The effect of topography on east African rainfall based on regional climate model

BOB ALEX OGWANG*, HAISHAN CHEN* and XING L. I.*

*Key Laboratory of Meteorological Disaster, Ministry of Education, Nanjing University of Information Science and Technology, China
#Uganda National Meteorological Authority, P. O. Box 7025, Kampala, Uganda

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e mail: bob_ogwang@yahoo.co.uk; obobalex@gmail.com

ABSTRACT. The effect of topography on June to August (JJA) rainfall over east Africa is investigated using the International Centre for Theoretical Physics (ICTP) Regional Climate Model (RegCM4.0). Grell convection scheme with Fritsch-Chappell closure assumption is used. The control simulation is done with actual topography and sensitivity experiments are carried out with topography reduced to 75%, 25% and to zero. The model output was evaluated against Climate Research Unit (CRU) dataset, gridded at 0.5 degree resolution and ERA-interim datasets, gridded at 0.75 degree resolution. Results show that the mean JJA rainfall significantly reduces over the region when topography elevation is reduced. Based on the model, when the topography over the selected region (KTU) is reduced to 25%, the mean JJA rainfall over east Africa is reduced by roughly half. The maximum rainfall reduction is however observed around the region over which topography is reduced. The reduction in topography resulted into an anomalous moisture divergence over the region at low level (850 hPa). Divergence at low level results in vertical shrinking which suppresses convection due to subsidence. The strength of moisture transport and the zonal wind speed at 850hpa increased with decrease in topography, which may be responsible for the observed shift in moisture convergence zone from western Kenya to northern Uganda. The findings from this study would provide insight into the effect of topography on the east African climate and call for more detailed investigative research, particularly in the region. The results may motivate researchers and modeling centers to further improve on the performance of the model over the region.

Key words – Regional climate model, Topography, Rainfall, East Africa, RegCM4.0.

1. Introduction

In the tropics where the domain of this study lies, the most important climate element is rainfall (Okoola, 1999).

In recent years, east Africa has suffered frequent events of both excessive (Webster et al., 1999; Latif et al., 1999) and deficient rainfall (Hastenrath et al., 2007) which impacted negatively on the economy since most of the
economic sectors largely depend on water resources. Rainfall variability and predictability is therefore important aspects to address in climate research, especially over the region. The patterns of rainfall (precipitation) over east Africa are generally controlled by the seasonal migration of the inter-tropical convergence zone (ITCZ) that migrates, north-south, across the region twice a year. The ITCZ thus tends to impose a significant influence on the climatological rainfall and temperature patterns. ITCZ influences and defines the bimodal rainfall regime experienced in most parts of the region during March to May (MAM) and October to December (OND). Normally, the passage of ITCZ leads the onset of the two rainy seasons by 3 to 4 weeks, but this may be modulated from season to season by the interactions between the ITCZ and perturbations in the global climate circulation, as well as with changes in the local circulation systems initiated by land surface heterogeneity induced by variable vegetation characteristics, large inland lakes and topography. Over southern Tanzania, a unimodal rainfall regime dominates, with the only rainfall season central around southern hemisphere summer (December to February). Parts of western Kenya, western and northwestern Uganda are however characterized by trimodal regimes since they often receive significant amounts of rainfall during July through September (JJA) due to penetration of mid-tropospheric moist westerly flow from the Atlantic Ocean and tropical Congo rainforest air mass (Davies et al., 1985; Mutai et al., 1998; Owiti and Zhu 2012; Ogwang et al., 2012).

Seasonal forecasts or long-term climate projections is nonetheless reliant on the ability to resolve at a sufficiently high resolution, the detailed patterns of rainfall distribution. This question can be addressed via downscaling method. This method is particularly critical and a demanding exercise in east Africa. This is due to the complex topography, which includes several mountains and large lakes embedded in contrasted topographical settings. Alongside statistical methods, numerical simulations based on Regional Climate Models (RCMs) are increasingly being used to downscale atmospheric variables associated with large-scale climate forcing. RCMs have been widely used in different parts of the world to understand regional climate processes, seasonal climate variability and regional climate change, among others. Various versions of RCMs have so far been used in different regions (Giorgi et al., 2004; Ata and Afsaal 2006; Gao et al., 2006; Abiodun et al., 2007; Seth and Giorgi 1998; Sylla et al., 2010; Singh et al., 2006; Ozturk et al., 2012; Diro et al., 2012).

Regional climate simulations previously dedicated to east Africa have mostly used the lower versions of the ICTP RCM (Sun et al. 1999a,b; Anyah and Semazzi, 2004; Davis et al., 2009; Anyah and Semazzi, 2007). Otieno and Anyah (2012) investigated the effects of land use changes on climate using RegCM4.0, focusing over Kenya. The use of RegCM4.0 is generally lacking over the east African region, especially in climate research. In this study we use the regional climate model (RegCM4.0) to investigate the effect of topography on rainfall over east Africa, focusing on JJA season. A brief description of the model is given in section 2. Section 3 provides data and model setup. Results and discussion in section 4, while summary and conclusion are given in section 5.

2. Model description

The Regional Climate Model (RegCM4) is the latest version of the Abdus Salam International Center for Theoretical Physics (ICTP) regional climate model (Giorgi et al., 2012; Giorgi and Anyah, 2012). It is an evolution of the previous version (RegCM3), described by Pal et al. (2007). The dynamical structure of RegCM4.0 is the same as that of the hydrostatic version of the mesoscale model, version 5 (MM5) of the National Center for Atmospheric Research (NCAR) and Pennsylvania State University (Grell et al., 1994). RegCM4.0 and the available model options are briefly summarized as follows.

It is a hydrostatic, compressible, sigma-p coordinate model run on Arakawa B-grid in which wind and thermodynamical variables are horizontally staggered (Giorgi et al., 1993a). The radiative transfer scheme used is that of the global model CCM3 (Kiehl et al., 1996; Giorgi et al., 1999). The planetary boundary layer (PBL) used is the modified Holtslag (Holtslag et al., 1990) and a new PBL scheme of the University of Washington (Grenier and Bretherton, 2001; Bretherton et al., 2004) is implemented in the model.

Three cumulus convection schemes exist. The simplified version of the Kuo-type scheme of Anthes (1977) described by Anthes et al. (1987) and has been present since the earliest version (RegCM1). The second and the mostly used scheme is that of Grell (1993) in the implementation of Giorgi et al. (1993b). Two different closure assumptions can be adopted (Arakawa-Schubert or Fritsch-Chappell). The third is the MIT scheme, introduced in RegCM3 (Pal et al., 2007; Emanuel, 1991; Emanuel and Zivkovic-Rothman, 1999).

The resolved scale precipitation scheme is essentially based on the SUBEX (sub-grid explicit moisture scheme) parameterization of Pal et al. (2000) and includes a prognostic equation for cloud water (The scheme is not significantly changed in RegCM4.0 compared to RegCM3, other than in some parameter settings).
The Land surface processes are described via the Biosphere-Atmosphere Transfer Scheme (BATS) of Dickinson et al. (1993), Subgrid BATS (Giorgi et al., 2003) and the Community Land Model version CLM3.5 (Steiner et al., 2009; Tawfik and Steiner, 2011). Compared to BATS, CLM is a more advanced package described in detail by Oleson et al. (2004, 2008). For the ocean fluxes, it makes use of the drag-coefficient parameterization included in the BATS package (Dickinson et al., 1993), and to improve the calculation of diurnal fluxes over the ocean, the prognostic sea surface temperature (SST) scheme described by Zeng & Beljaars (2005) was implemented in the model. In RegCM3, Pal et al. (2007) implemented the scheme of Zeng et al. (1998), which is based on a Monin-Obhukov turbulence representation. This scheme was added in order to improve the excessive evaporation over warm tropical oceans found in the BATS option.

A simplified aerosol scheme specifically designed for application to long-term climate simulations has been incrementally developed within the RegCM system. Solmon et al. (2006) first implemented a first-generation aerosol model including SO2, sulfates, organic carbon, and black carbon. Zakey et al. (2006) then added a 4-bin desert dust module, and Zakey et al. (2008) implemented a 2-bin sea salt scheme. Additionally in RegCM4, the dust emission scheme accounts for sub-grid emissions by different types of soil, and the soil texture distribution has been updated according to Laurent et al. (2008). The dust emission size distribution can now also be treated according to Kok (2011). When all aerosols are simulated, 12 additional prognostic equations are solved in RegCM4.0, including transport by resolvable scale winds, turbulence and deep convection, sources, and wet and dry removal processes (Giorgi et al., 2012). The RegCM system includes an interactive 1-dimensional thermal lake model which has been applied in different regional settings (Hostetler et al., 1993; Small et al., 1999). The tropical band configuration is also implemented in RegCM4. In this configuration, the model uses a Mercator projection centered over the equator for a band covering the entire tropical region, from 45° S to 45° N. The use of the Mercator projection allows the model grid to exactly cover the tropical band with the end points in the longitudinal direction exactly overlapping (Coppola et al., 2012).

3. Data and model setup

In this study, Grell convection scheme with Fritsch-Chappell closure assumption (Grell-FC) is used, as in Sylla et al., (2010). Adeniyi (2013) similarly observed that Grell-FC offers a better simulation over west Africa. The model was run at a resolution of 50 km (Table 1) over the period 1999-2008.

| TABLE 1 |
| Model configuration used in the study over the period 1999-2008 |
| Content | RegCM4.0 |
| Resolution | : 50 km |
| Map projection | : Normal Mercator |
| Horizontal dimension | : 192 × 110 (j,xi) |
| Vertical levels | : 18 |
| Cumulus convection | : Grell (Grell, 1993) |
| Planetary boundary layer | : Holtslag et al. (1990), Bretherton et al. (2004) |
| Microphysics | : SUBEX (Pal et al. 2000) |
| Land Surface Processes | : CLM3.5 (Steiner et al. 2009; Tawfik and Steiner, 2011) |

The experiments were done with the initial and lateral boundary conditions obtained from ERA-interim gridded re-analysis data at 1.5 degree resolution (Uppala et al., 2008). The data is a third generation of the European Centre for Medium-Range Weather Forecast (ECMWF) re-analysis product. The sea surface temperatures are obtained from the National Oceanic and Atmospheric Administration (NOAA). It is the Optimum Interpolated Sea Surface Temperature (OISST), produced weekly on a 1 degree resolution (Reynolds et al., 2002). The SST and the boundary conditions are updated 6 hourly in the model.

Four sets of experiments were done. The control experiment with actual topography (TP100) and sensitivity experiments with topography reduced to 75% (TP75), 25% (TP25) and zero (TP00). The area over which topography is reduced lies between longitudes 34°E – 38°E and latitudes 6°S – 2°N. It will hereafter be referred to as KTU since it covers high mountains in parts of Kenya, Tanzania and Uganda (KTU) including Mt. Elgon, Mt. Kenya, Mt. Kilimanjaro, Mt. Meru, Usambara Range and Ngorongoro Crater, among others. Researchers such as Shi et al., (2008), Fleisch and Reuter (2012) and Lee et al., (2013) used a similar approach in their studies.

Precipitation dataset used to evaluate the model performance over east Africa is the Climate Research Unit, CRU TS3.10 dataset (Harris et al., 2013; Mitchell
Fig. 1. The model domain and elevation (in m). The rectangle (EA) is the area of study (East Africa), located over longitudes 28° E - 42° E and latitudes 12° S - 5° N. The inner rectangle (red) is the area (KTU) over which topography is reduced [34° E - 38° E and 6° S - 2° N] in the sensitivity experiments.

Fig. 2. The mean annual cycle of precipitation (in mm/day) for the period 2000-2008, averaged over longitudes 28° E - 42° E and latitudes 12° S - 5° N. TP100 is due to the simulation with actual topography (control experiment), TP75, TP25 and TP00 represent simulations with topography reduced to 75%, 25% and to zero, respectively.

The climatology of the annual cycle is characterized by unimodal, bimodal and trimodal rainfall regimes in different zones over east Africa (Section 1). However the climatology of the observed area average annual cycle of rainfall over the region [28° E - 42° E, 12° S - 5° N] has higher amounts of rainfall received in October through May, with lower values received between June and September. This climatology is well captured by the model over the period 2000-2008 (Fig. 2), where the simulation with actual topography (TP100 or control experiment) exhibits higher amount of rainfall received over east Africa, followed by simulation with the topography over the region KTU reduced to 75% (TP75), 25% (TP25), and the least amount is received when the topography is reduced further to zero (TP00), implying that rainfall over the study area decreases with decreasing KTU topography. The presence of KTU topography thus enhances rainfall over the study area.

4. Results and discussion

In this section, the model results are provided and discussed. Fig. 1 shows the model domain and elevation in meters, the study area (EA) and the region KTU over which topography is reduced in the sensitivity experiments.

4.1. Annual cycle

Under a changing climate, the annual cycle is expected to vary and thus the observed increasing intensity of global warming in recent years could significantly offset the subtle balance among the various climatological sources of climate variability over the region (Owiti and Zhu, 2012). For example, in the period 1996 to 2005, 9 out of the 10 years are among the years with the highest annual temperature on record prior to the Intergovernmental Panel on Climate Change report (IPCC, 2007). Knowledge of variability of rainfall in terms of annual cycle is therefore an important component in the understanding of climate variability.

4.2. June to August (JJA) rainfall

As discussed in section 1, significant amounts of JJA rainfall over EA is mainly received over parts of western Kenya, western and northwestern Uganda (JJA Rainfall maxima Region (RMR)). This is due to the penetration of mid-tropospheric moist westerly flow from the Atlantic Ocean and tropical Congo rainforest air mass (Davies et al., 1985; Mutai et al., 1998; Owiti and Zhu, 2012). Rainfall is modulated from one season to another by the interaction between the ITCZ and perturbations in the global climate circulation, as well as with changes in the local circulation systems initiated by land surface heterogeneity induced by variable vegetation characteristics, large inland lakes and topography (Owiti and Zhu, 2012).
In this section, the effect of KTU topography on JJA rainfall over east Africa is examined. Results [Figs. 3(a-f)] show that the model captures the observed pattern of JJA rainfall over the region, with maximum rainfall over RMR. The sensitivity tests, Figs. 3 (b&c) reveal that there is a general reduction in rainfall over the region when topography over KTU is reduced to 25% [Fig. 3(c)]. There exists a significant reduction in rainfall around the region over which topography is reduced [Fig. 3(f)], extending towards north and west. This corroborates the findings by Flesch and Reuter (2012) that the maximum reduction in rainfall amounts is registered over the mountains and foothills. The reduction in rainfall is associated with the reduction in orographic lifting and the associated vertical water vapor flux (Flesch and Reuter, 2012).

4.3. Wind and moisture transport

Atmospheric circulation is important to precipitation because its ultimate effect is to increase the water vapor in the local air and lower the air temperature by transporting water vapor and invading cold air, leading to air saturation (Lu, 2012). In order to offer possible explanation in regard to the observed reduction in rainfall over the region, we investigate the moisture transport at 850 hPa and the associated moisture convergence/divergence during JJA season. The climatology of the observed moisture transport is characterized by a high moisture convergence over western Kenya, among others [Fig. 4(a)]. This convergence is realistically captured by the control experiment [Fig. 4(b)]. However, in the sensitivity experiment [Fig. 4(c)] where the topography over KTU is reduced to 25%, the high moisture convergence zone shifts from western Kenya to northern Uganda. Fig. 4(d) shows anomalous moisture divergence over most parts, with maximum divergence covering most parts of KTU. Divergence at low level results in vertical shrinking which suppresses convection due to subsidence (Barry and Chorley, 2003), which may explain the observed reduction in rainfall over the region. The magnitude of the mean JJA
Figs. 4(a-d). Climatology of JJA water vapor/moisture transport (MTR) at 850hpa in g kg$^{-1}$ms$^{-1}$ over the period 2000-2008. The shaded regions indicate moisture convergence (Positive), moisture divergence (negative), and the vectors show water vapor transport. (a) ERA interim observed MTR, (b) Simulated MTR using actual topography (TP100), (c) Simulated MTR when KTU topography is reduced to 25%, (d) Difference in MTR [(c) minus (b)].

Table 2

Statistics of the model simulated mean JJA rainfall (mm) over east Africa, averaged over 28°E - 42°E, 12°S – 5°N for the Control experiment (TP100), sensitivity experiments with topography reduced to 75% (TP75), 25% (TP25), zero (TP00) and the observed CRU rainfall. B*CRU and B*TP100 are biases when compared with CRU and TP100, respectively.

| Rainfall  | B*CRU  | B*TP100 | Percentage bias |
|-----------|--------|---------|-----------------|
| CRU       | 36.7   | -       | -               |
| TP100     | 28.0   | 8.7     |                  |
| TP75      | 20.3   | 16.4    | 7.7             | 27.5%           |
| TP25      | 14.1   | 22.6    | 13.9            | 49.6%           |
| TP00      | 12.5   | 24.2    | 15.5            | 55.4%           |

Fig. 5. The mean annual cycle of the zonal wind magnitude (in ms$^{-1}$) for the period 2000-2008, averaged over longitudes 28° E – 42° E, and latitudes 12° S - 5° N. TP100 is due to the simulation with actual topography, whereas TP75, TP25, and TP00 denote simulations with topography reduced to 75%, 25% and to zero, respectively.
zonal wind speed at 850 hPa over the EA region is observed to increase with decreasing topography elevation (Fig. 5). The reduction in rainfall is associated with the reduction in orographic lifting and the associated vertical water vapor flux (Flesch and Reuter, 2012). It thus partly explains why rainfall over KTU region reduced, which in turn reduced the area average rainfall amount in the entire region of east Africa by roughly half (49.6%, Table 2).

5. Summary and conclusion

In this study, we use the International Centre for Theoretical Physics (ICTP) Regional Climate Model (RegCM4.0) to examine the influence of topography on June to August (JJA) rainfall over east Africa. The control simulation was done with actual topography and sensitivity experiments were carried out with topography reduced to 75%, 25% and to zero. The model output is evaluated against Climate Research Unit datasets, gridded at 0.5 degree resolution (Harris et al., 2013) and ERA-interim datasets, gridded at 0.75 degree resolution (Dee et al., 2011).

Results show that the JJA rainfall significantly reduces over the region when topography elevation is reduced. Based on the model, when the topography over KTU is reduced to 25%, the JJA area average rainfall over EA region is reduced by about half. The maximum rainfall reduction is however observed around KTU region, which corroborates the findings by Flesch and Reuter (2012) that the maximum reduction in rainfall amounts is registered over the mountains and foothills. This may be explained by the anomalous moisture divergence exhibited over the region. Divergence at low level results in vertical shrinking which suppresses convection due to subsidence (Barry and Chorley, 2003). According to Flesch and Reuter (2012), the reduction in rainfall is associated with the reduction in orographic lifting and the associated vertical water vapor flux. The reduction in topography also leads to an increase in the strength of moisture transport and zonal wind speed at 850 hPa, which may be responsible for the observed shift in the high moisture convergence zone from western Kenya to northern Uganda.

The findings from this study would provide insight into the effect of topography on the east African climate and call for more detailed investigative research, particularly in the region. The results may motivate researchers and modeling centers to further improve on the performance of the model over the region.

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