Atmospheric Research 161–162 (2015) 57–64

Contents lists available at ScienceDirect

Atmospheric Research

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

Evaluation of regional climate model simulations of rainfall over the Upper Blue Nile basin

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ARTICLE INFO

Article history:
Received 2 September 2014
Received in revised form 16 March 2015
Accepted 17 March 2015
Available online 26 March 2015

Keywords:
Upper Blue Nile
Climate change
RCM
GCM
Rainfall evaluation

ABSTRACT

Climate change impact and adaptation studies can benefit from an enhanced understanding about the performance of individual as well as ensemble simulations of climate models. Studies that evaluate downscaled simulations of General Circulation Models (GCMs) by Regional Climate Models (RCMs) for African basins are noticeably missing. Recently, the Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative has made multiple RCMs' outputs available for end users across the African continent. Before climate simulations receive applications in impact and adaptation studies, accuracy of the simulation results has to be evaluated. In this study, the rainfall accuracy of eight independent GCMs at a wide range of time scales over the Upper Blue Nile Basin (UBN) in Ethiopia is evaluated. The reference data for performance assessment was obtained from the rain gauge network of the National Meteorological Agency of Ethiopia (www.ethiomet.gov.et/). The models were evaluated using a suite of statistical measures such as bias, Root Mean Squared Error (RMSE), and Coefficient of Variation (CV). Plots of observed vs. simulated rainfall amounts are also used. Findings of this study indicate that the models have some limitations in simulating light (<1 mm) daily rainfall and heavy (>10 mm) daily rainfall amount. The annual rainfall bias of the models varies between −1.4% and −50% suggesting underestimation. In many aspects the MPI-ESM-LR climate model performed best in terms of bias and RMSE. However, it was found that the performance of the models differs subject to the performance measures used for evaluation. The use of the ensemble mean rainfall simulation did not improve representation of assessed rainfall characteristics in the basin. Based on the findings in this study, we suggest to use multi-models' simulations in order to capture different aspects of the Upper Blue Nile basin rainfall. Topography and rain rate dependent bias correction algorithms should be evaluated for the basin. This study is expected to be valuable for climate change impact and adaptation studies in the UBN basin.

1. Introduction

Upper Blue Nile (UBN) basin has key regional importance as it is the largest contributor to the Nile River flow. As such, any change in the climate of UBN has transboundary effect and may affect and possibly threaten water supply to downstream Nile Basin countries. In the UBN and Nile basin at large, irrigation and hydropower schemes are planned which are expected to contribute to improved food security and energy provision in the region (McCartney et al., 2010). The reliability and sustainability of these schemes are subject to climatic fluctuation and change which may add to existing challenges in water resources management in the basin. Livelihood of farmers in the basin is sensitive to climate conditions as crop cultivation is dominantly rainfed. Also livestock population is large and provides a major source of income. Therefore, climate change assessment studies are important not only to advance knowledge but also to create awareness and to develop adaptive water resources and management plans in UBN.

Climate change impact and adaptation studies can benefit from an enhanced understanding about the performance of individual General Circulation Models (GCMs) as well as ensemble simulations of GCMs when dynamically downscaled using Regional Climate Models (RCMs). Because of the crucial role of climate models in this process, it is essential to characterize their strengths, weaknesses and uncertainties (Kim et al., 2014; Walther et al., 2013; Xue et al., 2014).

In UBN, rainfall is largely variable both in geo-space and time dimensions. Variability is affected by the Inter Tropical Convergence Zone (ITCZ), the Saharan anticyclone, and the Arabian heights which produce thermal lows during the inter-seasonal periods. Aspects of large scale wind circulation over the study area were studied in Camberlin (1997). Findings indicated that during the rainy season a general south-westerly monsoon flow can be noticed whereas in eastern Africa as a whole, wind flows are distinctly affected by topography features. Further, in Camberlin (2009) it is described that topography is the most important factor that modifies the general circulation

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http://dx.doi.org/10.1016/j.atmosres.2015.03.013

pattern and refers to Haile et al. (2009); Rientjes et al. (2013) for studies in the UBN basin. For climate change assessments this raises the need for relatively high resolution simulations possibly from RCMs to improve representation of the highly variable climatic condition.

Accurate and reliable simulation of the climate over the African continent by means of GCMs and RCMs is a major challenge partly due to the complexity and the diversity of processes to be represented (after Laprise et al., 2013). Other facets relate to scale issues by i) large differences in the spatial and temporal scales which the processes occur, ii) the processes are observed and iii) the processes are simulated. We note that outputs of GCMs and RCMs mostly are at pixel sizes in the order of 250 km × 250 km and 50 km × 50 km, respectively. Also, poor reliability of GCM outputs at fine temporal scales such as daily cause that results must be exercised with care (Abdo et al., 2009). For the use of GCM outputs in hydrological impacts assessment and adaption studies, downscaling of outputs to smaller scales is advocated and refer to the World Climate Research Program (WCRP) who initiated and sponsored the CORDEX program (http://wcrp.ipsl.jussieu.fr/Workshops/Downscaling/DirectionVenue.html).

CORDEX is an internationally coordinated effort to support climate change impact and adaptation studies by making relatively fine scale (approximately 50 km × 50 km) climate projections readily available to users. Downscaling is through a RCM by using initial conditions and boundary conditions as obtained from selected GCMs or from reanalysis data which is merged climate model and observed data. The numerical boundary conditions for RCM simulations can, for instance, include vertical profiles of climate variables and surface conditions over oceans. In principle RCMs cannot remove GCM biases related to large scale variables. However, downscaling GCM outputs by RCMs may lead to improved simulation at the GCM sub-grid scale as a result of using relatively high resolution data such as topography and land cover. Whereas simulations by RCMs are spatially more accurate by the much smaller grid element scale it is often assumed and expected that reliability of the estimates also increases. As such it is assumed that downscaling leads to reduction of bias and errors though this is not always true as some errors may remain uncorrected or are even amplified by RCM simulation (e.g. Laprise et al., 2013).

Kim et al. (2014) stated that the CORDEX program can serve several purposes which include GCM and RCM evaluation, uncertainty assessment of climate simulations and construction of multi-model ensembles. It is expected that Africa will particularly benefit from the CORDEX program as the continent is highly vulnerable to climate change by low adaptive capacity and since RCM simulations for the continent were noticeably few (Giorgi et al., 2009). Therefore, downscaled GCM outputs by a RCM may provide important information to climate adaptation practices, risk assessment studies and policy planning. Though GCMs and RCMs have wide application across the globe, there are only limited applications in Africa. CORDEX-Africa provides a good opportunity to study the models' performance in simulating the key elements of the African climate (Hernández-Diáz et al., 2013) outside of their native region. We note that sound evaluation of simulation results by RCMs at sub-regional scales across the continent is hindered by poor observation networks and lack of data sharing.

Evaluation studies on RCM simulation results over the major river basins of Africa only are few. Kim et al. (2014) reported that five out of ten models of CORDEX-Africa (http://cordex.dmi.dk/joomla/) somewhat captured the magnitude of inter-annual rainfall variability across the continent. In the same study spatial variability of annual mean rainfall over the Ethiopian highlands was overestimated by the models. Findings in Endris et al. (2013) for the Ethiopian highlands indicate that simulation results of ten models of CORDEX-Africa captured the shape of the monthly rainfall distribution and the annual rainfall anomaly but overestimated the mean monthly rainfall amount. The study showed that the correlation coefficient between annual rainfall of the models and the reference data set is higher than 0.7 for four RCMs and between 0.4 and 0.7 for six models.

Laprise et al. (2013) evaluated the fifth-generation Canadian Regional Climate Model (CRCM5) over the CORDEX Africa domain. The boundary condition data set was obtained from simulations of the MPI-ESM-LR and CanESM2 Global Climate Models (GCMs) of the Max-Planck-Institute für Meteorologie (http://www.mpimet.mpg.de/en/home.html) and the Canadian Centre for Climate Modeling and Analysis (http://www.cccma.ec.gc.ca/), respectively. The authors reported that CRCM5 was able to reduce the biases to rainfall estimates of the two GCMs in most cases though in some instances biases remained uncorrected or even amplified in the elevated areas of Ethiopia and Sudan.

The aforementioned studies used globally available gridded data sets as reference to evaluate RCMs' outputs by the CORDEX-Africa program. Gridded data sets available in the public domain are gauge only rainfall data (e.g. New et al., 2002), satellite only rainfall estimates (e.g. Joyce et al., 2004) or combined satellite-gauge data (e.g. Huffman et al., 2007). Gauge based gridded data sets are interpolated rainfall network data based on the most direct rainfall observation. However, rainfall representation by a network of stations has constraint and, moreover, not all time series from meteorological offices are available by restrictions on data sharing. Alternative to gauged rainfall is satellite rainfall which provides spatial coverage but estimates are uncertain (e.g. Rientjes et al., 2013) and have significant random and systematic errors over the Ethiopian highlands (e.g. Haile et al., 2013). As a result, the various global gridded data products are characterized by marked differences in their estimates of rainfall inter-annual, intra-annual and diurnal cycles over Africa (Nukilin et al., 2012; Kim et al., 2014). Over the East Africa region such differences were reported to be large (Habib et al., 2012; Dinku et al., 2007).

The objective of this study is to evaluate the CORDEX-Africa RCM results for historical rainfall over the UBN basin. We conducted the evaluation for annual, season and daily time scales in order to improve our understanding of reliability of dynamically downscaled simulations of eight GCMs which were part of the Coupled Model Intercomparison Project Phase 5 (CMIP5). The downscaling was accomplished by the recent version of the Rossby Centre using the Regional Climate Model — RCA4 (http://www.smhi.se/en/). Recent evaluation of CORDEX-Africa simulations focused on the entire continent or regions using global data sets as reference. However, our evaluation is for the UBN basin with rainfall time series from the National Meteorology Agency (NMA) observation network which serves as reference data set. Further details are added in the following sections.

2. The Upper Blue Nile basin

The Upper Blue Nile (UBN) basin covers a surface area of 173,000 km^2 which extends between latitudes of 7°44′32″ to 12°45′19″ north and longitudes of 34 ° 29′20″ to 39°48′17″ east. UBN River originates by the outflow of Lake Tana which drains towards the south-east direction, follows the north–south direction and then meanders in the east–west direction towards the Sudan border. The length of the river in Ethiopia is about 800 km. Elevation varies between ~500 m (near the Sudan border) and ~4200 m (Choke-mountain and some ridges in the eastern part) with large variability but also extreme mountainous topography (Conway, 2000). The climate in the basin changes from humid at the higher elevation zones to semi-arid in lower zones. The traditional Ethiopian classification of climate is based on elevation with three distinct zones: 1) the Kolla zone below 1800 m with mean annual temperatures of 20–28 °C; 2) the Woina Dega zone between 1800 and 2400 m with mean annual temperatures of 16–20 °C and 3) the Dega zone above 2400 m with mean annual temperatures of 6–16 °C (after Conway, 2000). As a result of the contrasting terrain and climatic factors, there is large spatial rainfall variability across the basin. Haile et al. (2009) and Rientjes et al. (2013) show that intra-annual, inter-annual and diurnal rainfall distributions across the basin