Impact Assessment of Future Climate Change for the Blue Nile Basin, Using a RCM Nested in a GCM

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Abstract
This paper establishes a basis for evaluation of climate changes impacts within the Blue Nile River sub-basin, using the RegCM3 Regional Climate Model to simulate interactions between the land surface and climatic processes. The RegCM3 model nested with the ECHAM5 General Circulation Model (Max Planck institute) were applied and the obtained results are presented.. The results were then fed as inputs to the Nile Forecast System NFS) (a distributed rainfall runoff model of the Nile Basin) and the interaction between the climatic and hydrological processes on the land surface was fully coupled. Rainfall patterns and evaporation rates were generated using RegCM3, and the resulting runoff and Blue Nile streamflow patterns were simulated using the NFS. The results, obtained from the RegCM3 climate model, were compared to the observational datasets for precipitation and temperature from the Climate Research Unit (UK) and the NASA Goddard Space Flight Center GPCP (USA) for the period 1985-2000. The validity of the stream-flow predictions from the NFS is assessed using historical gauge records. Finally, the modeling results of the A1B emissions scenario of the IPCC for the years 2034-2055 are presented. The results indicated that the future changes in rainfall might vary over different areas of the Upper Blue Nile catchment in Ethiopia. This suggested that there might be a good reason for developing climate models with finer spatial resolution than the commonly used GCMs.

Key words: Nile Basin, Hydrological processes, Regional climate modeling, NFS, ECHAM, climate change.

1. INTRODUCTION

Many researchers attempted to address the impact of future climate change on the Nile flows, using GCMs for a large set of SRES emissions scenarios (Conway, 2000, Elshamy, 2008). However; few studies used models capable of simulating key characteristics of the Nile. Sayed (2003) recommended that effort should be devoted to calibrate one or more of the regional climate models (RCMs) over the region, followed by linking the RCM(s) with a hydrologic simulation model. Such an effort should improve studies of climate impacts by:

- increasing the accuracy of precipitation and runoff estimates obtained from climate models
- enabling more complete consideration of local climate features that are poorly represented in GCMs.

Mohamed et al. (2005) presented results of the first coupled regional climatic-hydrologic model (RACMO) applied to the Nile Basin. The results obtained were considered satisfactory in the light of the extremely low runoff coefficients in the modeled area. Nevertheless, the study relied on observational data from only two stations for validation. In addition, RACMO does not appear to be currently operational [Y. Mohamed, personal communication].

The objective of this paper is to demonstrate an application nesting the RegCM3 Regional Climate Model with the ECHAM5 GCM over the Blue Nile Sub-basin. It was intended to use this nested model with the Nile Forecast System (NFS), a black-box, fine-scale hydrological model of the Nile Basin housed at the Nile Forecast Center of the Ministry of Water Resources and Irrigation in Egypt. Using the NFS, it was possible to quantify the impact of perturbations related to one climate change scenario on stream-flows. It was believed that this research might be useful for improving current understanding of climate change impacts on the hydrology of the Nile Basin, due to the finer spatial resolution and greater ability of RCMs to link changes in precipitation, temperature, and land use.

2. PREVIOUS ATTEMPTS

The RegCM3 model, updated from RegCM2 (Giorgi et al., 1993a,b), was developed at The Abdus Salam International Center for Theoretical Physics (ICTP) (Pal et al., 2003).1 The model is a primitive equation, hydrostatic, compressible, limited-area model with sigma pressure vertical coordinate. The soil-vegetation atmosphere interaction processes are parameterized through the BATS scheme (Biosphere-Atmosphere Transfer Scheme; Dickinson et al., 1993). RegCM3 uses the NCAR CCM3 (Community Climate Model 3; Kiehl et al., 1996) radiative transfer scheme, which includes the forcing effects of different greenhouse gases, cloud water, cloud ice and atmospheric conditions (Giorgi and Mearns, 1999).

Soliman et al (2008) calibrated and validated RegCM3 over the Blue Nile basin domain. While comparing the model results with different observational data sets, they found that the model was able to accurately simulate the climatology of the Blue Nile. The observed spatial and temporal pattern of temperature and the seasonality and spatial pattern of precipitation were well represented by the model outputs. The results obtained for the Sobat sub-basin, were unsatisfactory. They recommended to execute an additional study is to improve the model performance over a larger domain.

3. PRESENT STUDY

These findings were explained in details and the model outputs were used as input to the NFS. The results showed that the model was successful in simulating historical streamflow for 1985-2000 accurately at gauged stations located along the Blue Nile (90% correlation with the observed data). Then, RegCM3 was used to explore changes in the climate and stream-flow over this region for the future period 2034-2055, under A1B scenario conditions. The flow at the Deim station in Sudan, close to the Ethiopian border, was found to be more than the future period by 2%, relative to the historical period, with greater increases in June and July being offset by decreases in flow during the dry season. The seasonal and spatial pattern of precipitation also varies somewhat over this region.

4. STUDY AREA

The above was applied to a study area. This area is the upper Blue Nile River Basin which is located in the Ethiopian Highlands and has a drainage area of about 176,000 km2 measured at El Deim (Figure 1). The Blue Nile River runs from its origin, Lake Tana, to the Sudanese border and eventually meets the White Nile River at Khartoum, Sudan.

The climate of the study area varies from humid to semiarid. Most precipitation occurs in the wet Kiremt season (June through September), and the remaining precipitation occurs in the dry Bega season (October through January or February) and in the mild Belg season (February or March through May). The annual precipitation increases from northeast to southwest over the basin. Annual precipitation has been found to range from 1200 to 1600 mm, depending on the method and the period used (e.g., Gamachu, 1977; Conway, 1997, 2000; Tafesse, 2001; UNESCO, 2004; Kim and Kaluarachchi, 2007). The mean annual temperature from 1961 to 1990 was estimated to be 18.3 °C with a seasonal variation of less than 2 °C, and the annual potential evapotranspiration was found to be about 1100 mm (Kim et al., 2007).

More than 80% of annual flow in the Blue Nile results from the summer monsoon and is concentrated between July and October. This runoff flows directly to downstream countries due to the absence of storage capacity in Ethiopia. Small tributaries in the mountainous region experience large fluctuations of streamflow due to the high seasonal variation of precipitation (UNESCO, 2004). Using monthly discharge data at the Roseires/El Deim station just over the border in Sudan (National Center for Atmospheric Research (NCAR), http://dss.ucar.edu/datasets/, March 2006), the mean annual discharge was 49 km3 for the period 1921-1990, ranging from a minimum of 31 km3 (1972 and 1984) to a maximum 70 km3 (1929). Based on the same data set, the 30-year mean annual discharge ranged from

[4] For more documentation, see http://www.ictp.it/~pubregcm.

38 km3 (1978 and 1985) to 56 km3 (1955 and 1964). Previous Nile studies have estimated the mean annual discharge from the Blue Nile to be 46-54 km3 (Kim and Kaluarachchi, 2008)

Figure 1: Physical layout of the upper Blue Nile River Basin.

5. MODELING APPROACH

Figure (2) illustrates the steps of the used modeling approach. The first step was to configure and calibrate the RCM using observational data, specifically the National Center for Environmental Prediction (NCEP) Reanalysis (NNRP1) data (more details on these datasets follow below in Section 3.1). The second step was to examine the results of the calibration experiment in details and to perform a sensitivity analysis to define the suitable domain size and time step interval. In the third step; the RCM was nested with the ECHAM5 GCM by replacing the NCEP reanalyzed data used to calibrate the model with ECHAM5 climate outputs for a reference period (1985-2000) and a future period (2034-2055). The RCM was then used to simulate the climate in these two different periods. In step four, the grid factor bias correction method was used to correct the inconsistencies between the reanalysis and nesting experiments. The final step was to feed the bias-corrected rainfall outputs to the NFS rainfall-runoff model in order to quantify changes in river flow.

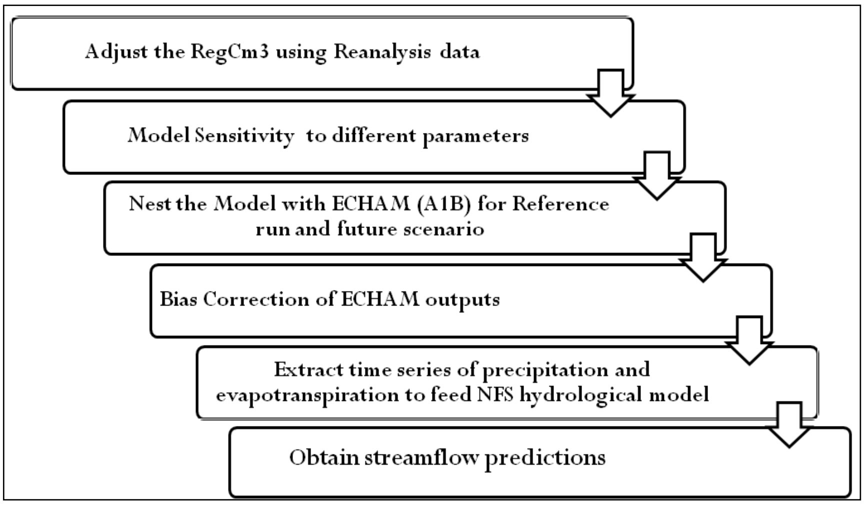


Figure 2: Research methodology

5.1 RegCM3 Model and the Implemented Data

The Regional Climate Model (RegCM) Version 3 (Pal et al. 2006) is a limited area model built around the hydrostatic dynamical component of the National Center for Atmospheric Research (NCAR)/Pennsylvania State University Mesoscale Model version 5.0 (MM5) (Grell et al. 1994). The model is compressible, based on primitive equations, and employs a terrain following r-vertical coordinate. The model includes parameterizations of surface, boundary layer and moist processes which account for the physical exchanges between the land surface, boundary layer and free atmosphere. The model's vertical resolution is composed of 18 levels, with seven levels below 800 hPa. A vertical interpolation is performed to account for differences in vertical resolution and topography between RegCM and the driving fields.

For the sake of the present study, the limited area domain was initialized once throughout the domain and driven by atmospheric lateral boundary conditions. Oceanic surface temperatures for the reference period were prescribed from observations using the National Center for Environmental Prediction (NCEP) Reanalysis (NNRP1) datasets (2.5 degree grid) (Kalnay et al. 1996). NNRP is derived from various data sources including rain sondes, surface marine data, aircraft data, surface land synoptic data, satellite sounder data, special sensing microwave imager, and satellite cloud drift winds. Quality control studies were performed and the data was assimilated using a numerical prediction model. SSTs were obtained from the NOAA Optimum Interpolation Sea Surface Temperature (OISST) analysis (Version 2) (Reynolds et al. 2002).2 In many regions, where observations are sparse, particularly in the tropics, the NNRP dataset highly relies on interpolated values.

Atmospheric lateral boundary conditions were derived from the NCEP/NCAR reanalysis (Kalnay et al. 1996), and from ensemble integrations of a global atmospheric model, the European-Hamburg (ECHAM) AOGCM (Roeckner et al. 1996).3 The ECHAM5 boundary forcing for RegCM3 was interpolated horizontally and vertically to the RegCM3 grid and topography, and was applied at 6-hour intervals.

RegCM3 uses a medium-resolution planetary boundary scheme developed by Holtslag and Boville (1993). In RegCM3, the radiation parameterization is specified according to the Community Climate Model (CCM3) and the radiation package of Kiehl et al. (1998). Exchanges of energy, moisture, and momentum between the land surface and the atmosphere are computed using the Biosphere-Atmosphere Transfer Scheme (BATS1E) land surface model (Dickinson et al. 1993). The Global Land Cover Characterization (GLCC) dataset – derived from 1 km Advanced Very High Resolution Radiometer (AVHRR) data spanning April 1992 to March 1993, with 20 vegetation/land cover types – was employed to specify land use and vegetation.4 Topographical data was taken from the United States Geological Survey (USGS).5

One convective parameterization scheme was employed in the present experiments (the Grell scheme). The clouds were thus defined as two steady state circulations consisting of an updraft and a downdraft with no mixing between cloudy air and environmental air except at the cloud top and base. The scheme employed a quasi-equilibrium closure assumption (Arakawa and Schubert 1974) based on the rate of destabilization. This is a single cloud scheme with updraft and downdraft fluxes and compensating motion that determines the heating and moistening profiles.

For the sake of this paper, the changes that would result from the emissions trajectory of the A1B Scenario (Nakicenovic and Swart, 2000) were selected to be analyzed. Thus the ECHAM A1B output obtained from the International Center for Theoretical Physics (ICTP) for use in RegCM3, for the two

[2] The OISST weekly mean data information is available at http://www.cdc.noaa.gov; NNRP initial and boundary conditions can be obtained from ftp://ftp.cdc.noaa.gov/Datasets/ncep.reanalysis/.

[3] The ECHAM model (version 5) is derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) spectral prediction model (Roeckner et al. 1996). It has a hybrid sigma-pressure vertical coordinate. In the ensemble members used in these experiments, ECHAM has a horizontal T42 spectral resolution (2.8 latitude–longitude) and has 19 vertical levels, with the top extending to 10 hPa. The model's prognostic variables are vorticity, divergence, surface pressure, temperature, specific humidity, and the mixing ratio of total cloud water. The mass flux scheme of Tiedtke (1989) is employed for both deep and shallow convection. For full details on the ECHAM model, readers may refer to Roeckner et al. (1996).

[4] More information regarding GLCC datasets can be found at: http://edcdaac.usgs.gov/glcc/glcc.htm

[5] Available at: http://www.ictp.trieste.it/ pubregcm/RegCM3/globedat.htm

time periods of interest, were prepared.

The A1 storyline and scenario family describes a future world of rapid economic growth, global population that peaks in the mid-21st century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B), where balance refers to a move away from heavy reliance on any one particular energy source. It was assumed that similar improvement rates apply to all energy supply and end-use technologies.

5.2 The Nile Forecast System Hydrological Model

The RCM outputs for rainfall and potential evapotranspiration were used to drive the Nile Forecast System (NFS). The NFS is a real-time rainfall-runoff model designed for forecasting Nile flows at designated key points (especially into Lake Nasser in Egypt) in the Nile Basin. The system is hosted at the Nile Forecasting Center (NFC) of the Ministry of Water Resources and Irrigation (MWRI), Giza, Egypt (version 5.1 NFC, 2007). The core of the NFS is a conceptual distributed hydrological model of the entire Nile Basin that includes accounting of soil moisture, hill slope and river routing, lakes, wetlands, and man-made reservoirs within the basin. The inputs to the model are rainfall and potential evapotranspiration. The system relies on satellite-based (METEOSAT) methods to estimate rainfall merged with gridded (to the METEOSAT grid) gauge estimates from freely available sparse gauge data. All rainfall data is stored in the Nile Basin Hydro-Meteorological Information System (NBHIS) which also holds flow records at key river gauges. Elshamy (2006) provided more details on the NFS, including an evaluation of its performance for long term simulations.

6. MODEL SETUP AND VALIDATION

Table 1 summarizes the configuration of the RegCM3 model, the final domain selected, and the data used for specifying the present experiments.

Table 1 Configuration used in defining the RegCM3 domain in the study

Item	**Reanalysis Experiment**	**GCM Nesting Experiment**
No. of Grid Points in y direction	40	40
No. of Grid Points in x direction	44	44
No. of Vertical Levels	18	18
Grid Point Separation in km	60	60
Central Latitude (center of domain)	36 E	37 E
Central Longitude (center of domain)	12 N	13 N
Map Projection	Rotated Mercator	Rotated Mercator
Boundary Conditions:	NRRP1	ECHAM 5
SST	GISST	A1B Scenario SST
Land use / vegetation	GLCC	GLCC
Topography / elevation	USGS	USGS
Time period	1985-2000	Reference: 1985-2000 Future: 2034-2055

Model outputs include a range of parameters, pertaining to radiation, atmosphere and surface data. The outputs of the precipitation and ground temperature, as well as the subsequent hydrological simulation results, as they are of primary interest for the processes were considered and presented here. In this section, these output parameters were compared with the global observation datasets for 1985-2000 listed below. The coming section then discusses the results of the future simulation under the A1B emissions scenario.

- Climate Research Unit (CRU) High Resolution Global Data for climate parameters over land; 6
- Global (GPCP) data sets provided by Precipitation Analysis Laboratory for Atmospheres, NASA Goddard Space Flight Center;
- The Nile Basin Hydro-Meteorological Information System (NBHIS) streamflow dataset.

The selected climatological and hydrological parameters related to the surface outputs were manipulated and appended for the entire simulation period to produce seasonal and monthly average values, for both the reanalysis experiment and the reference and future runs with the nested RegCM3 model.

6.1. Streamflow Results From the Reanalysis Experiment

In the reanalysis experiment (using CRU and GPCP data to specify the RegCM3 boundary conditions), rainfall estimates were routed in the NFS to generate daily runoff and streamflows at different stations along both the Sobat and the Blue Nile Rivers. The model correctly captured the flow seasonality and simulated the peak and low flow profile in both rivers (Soliman et al., 2008). The NFS-simulated flow at Deim (Blue Nile) was considered to be satisfactory, Figure (3). The correlation coefficient between the observed and simulated flows was 0.90 (RMSE = 0.80). However, in the Sobat Sub-Basin, the agreement between observed and simulated flow was not very good (Correlation at the outlet of the Sobat = 0.68). There is a number of possible explanations for these discrepancies:

- the simulation of some extreme storms (which do not exist in the actual data, especially during the 1999 and 2001 flood seasons) were noticed
- few gauges in this region, so there may be errors in the input data used for running the RegCM3 were evident
- the NFS rainfall-runoff model itself relied on sparse data for simulating runoff into the Sobat River
- there might be problems with the NFS routing of flows in this sub-basin, where overbank spills and complicated hydraulics were poorly-understood features of the seasonal swamps.

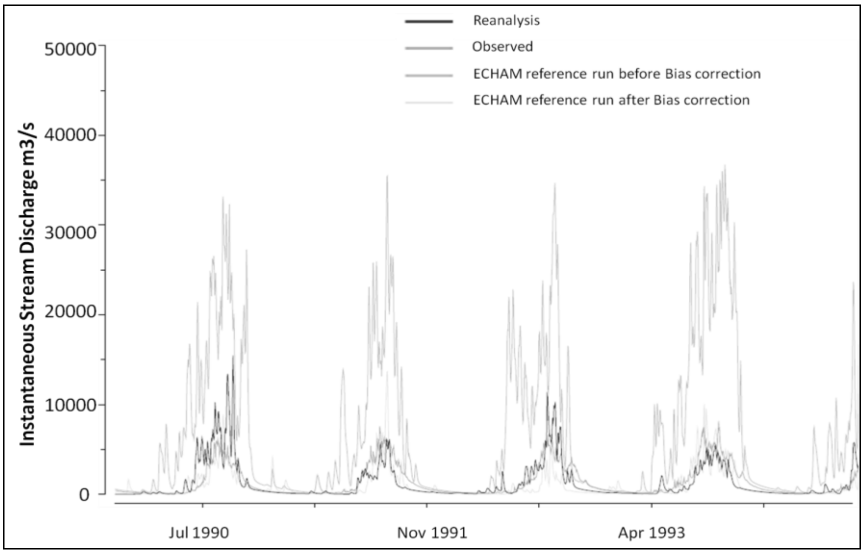


Figure 3: Simulated flow using RegCM3 versus actual flow for Diem

6.2. Setting the Domain Size

In order to set the domain size, 2 seven-year simulation experiments were performed. The implied stream-flow outputs were compared with the observed NBHIS flow. Table (2) presents the correlations between the simulated and observed parameters for the two domain sizes. As shown, the correlation

[6] Available at 0.5 degree resolution from: http://www.cru.uea.ac.uk/cru/data/.

increases as the domain size increases, and the root mean square error (RMSE) decreases. This indicates that using larger domains offers a clear improvement in simulating the stream-flow over this area. However, computational constraints prevented further enlargement of the domain. On the basis of the obtained results, it was concluded that the larger domain is preferable for properly simulating the climatology of the region. For illustration purposes, Figure (4) is given to show the precipitation outputs obtained for the large domain experiment for the SON (September-October-November) season. The correlation between model outputs and observations for these results is roughly 0.9. The level of agreement for other seasons was similar.

Table 2 Comparison between different domain sizes with respect to streamflow

Domain Size	**Monthly Streamflow**	
	Correlation	RMSE
Large (40*44)	Diem: 0.90 Roseires: 0.89	Diem: 0.82 Roseires: 0.78
Small (32*38)	Diem: 0.71 Roseires: 0.55	Diem: 0.89 Roseires:0.82

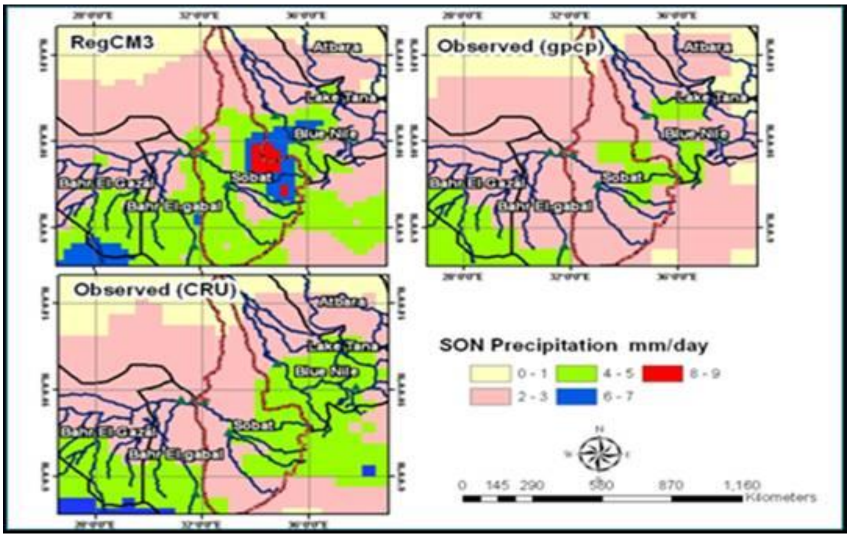


Figure 4: Precipitation outputs for SON compared with the GPCP and CRU datasets.

7. RESULTS OF THE RCM NESTED WITH ECHAM-5

7.1 Setting the Domain Size

In the calibration phase of the nesting experiment, the raw precipitation outputs for the RegCM3 model reference run period (1985-2000) with boundary conditions obtained from ECHAM-5 were compared to the observed precipitation and the precipitation outputs It was found that the nested RCM highly overestimated the rainfall during the JJA wet season, Figure (5).

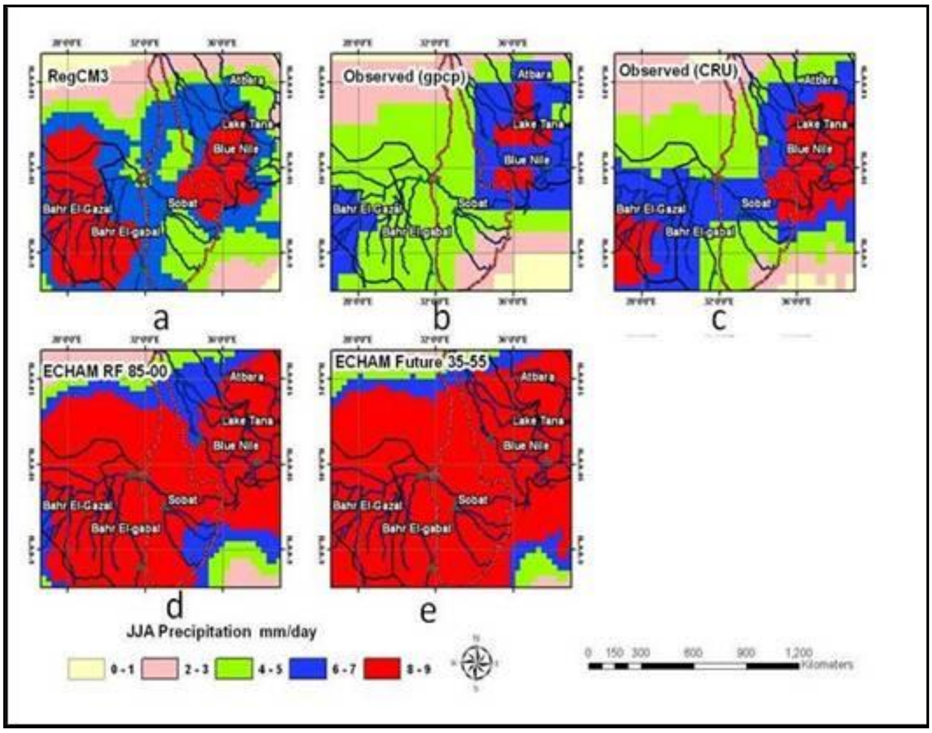


Figure 5: Comparison between JJA precipitation before bias correction from; a) RegCM3 using reanalysis data for boundary conditions (1985-2000), b) GPCP observed data (1985-2000), c) CRU observed data (1985-2000), d) RegCM3 nested with ECHAM; base period (1985-2000), and e) RegCM3 nested with ECHAM; future period (2034-2055).

Therefore, a bias correction scheme was used in order to produce loser outputs to the observed precipitation patterns. A monthly grid of spatially-varying bias correction factors was generated based on the difference between the average observed and average simulated values. The steps of the bias correction mechanism, Figure (6), could be summarized as:

- Average the simulated precipitation of the reference run to produce monthly average grid data (Pre-Rf);
- Average the observed data to produce monthly average grid precipitation (Pre-Obs);
- Divide the observed data monthly grids (Pre-Obs) by the simulated output monthly grids (Pre-Rf);
- The result is a 12 month factor grid which is then multiplied by the daily precipitation outputs for the GCM-nest experiment.

The comparison of the simulated and observational (CRU and GPCC) datasets following bias correction showed a better agreement for the rainy season, Figures (7, 8, 9, and 10). For each of the four climatologically seasons DJF, MAM, JJA, SON) showed the seasonal values of average daily precipitation for the initial simulation using reanalyzed data Panels B and C show that the data obtained from the observed datasets (CRU and GPCP). Panel D displays the simulation outputs from the RegCM3 model nested with ECHAM-5 for the reference period (1985-2000). Panel E shows the outputs for the nested RegCM3 model for the future period (2034-2055; A1B scenario).

The outputs obtained from the nested model reproduced accurately the spatial and seasonal variation in precipitation over Blue Nile. However, consistent with the difficulties encountered in simulating streamflow in the Sobat in the reanalysis experiment, it was noticed that the model overestimated the rainfall over the Sobat Sub-Basin during the dry season. In general the model simulated precipitation reasonably well over the combined Blue Nile and Sobat sub-basin.

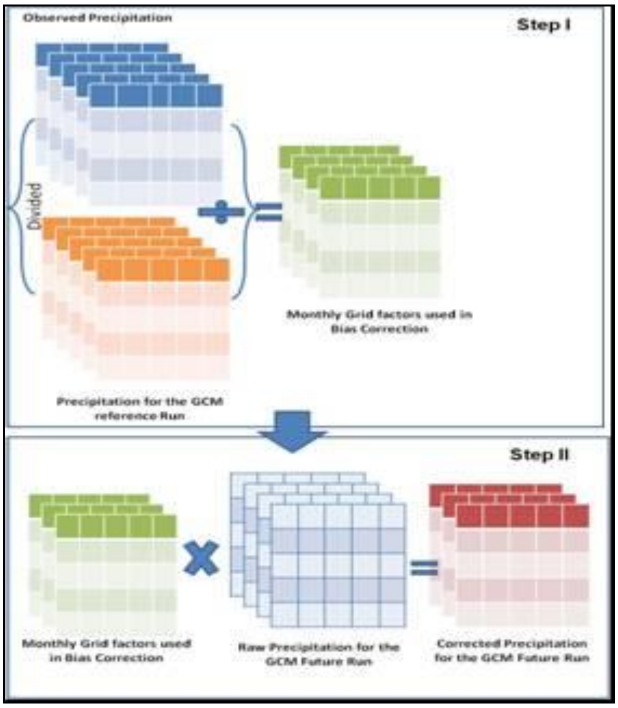


Figure 6: Procedure used to remove precipitation bias

In order to facilitate the comparison of the rainfall patterns between the reference and future simulations, , the precipitation outputs over portions of this river basin was examined prior to the simulation of Blue Nile streamflow using the averaging tools in the NFS. Two smaller catchments at Mendaya and Border, two potential sites for large reservoir projects in Ethiopia were defined. The Mendaya catchment covers roughly 57% of the Upper Blue Nile Sub-Basin in Ethiopia, with the Border catchment covering the rest. Figure (11) shows that the rainy season over the Mendaya sub-catchment lasts somehow longer than the Border catchment further downstream. In general, these results predicted small changes in rainfall, with a small decrease in areal precipitation over the Mendaya sub-catchment (~5%) offset by a slightly increase in areal precipitation over the Border sub-catchment (~7%).

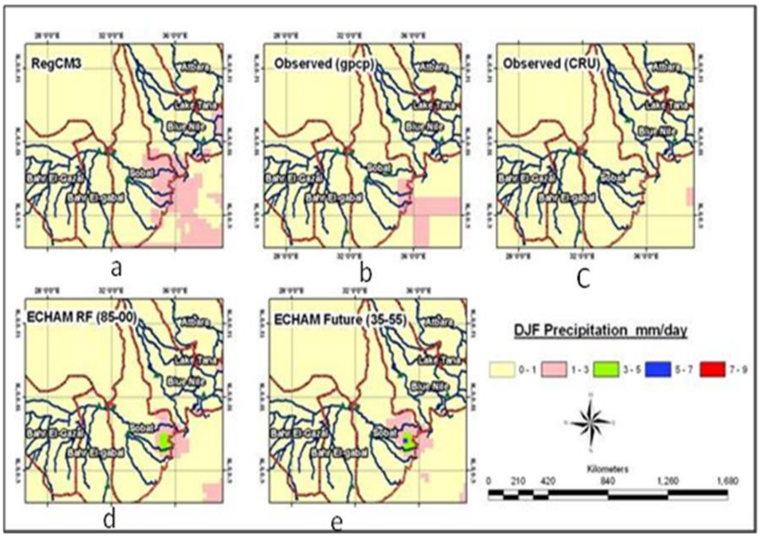


Figure 7: Comparison of precipitation for DJF from a) Regcm3 reanalysis (1985-2000), b) GPCP observed data (1985-2000), c) CRU observed data (1985-2000), d) ECHAM base period (1985-2000), and e) ECHAM future period (2034-2055).

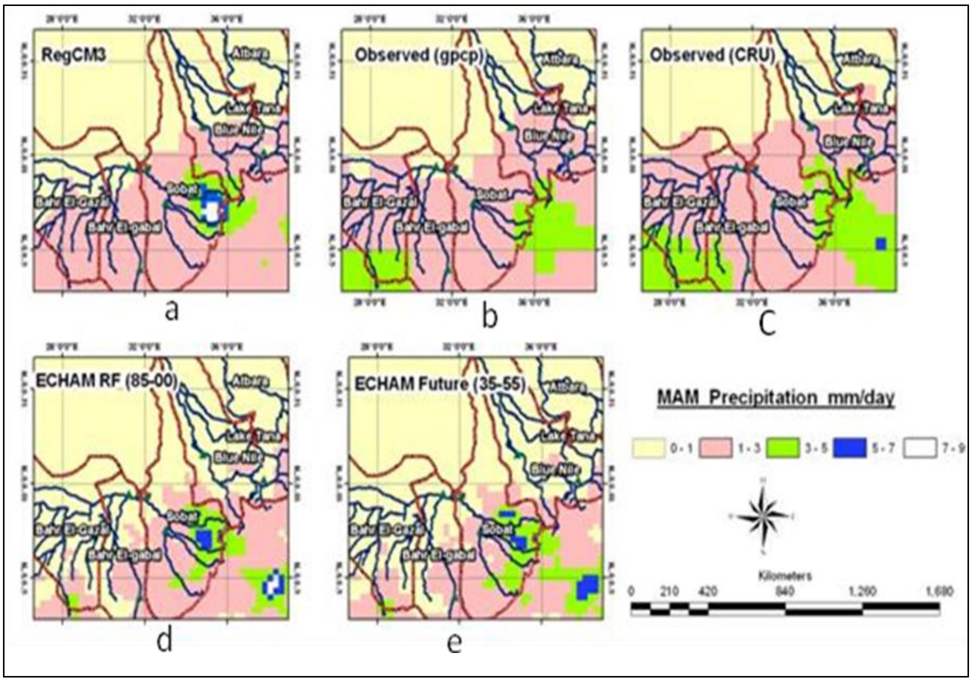


Figure 8: Comparison of precipitation for MAM from a) Regcm3 reanalysis (1985-2000), b) GPCP observed data (1985-2000), c) CRU observed data (1985-2000), d) ECHAM base period (1985-2000), and e) ECHAM future period (2034-2055).

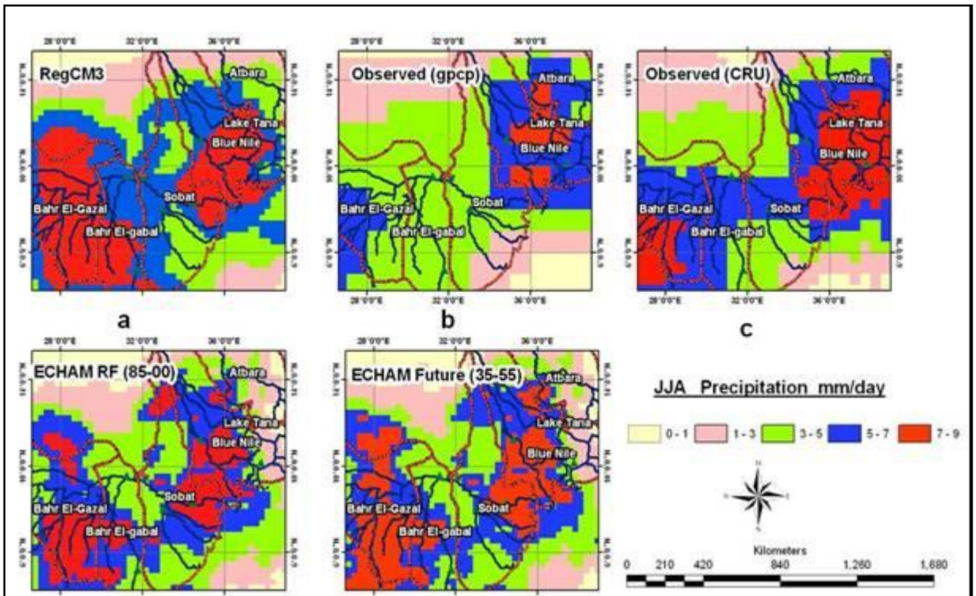


Figure 9: Comparison of precipitation for JJA from a) Regcm3 reanalysis (1985-2000), b) GPCP observed data (1985-2000), c) CRU observed data (1985-2000), d) ECHAM base period (1985-2000), and e) ECHAM future period (2034-2055).

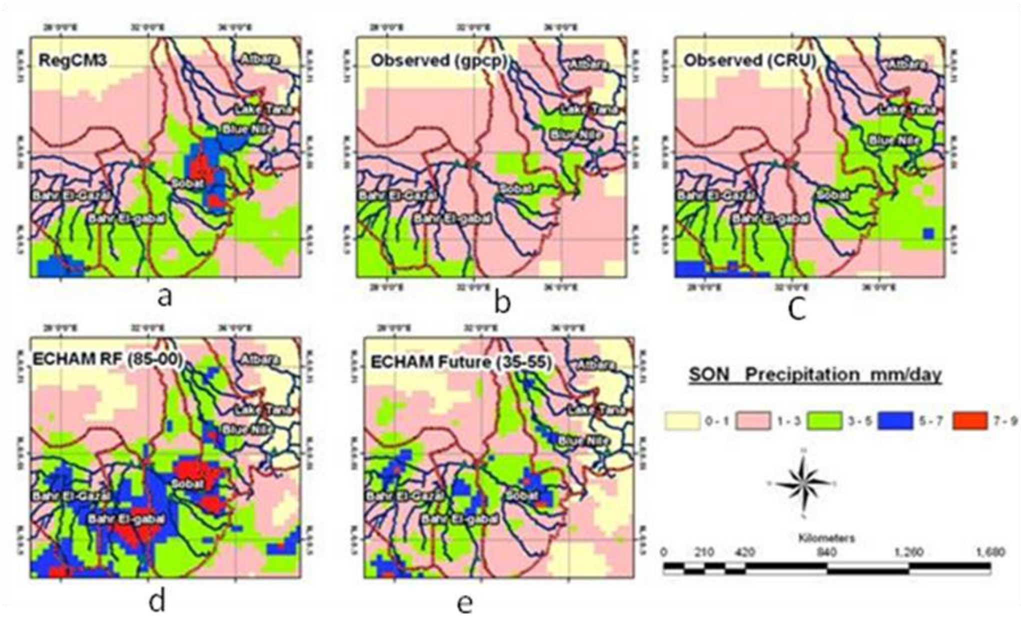
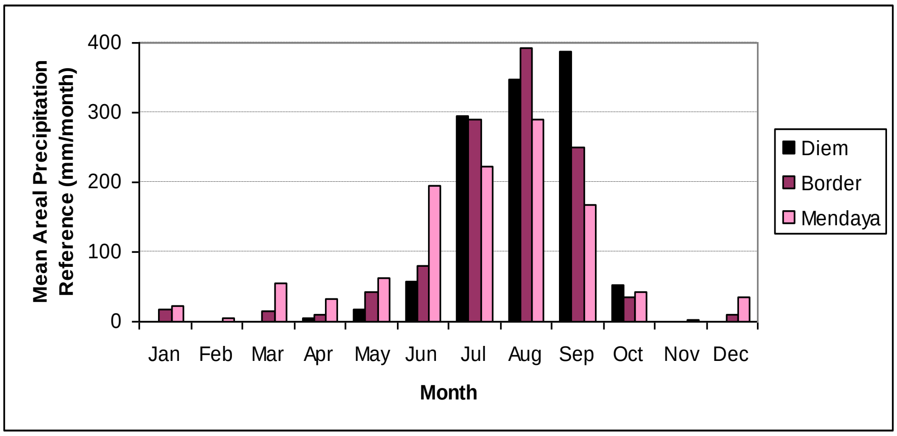


Figure 10: Comparison of precipitation for SON from a) Regcm3 reanalysis (1985-2000), b) GPCP observed data (1985-2000), c) CRU observed data (1985-2000), d) ECHAM base period (1985-2000), and e) ECHAM future period (2034-2055).



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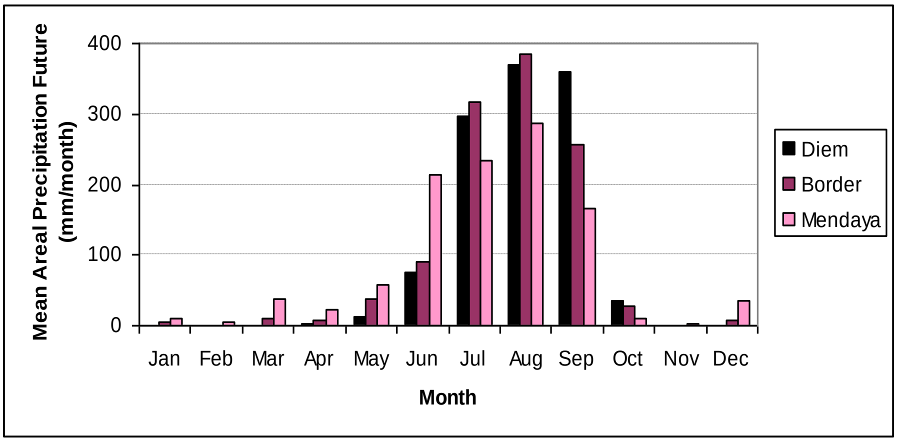

B

Figure 11: Mean areal precipitation for Diem, Border and Mendaya Sub-Catchments for the A) RegCM3 reference run and B) RegCM3 future simulation.

7.2 Blue Nile Stream-flow

To assess the reliability of the RegCM3 predictions for exploring eventual changes in streamflow, the simulated rainfall estimates were used as inputs in the NFS to generate basin runoff and daily streamflows at stations with reliable gauge measurements along the Blue Nile.

The model appeared to correctly capture the flow seasonality and to simulate the peak and low flow profile at Deim station in Sudan, although high flows appeared to be somehow underestimated. The Root Mean Square Error (RSE) was estimated to be 0.75. Errors bars between the actual and simulated data are presented on Figure (12). The correlation coefficient between observed and simulated flows was 0.87. Obvious was that the results confirmed the substantial error in simulating the magnitude of peak flows even though their seasonality was accurate. Results obtained for a comparison of simulated and observed streamflow at the Roseires station further downstream were similar (please explain this statement).

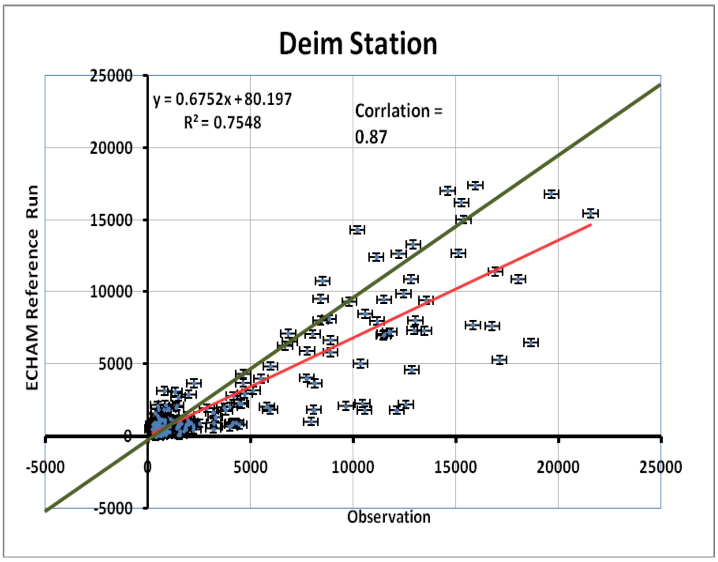

Figure 12: Simulated flow using RegCM3 versus actual flow for Diem

In order to illustrate the seasonality of the flows in a better way, a subset of the streamflow for the future simulation is given, using the flow series for the five years leading up to year 2055, Figure (13). The inter-annual variation in flow over this period is fairly high, consistent with the observed river flows for the Upper Blue Nile. Figure (14) compares the monthly flows in the reference and future runs as well as the % change in flow. The overall annual change in flow is small: +1.5%. However, the seasonality of flow increased. In average, early flood season flows in JJA increase by 10%, while dry season and late flood season flows decrease.

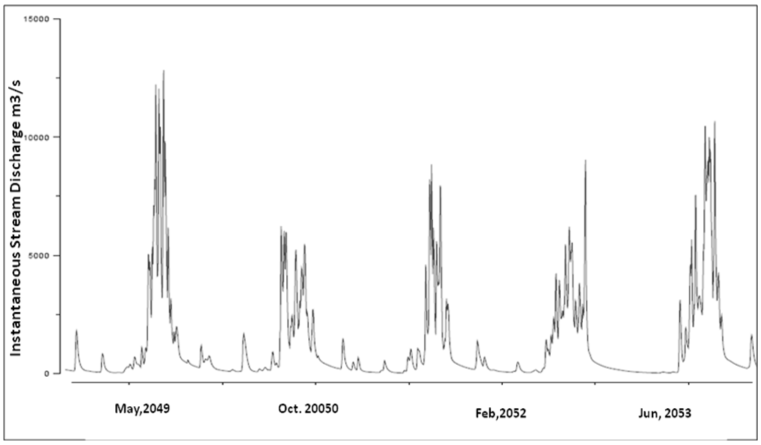

Figure 13: Prediction of future flow for Diem Station on the Blue Nile in Sudan

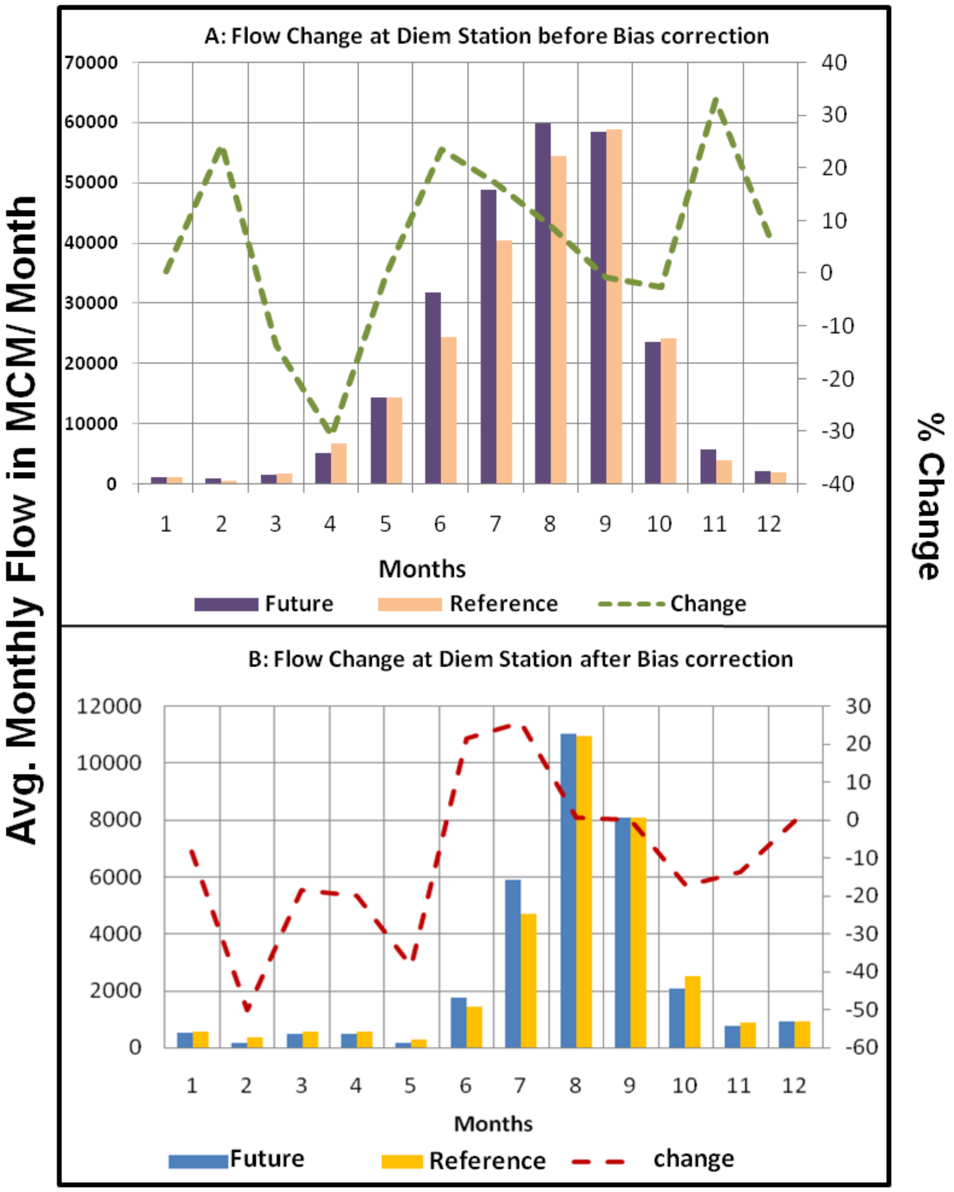

Figure 14: Changes in mean monthly streamflow of the Blue Nile at Diem; A) before bias correction and B) after bias correction.

8. CONCLUSION AND RECOMMENDATIONS

In general, it appears that the RegCM3 is able to reproduce the precipitation patterns observed over the Upper Blue Nile, correctly, thus reproducing the seasonality and spatial variation of rainfall, and providing inputs to the NFS model which resulted in obtaining accurate predictions of streamflow observed at Diem. For the Sobat basin, clear was that the model might require some additional study and adjustments.

The model behavior could be summarized as follows:

- The spatial pattern of precipitation was well captured by the model both in the summer and winter. Using the RegCM3 model nested with ECHAM-5, precipitation was predicted to decrease slightly over the Mendaya sub-catchment of the Blue Nile (-5%), and to increase somehow over the Border sub-catchment (+7%) in the A1B scenario
- The multi-year flow simulation using RegCM3 output data fed to the NFS showed good performance in capturing the seasonality of flows, although high flows were underestimated in the simulation experiments

- The prediction of future change in Nile flow at Diem Station was calculated as 1.5% on a yearly basis (~740 MCM/year). However, the flow change was larger during the beginning of the flood season (+10%), while the flow was predicted to decrease towards the end of the rainy season in October and November, as well as in the dry season.
- It was thus recommended to extend this analysis by:
- Continuing to work with this RCM to investigate temperature predictions;
- Reconfiguring the RCM (and obtaining the necessary computational resources to run it) with a larger domain that encompasses the entire Nile Basin in order to reduce errors related to domain size as well as improve the applicability of model results for conducting hydrological analyses related to the Nile Basin (this appears particularly important in light of the fact that the precipitation was overestimated in the rainy season for the domain studied here);
- Attempting to nest RegCM3 with other GCMs;
- Extending the analysis to include more climate scenarios;
- Exploring the relationship between climate and land use in the Blue Nile Sub-Basin, especially as it relates to watershed restoration projects or the construction of new storage reservoirs in Ethiopia;
- Using these results to explore the value of increasing spatial resolution in predictions of future climate for the purposes of water resources planning and management.

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10. LIST OF ABBREVIATIONS

AVHRR	Advanced Very High Resolution Radiometer
BATS	Biosphere-Atmosphere Transfer Scheme
CRU	Climate Research Unit, United Kingdom
GLCC	Global Land Cover Characterization
GPCP	Global precipitation control points provided by Goddard Space Flight Center
hPa	Unit of measurement of pressure (height in Pascal)
ICTP	Abdus Salam International Center for Theoretical Physics
NBHIS	Nile Basin Hydro-Meteorological Information System
NCAR CCM3	National Center for Atmospheric Research Community Climate Model
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NFC	Nile Forecasting Center
NFS	Nile Forecast System
NOAA	National Oceanic & Atmospheric Administration
OISST	Optimally Interpolated Sea Surface Temperature
RCM	Regional Climate Model
RMSE	Root Mean Squared Error
SST	Sea Surface Temperature
USGS	United States Geological Survey

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