GCMs were evaluated using statistical indicators and graphical techniques for evapotranspiration, rainfall and temperature variables using observed daily meteorological datasets collected from five stations (Addis Zemen, Bahirdar, Debretabor, Woreta and Yifag) for the control period 1971-2000. Analysis results showed that the correlation coefficient of all models for mean monthly (MM) rainfall are 12% - 45%; and the Bias and RMSE -46 mm to +169 mm and 62 mm to 241 mm, respectively. The Bias and RMSE for MM maximum temperature are -2.5 °C to +35 °C; and 1 °C to  $35^{\circ}$ C whereas for MM minimum temperature  $-6^{\circ}$ C to  $+22^{\circ}$ C and  $1.7^{\circ}$ C to  $23^{\circ}$ C, respectively. For the case of MM evapotranspiration, which is estimated using FAO-Penman-Montheith equation, the Bias and RMSE values vary from -35 mm to +10mm; and +11 mm to +36 mm, respectively. The variation in the performance level of these models indicates that there is high uncertainty in the GCM outputs. Therefore, to use these GCM models for any climate change studies in the basin, careful selection has to be made.

# **Keywords**

Blue Nile, Downscaling, GCM, Validation

## **1. Introduction**

Climate change caused by increasing concentrations of carbon dioxide and other trace gases in the atmosphere has been a major concern in recent decades. One of the major effects of climate change is likely to be alterations in hydrologic cycles and changes in water availability. Increased evaporation, combined with changes in precipitation, has the potential to affect runoff, the frequency and intensity of floods and droughts, soil moisture, and availability of water for irrigation and hydroelectric generation [1].

Currently, there are two distinct definitions for the phrase "climate change". These are from the Intergovernmental Panel on Climate Change (IPCC) and United Nations Framework Convention on Climate Change (UNFCCC). According to IPCC, climate change is defined as a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and which persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity, unlike that of UNFCCC that defines climate change as a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere in addition to natural climate variability observed over comparable time periods [2].

In the past decades, much attention is given to climate change impact studies on hydrology of rivers in the Nile basin [1] [3] [4] [5]. One of the important and sensitive basins towards climate change is the Blue Nile [6] [7] [8] where Ribb and Gumera sub basins are located. [5] used two conceptual hydrological models that were calibrated and used to carry out climate change impact assessment for two future Special Report on Emissions Scenario (SRES) A1B and B1 for 2050s using 17 GCMs for Nile basin. The result of the study has showed that there is unclear trend (like [9] and [10]) in Lake Tana sub-basin for projected flows (mean and high/low) and this is mainly attributed to Global Climate Models (GCMs) uncertainty.

[1] also demonstrates in the period 1980-2000 and 2080-2100 fifteen GCMs do not show consistent and statistically significant differences in total precipitation. Hence, carrying out additional studies may provide better understanding of the impact of climate change on the hydrologic cycle of these sub-basins with the current GCMs outputs produced for IPCC Assessment Report 5 (AR5).

The investigation of [1] on climate change impact on agricultural water resources variability in the Lake Tana sub-basin in using 15 GCM models shows that there is an increase in temperature around  $2^{\circ}C - 5^{\circ}C$  for the period 2080-2100. Regarding the future precipitation, according to this study, it remains unclear because of both increasing and decreasing projection of precipitation. Therefore, it is difficult to provide strong conclusions on the future trend of precipitation in the region.

Moreover, it is important to study the impact of climate change on the extreme flows of the sub catchments. This is an important aspect since flooding is frequently caused by the two rivers at the downstream of their catchments, especially on Fogera flood plain located in the catchment. It is well documented that Fogera flood plain frequently floods due to the two rivers and backflow from Lake Tana [11] [12] [13]. The main inputs to climate change impact studies are climate variables from GCM. Before using GCM models for any climate change studies, it is important to validate their performance over the selected study area.

Most of the studies conducted on validation of GCM models over Blue Nile River are based on previous version of IPCC Assessment Report 4 (AR4) where as this study is based on the current IPCC product of Assessment Report 5 (AR5). The two Assessment Reports have different GCM products having different scenarios. GCM products from these reports are expected to have different performance levels over Blue Nile Catchment as well. Therefore, the main objectives of this study is validation of selected 15 GCMs from IPCC-AR5 and identify better performing models so as to use them for further climate change studies in the catchment.

## 2. Materials and Methods

#### 2.1. Description of the Study Area

Ribb-Gumara sub-basin, drained by Ribb and Gumara Rivers, is located between 11°30'N and 12°30'N latitude and 37°30'E and 38°30'E longitude. The elevation of this area ranges from 1755 m to 4103 m. This sub-basin is part of the upper Blue Nile River basin and more particularly that of the Lake Tana basin located on the Northeastern side of Lake Tana.

It has an area of about 3000 km<sup>2</sup> (Gumera = 1400 km<sup>2</sup> and Ribb = 1600 km<sup>2</sup>). Fogera district, which has an area of 1110 km<sup>2</sup>, totally lies in this catchment. This district is found in the downstream part of the catchment where Ribb and Gumara Rivers join to Lake Tana. Overflow of these rivers and back flow of Lake Tana frequently floods this districtmore than other districts in the sub-basin. These rivers have their sources in a mountainous area and in their lower reaches and flow through a large flat to very gentle sloping plain, which is exposed to severe flooding. The total annual rainfall ranges from about 1100 - 1530 mm/year. The spatial distribution of rainfall showed that eastern and central parts of the district receive highest rainfall while the northern portion receives the lowest. The seasonal rainfall has a monomodal distribution with the main rainy season being from June to September and peaking in July. The dry period is from October to April. The mean monthly temperature of the area is about 19°C, monthly mean maximum temperature is about 27.3°C, and monthly mean minimum temperature is 11.5°C. Climate of the region is tropical highland monsoon. Land use map classification of 2000 shows that there are seven different land use classes; and the most dominant land use in the Ribb-Gumera catchments is agricultural land use.

## 2.2. Data

In this study two types of datasets were used: observed and GCM outputs. The historical period selected is 1971-2000. The meteorological variables included in the study were maximum and minimum temperature; rainfall and evapotranspiration.

The observed meteorological data, rainfall and temperature, recorded at five stations were used for evaluation of the GCMs for the study period selected. Out of the available meteorological stations in and around the catchments, four rainfall stations and one temperature station were selected. The location and name of the meteorological stations used in this study are given on **Table 1**.

				_
NAME OF STATIONS	X (m)	Y (m)	ELEVATION (m)	
ADDISZEMEN	377,036	1,340,078	2105	
BAHIRDAR	3,776,188	1,171,600	1800	
DEBRETABOR	394,371	1,317,892	2314	
WORETA	356,257	1,319,157	1799	
YIFAG	360,685	1,334,620	1838	
				_

Table 1. Name and location of meteorological stations used for the study.

The resolution of the GCM products used in this study ranges from  $1.112^{\circ} \times 1.125^{\circ}$  up to  $2.784^{\circ} \times 2.8125^{\circ}$ , where  $1^{\circ} \times 1^{\circ}$  represents a grid size of approximately 101 km × 101 km. The name of GCM models, developers and corresponding resolutions are given on **Table 2**.

#### 2.3. GCM Models Performance Evaluation

The performances of 15 GCM models were evaluated by both statistical indicators and graphical techniques. The statistics used for evaluation were root mean square error (RMSE), bias and correlation coefficient; and the corresponding formulas for each of these statistics used are shown in equations 1, 2 and 3. Using graphical techniques, 15 GCMs (control period) were compared with observed rainfall, maximum temperature, minimum temperature and evapotranspiration. The evapotranspiration used here was estimated using FAO-Penman-Montheith equation and the input variables used are minimum and maximum temperature for both observed and control periods.

$$RMSE = \sqrt{\frac{1}{n}} \sum (M - O)^2$$
(1)

$$Bias = \frac{1}{n} \sum (M - O)$$
 (2)

 $Correlation(r) = r_{MO}/r_M \cdot r_O$ (3)

where: M: is control period (GCMs) time series,

*O*: is corresponding time series of observation of the same physical quantity, (Rainfall, Temperature and Evapotranspiration),  $r_{MO}$ : Covariance between control period (GCMs) and observation,

 $r_{M}$ : Standard deviation of control period (GCMs),

r<sub>o</sub>: Standard deviation of observation.

# 3. Results and Discussion

## 3.1. Rainfall

After analysis of the areal rainfall of the Ribb-Gumera catchment, it is found that nearly all the models except cnrm-cm5 under estimated the seasonal rainfall during the main rainy season (June-September) and also some models didn't captured the peak rainy month (the models showed it is August but the observed data shows it is July). The other point is that during dry season all the models over estimated as compared to the observed data. Two extreme performances of these models is clearly observed on the

Model name	Developed by	Resolution (lat. $\times$ lon.)	
BCC-CSM1.1m	China	$1.112^{\circ} \times 1.125^{\circ}$	
CMCC-CMS	Europe	$1.861^{\circ} \times 1.875^{\circ}$	
CNRM-CM5	France	$1.397^{\circ} \times 1.406^{\circ}$	
MIROC5	Japan	$1.397^{\circ} \times 1.406^{\circ}$	
MRI-CGCM3	Japan	$1.119^{\circ} \times 1.125^{\circ}$	
CSIRO-MK3.6.0	Australia	$1.861^{\circ} \times 1.875^{\circ}$	
HadGEM2-CC	UK	$1.25^{\circ} \times 1.875^{\circ}$	
HadGEM2-ES	UK	$1.25^{\circ} \times 1.875^{\circ}$	
INMCM4	Russia	$1.5^{\circ} \times 2^{\circ}$	
IPSL-CM5A-MR	France	$1.268^{\circ} \times 2.6^{\circ}$	
MPI-ESM-MR	Germany	$1.861^{\circ} \times 1.875^{\circ}$	
MPI-ESM-LR	Germany	$1.861^{\circ} \times 1.875^{\circ}$	
BCC-CSM1.1	China	2.784° × 2.8125°	
CanESM2	Canada	2.784° × 2.8125°	

Table 2. GCM models, name of developers and resolutions (Lat. × Lon.).

Source: [15].

seasonal rainfall variation. The two models (lpsl-cm5a and bcc-csm1.1) very poorly performed where as CanESM2, mpi-esm-mr and mpi-esm-lr performed better as compared to the observed data with regard to seasonal rainfall. But cnrm-cm5 showed unexpected overestimation of rainfall during the main rainy season (June-September). The seasonal rainfall variation for all the models with measured dataset is showed on **Figure 1**.

The graph for RMSE and BIAS are shown on **Figure 2** and **Figure 3**, respectively. The BIAS and RMSE values ranges (-80 - 169 mm/month) and (62 - 241 mm/month), respectively. The correlation coefficient between the observed rainfall time series and the control period GCMs were computed; and all of the correlation coefficient values for the models are less than 0.5; and the maximum and minimum values are 0.45 and 0.12 for micoc5 and HadGEM2-CC, respectively and these shows that all the models are not fully trusted to use for climate change impact studies.

Besides the statistics used for GCM models' performance evaluation, frequency quantile analysis (as shown on **Figure 4**) has been done to check the models' performance for extreme events at daily scale. The analysis is based on ranked daily rainfall values of both control period and observed areal rainfall time series, where the corresponding values are compared for the same empirical return period. The empirical return period is calculated using the formula in the equation4below.

$$T = n/r \tag{4}$$

where: *T*: is return period in years;

*n*: is total number of years the data taken from and

*r*: is the rank number of daily rainfall data.

The analysis showed that for all return periods six models over estimated and nine models under estimated the quantile rainfall but all the models captured the pattern of



Figure 1. GCM model performance evaluation for Seasonal rainfall over the study area.



Figure 2. GCM model performance evaluation for rainfall using RMSE.

observed data nearly in good way.

Finally it is found that the best model for rainfall analysis among 15 selected models is mpi-esm-mr based both least BIAS (-15 mm/month) and least RMSE (62 mm/month); and with regard to capturing seasonal rainfall over the study area it is mpi-esm-lr model.

### 3.2. Temperature

The maximum and minimum mean monthly temperatures were analyzed for both the



Figure 3. GCM models performance evaluation for rainfall using BIAS.



Figure 4. GCM models performance evaluation for rainfall using frequency quantile analysis.

GCMs and observed value, which is recorded at Bahirdar station for the period (1971-2000). The analysis shows that most of the models (12 models) overestimate the mean monthly minimum temperature and few of the models (3 models) underestimate; but almost all of the models captured the pattern except Inm-cm4, which showed unexpected pattern. The two GCM models (cnrm-cm5 and Inm-cm4) underestimated and the remaining 12 models overestimated the mean monthly maximum temperature val-

ues. All of the models followed the pattern of the observation in nice way. Performance of these models is at different level for maximum and minimum temperature; and most of the models performed better for maximum temperature than minimum temperature. For both temperatures, the performance level was showed on Figure 5 and Figure 6.

#### 3.3. Evapotranspiration

Using the maximum and minimum temperature as an input to Evapotranspiration



Figure 5. GCM model performance evaluation for average monthly minimum temperature.



Figure 6. GCM models evaluation for average maximum monthly temperature.



Figure 7. GCM models performance evaluation for ETo using BIAS.



Figure 8. GCM models performance evaluation for ETo using RMSE.

which is developed based on FAO-Penman-Montheith equation [14], the evapotranspiration was estimated for the observation and the control period.

Due to lack of data for all required climatic inputs the FAO-Penman-Montheith method of estimating  $ET_0$ , with limited data option was applied in this study. The method estimates the other variables (radiation, wind speed, relative humidity, and air pressure) based on the observed maximum and minimum temperature and the geographic location of the catchment. As it can be seen from analysis result of BIAS & RMSE for ETo estimation for the control period, Cisro-mk-3.6.0 has the least and bcc-ssm1.1-m has the highest negative BIAS among the models. With regard to RMSEmiroc-esm has the least and bcc-csm-1.1-m & CanESM2 have the highest RMSE. The best performed model for ETo is miroc-esm and the least performed is bcc-csm-1.1-m. Evaluation of all the models for Evapotranspiration is shown on **Figure 7** and **Figure 8** for BIAS and RMSE, respectively.

## 4. Conclusions

The performances of the downscaled outputs of 14 GCMs were evaluated using statistical indicators (BIAS, RMSE & correlation coefficient.) and graphical techniques for evapotranspiration, rainfall and temperature variables using observed daily meteorological datasets (maximum temperature, minimum temperature and rainfall) collected from five meteorological stations (Addis Zemen, Debretabor, Woreta and Yifag) for the control period (1971-2000).

Analysis results showed that the correlation coefficient of all models for mean monthly rainfall ranges between 12% to 45%; and the Bias and RMSE varies from -46 mm to +169 mm and 62 mm to 241 mm, respectively. The Bias and RMSE are in the range of  $-2.5^{\circ}$ C to  $+35^{\circ}$ C and  $1^{\circ}$ C to  $35^{\circ}$ C for mean monthly maximum temperature whereas for mean monthly minimum temperature it is in the range of  $-6^{\circ}$ C to  $+22^{\circ}$ C and  $1.7^{\circ}$ C to  $23^{\circ}$ C, respectively. For the case of mean monthly evapotranspiration, which is estimated using FAO-Penman-Montheith equation, the Bias and RMSE values vary from -35 mm to +10 mm and 11 mm to 36 mm, respectively.

The variation in the performance level of these models indicates that there is high uncertainty in the GCMs outputs. As it is seen from the correlation coefficient for rainfall (0.12 - 0.45) which is less than 0.5, all the models cannot be fully relayed on for climate change impact studies with regard to rainfall. Similarly, this is also true for the other variables as it is can be seen from BIAS and RMSE values which are large. The performance variation among the models also demonstrates that there is high uncertainty in the GCM outputs. The other finding of this study is that a given model may perform well for a given meteorological variable and may not perform well for another meteorological variable; and also making conclusion about performance of a given model based a single evaluation statistics (BIAS, RMSE, r) or single graphical evaluation technique may miss lead to wrong conclusion. For example according to this study the best performed models for rainfall are mpi-esm-mr and mpi-esm-lr where as for evapotranspiration it is miroc-esm. Therefore, to use these GCM models for climate change studies in the basin, careful selection has to be made based on different performance evaluation techniques.

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