Physics and Chemistry of the Earth 35 (2010) 618–633

Contents lists available at ScienceDirect

Physics and Chemistry of the Earth

journal homepage: www.elsevier.com/locate/pce

# Evaluation and inter-comparison of Global Climate Models' performance over Katonga and Ruizi catchments in Lake Victoria basin

P. Nyeko-Ogiramoi [a,c,*], G. Ngirane-Katashaya [b], P. Willems [c,d], V. Ntegeka [c]

[a] Directorate of Water Development, Rural Water Division, Ministry of Water & Environment, PO Box 20026, Kampala, Uganda
[b] Makerere University, Civil Engineering Department, PO Box 7062, Kampala, Uganda
[c] Katholieke Universiteit Leuven, Department of Civil Engineering, Hydraulics Division, Kasteelpark 40, 3001, Belgium
[d] Vrije Universiteit Brussel, Department of Hydrology & Hydraulic Engineering, Pleinlaan 2, 1050 Brussels, Belgium

ARTICLE INFO

*Article history:*
Received 3 February 2010
Received in revised form 19 July 2010
Accepted 31 July 2010
Available online 5 August 2010

*Keywords:*
Climate models
Consistency
Evaluation
Extremes
Rainfall
Quantile analysis

ABSTRACT

Regional impact assessments of climate change on hydrological extremes require robust examinations of climate model simulations. The climate models may satisfy mean statistics but fail to reproduce extreme quantiles which are crucial for applications of climate change impact analysis on water resources. Through statistical analysis, this paper evaluates and inter-compares the performance of Global Climate Model (GCM) simulations for their ability to predict changes in hydrological extremes for given locations or catchments in the Nile basin. Two catchments were considered: Katonga and Ruizi catchments in the Lake Victoria basin. Models that differ significantly from the observed extremes were considered unreliable for impact assessments on hydrological extremes. A graphical approach (rainfall quantile/frequency analysis), which allows for easy spotting of discordant models, in combination with several statistics, was used to evaluate 18 GCM control simulations against observed rainfall data. Standard deviation, coefficient of variation and root mean squared error (about the mean) of the observed rainfall, were used to derive error margins against which GCM simulations were evaluated. Model results outside the error margins were considered inconsistent with the observed rainfall. Model inter-comparison was also carried out for the rainfall change projections till the 2050s and 2090s through analysis of perturbations and percentage changes based on A1B, A2, and B1 SRES scenarios. It is noted that the GCM outputs are more consistent in reproducing rainfall signatures at annual aggregation level than at monthly aggregation levels with tendency of overestimation of the rainfall depths but with significant variation among different GCM simulations. The GCMs perform better in reproducing rainfall frequency with higher return periods compared with lower return periods. Most of the GCMs perform better for the wet months than the drier months. The GCMs CGCM3.2a, CM3.O, CM4.1, PCM1, CGCM3.1T47, MIROC3.2.HIRES, CCSM3.0 and FGO-ALS, are the most inconsistent with the observed rainfall for both catchments. Good performing models are MK3.5, MK3.0, ECHAM5, CM2.1U.H2 and CM2.0. In general, most GCMs perform poorly for both catchments. This signals the need for significant improvements in the rainfall modelling of the climate models for the study region. There is no strong evidence to suggest that GCM performance improves with higher spatial resolution. Models which are highly inconsistent with other models in reproducing the observed rainfall are not necessarily inconsistent with other models in the future projections. Differences in projections for the A1B, B2, and B1 scenarios were found to be smaller than the differences between the GCM simulations.



## 1. Introduction

Climate change impact on a catchment is determined from the impact comparison of the historical hydrological state and the future hydrological state after perturbations of the hydro-climatic variables (Gosain et al., 2006; Dagnachew et al., 2003; Notter et al., 2007; Yanjun et al., 2008; Shen et al., 2008). Most often, the Special Report on Emission Scenarios (SRES) (Nakicenovic et al., 2000) based scenarios are adopted; which set various climate model predictions in different future scenarios. Today, several climate models' simulation results of the past, present and projected future climate exist. Evaluation of the performance of the climate models is an important step in climate change impact assessment.

The credibility of a Global Climate Model (GCM) to predict the future climate depends on its ability to reproduce current and past

* Corresponding author at: Katholieke Universiteit Leuven, Department of Civil Engineering, Hydraulics Division, Kasteelpark 40, 3001, Belgium. Tel.: +32 16321174; fax: +32 16321989.

*E-mail address:* nyeko_ogiramoi@yahoo.co.uk (P. Nyeko-Ogiramoi).

1474-7065/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pce.2010.07.037

climate, either for a particular region and/or for the globe. In addition, a compelling case is the ability of the GCM not only to predict the average climate conditions but also the variability in hydro-climatic variables (Katz, 1992). Regardless of the result, the model can be viewed critically in order to better understand the reasons of good performance or unrealistic prediction. In weather prediction, forecasts are produced on a regular basis and testing against what actually happens can be quickly performed. In contrast, climate predictions are designed for much longer periods of time or many decades and for conditions without precise past analogues. One direct way to gain confidence about a model for performing such predictions is to compare its predictions with known historical measurements or indirect evidence when records are missing. Results of climate model simulations are needed in impact analysis but for simulation to be considered appropriate, the results should fulfill some quality criteria (Christensen et al., 2007a,b). Simulation of climate, for periods for which data are available and to acceptable accuracy, is one of the most important qualities of a reliable climate model. The difficulty here is in determining what is acceptable or reasonable. Statistical metrics can be used to define the quality criteria and acceptability for a reasonable simulation. Although the field of statistics has played a relatively minor role in the development of GCMs, its importance in validating the models is indispensable.

Statistics of errors, biases, correlations and trends have been used to quantify statistical inconsistencies between the model simulations and the historical time series (Walsh et al., 2008; Ntegeka et al., 2008; Ntegeka and Willems, 2008; Christensen et al., 2007a,b; Emori et al., 2005; Wild et al., 1995; Katz, 1992). This approach can satisfy mean statistics of the considered parameters. Due to the nonlinear character of the weather and climate evolution, the precision with which the actual climate must be represented by model simulations is simply unknown. Despite the weak relation between certain measures of the models to simulate correctly the climatology and the precise prediction of future climate, revealed by some studies (Randall et al., 2007; Houghton et al., 2001), it still remains unclear what are the minimum criteria a model should meet to be considered a reliable prediction tool.

The model-testing phase has many aspects. Climatic model must first of all be tested at system level; that is running the full model, including all components, and comparing the results with observations. But because of the model complexity, the problems discovered are difficult to trace back to their source. This suggests a more modular testing procedure: instead of comparing the full model results with the observations, one can proceed to test the model at component level, that is, isolate the individual model components and test each independently from the others. This is a common practice in model testing. The components of a climatic model usually tested in this approach are the atmospheric, oceanic, sea ice and land-surface components (Emori et al., 2005). Despite the former, evaluating a climate model's performance at catchment scale would require archiving all observed variables at a central point and performing a testing exercise. This is impractical as data availability, storage and computational requirements can impose a large constraint.

Impact analysis of climate change on hydrology of a catchment is inherently tied to the study of extreme values of certain meteorological variables (Carter et al., 2007). In the context of model testing, GCM simulations may satisfy mean statistics of a given variable but fail to reproduce extreme quantile signatures, which are crucial for their selection and applications in impact analysis on extremes. What is of great interest in such impact analysis is a quantitative measure and description of the data set values lying in the extremes of the data distribution. Classically, one can always calculate absolute and mean (over given time intervals) extreme values (minimum and maximum), and provide an empirical estimation of the frequency of occurrence of events resulting in such extreme values. This is in contrast with performance assessment when bias and mean square errors are used (Walsh et al., 2008), in which it is difficult to correlate the signature of simulated extreme events with that of observations. In the case of hydrology, these will be weather/storm events. The ability of a GCM to reproduce extremes in the observations may provide an indication of its strength to predict future extreme events.

Since water resources, in many parts of the world, are managed at catchment scale and adaptation is local, assessing the impact of climate change at both micro and macro scale is essential. This means that assessing the performance of GCM at catchment scale, for the areas where GCMs outputs are the only data available for performing climate change impact study, is an important step in selecting the climate model results to be used. Rainfall plays a very important role in hydrology and constitutes the most fundamental meteorological variable at catchment scale. The models' performance is therefore evaluated for rainfall.

In this study, quantile/frequency analysis techniques and other statistical metrics (Ntegeka et al., 2008; Baguis et al., 2010) are used to evaluate the performance of 18 GCM simulations in reproducing observed rainfall over the Katonga and Ruizi catchments in the Lake Victoria basin (Nile source region). Although there is little consensus on the future climate, model results that differ significantly from the observed rainfall and/or from other model results, will be considered inappropriate for climate change impact analysis at catchment scale.

Section 2 gives an overview of the study area and the data used in the study. The statistical evaluation metrics are also presented in this section. In Section 3, a detailed study of the performance of the GCM simulations is presented and in Section 4 the findings are summarized.

## 2. Methods

### 2.1. Study area

Katonga and Ruizi catchments are local catchments within the Lake Victoria basin (Fig. 1). The sizes of Katonga and Ruizi catchments are in the order of 1000–3000 sq km, respectively. The long term average discharges downstream in the catchments are 5.1 m3 $s^{-1}$ and 3.8 $m^3\,s^{-1}$ for Katonga and Ruizi, respectively. These flows contribute about 3% of the total inflow into Lake Victoria. The mean annual observed rainfall depths in the two catchments are 1136 mm and 680 mm, for Katonga and Ruizi catchments, respectively implying that Katonga catchment receives about twice as much rainfall as that of Ruizi catchment.

The topography of Katonga catchment is generally flat, allowing satellite wetlands to predominate. River Katonga originates from Lake Wamala and empties its entire flow into Lake Victoria. Meanwhile Ruizi catchment is partly flat and sloppy with most parts of the catchment being degraded by runoff, deforestation, overgrazing and inappropriate agricultural practices. Discharge from River Ruizi enters River Kagera before it is emptied into Lake Victoria. The two catchments have seen significant environmental changes and provide an opportunity for climate change impact analysis on their respective hydrology. Also, because water is managed at micro to macrocatchment level, predicting possible hydrological changes in the two catchments is significant for water managers. Given that the major water resources problems in the study catchments are related to both droughts and floods, focus is given on the study of rainfall extremes.

### 2.2. Observed data

Daily observed data were obtained, mainly, from the FRIEND/ Nile (River Nile basin Flow Regimes from International, Experimen-