

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

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**सार** – अंतरराष्ट्रीय सैद्धांतिक भौतिकी केंद्र (ICTP) के क्षेत्रीय जलवायु मॉडल (Reg CM 4.0) का उपयोग करके पूर्वी अफ्रीका में जून से अगस्त (JJA) की वर्षा के प्रभाव की जाँच की गई है। फ्रिश-चैपल क्लोजर एजम्पशन के साथ ग्रेल कन्वेक्शन स्कीम का उपयोग किया गया है। वास्तविक स्थलाकृति के साथ नियंत्रण अनुकरण किया गया है और 75 प्रतिशत, 25 प्रतिशत और शून्य तक की स्थलाकृति के साथ संवेदनशीलता प्रयोग किए गए। जलवायु अनुसंधान एकक (CRU) डाटासेट, 0.5 डिग्री विभेदन पर गिडिड तथा ERA अंतरिम डाटासेट, 0.75 डिग्री विभेदन पर गिडिड की तुलना मॉडल आउटपुट के साथ की गई। परिणाम दर्शाते हैं कि जब स्थलाकृति उत्थान कम रहा तब क्षेत्र में औसत JJA वर्षा महत्वपूर्ण रूप से कम रही। मॉडल के आधार पर जब चयनित क्षेत्र (KTU) में स्थलाकृति 25 प्रतिशत रही तब पूर्वी अफ्रीका में औसत JJA वर्षा लगभग आधी हुई। तथापि जहाँ स्थलाकृति कम हुई उस क्षेत्र के आसपास अधिकतम वर्षा में कमी देखी गई। स्थलाकृति में कमी के कारण निम्न स्तर (850 है.पा.) क्षेत्र में विसंगत नमी अपसरण हुआ। निम्न स्तर पर अपसरण के कारण उर्ध्वधर सिकुड़न हुई जो अवतलन के कारण संवहन को कम करता है। नमी संवहन और 850 है.पा पर क्षेत्रीय पवन गति में स्थलाकृति में कमी के कारण वृद्धि हुई जो पश्चिमी केन्या से उत्तरी युगांडा तक के नमी अभिसरण क्षेत्र में परिवर्तन के लिए जिम्मेदार हो सकता है। इस अध्ययन के परिणामों से पूर्वी अफ्रीका की जलवायु पर स्थलाकृति के प्रभाव पर प्रकाश पड़ेगा तथा विशेष रूप से इस क्षेत्र में और अधिक विस्तृत अनुसंधान किया जा सकेगा। इस शोध से प्राप्त परिणामों से शोधकर्ता और मॉडल केंद्र इस क्षेत्र में मॉडल के निष्पादन में और सुधार करने के लिए प्रोत्साहित होंगे।

**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 Afzaal 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 SO<sub>2</sub>, 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

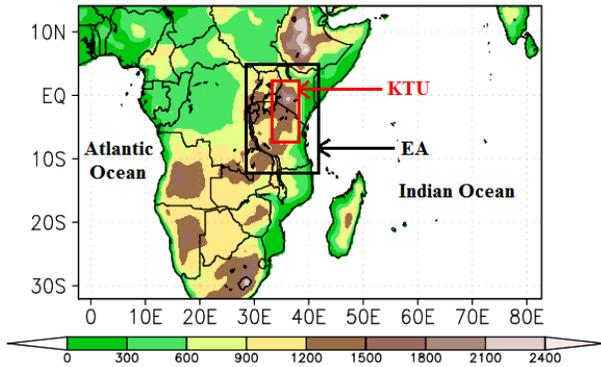
Model configuration used in the study over the period 1999-2008

Content	RegCM4.0
Resolution	: 50 km
Map projection	: Normal Mercator
Horizontal dimension	: 192 × 110 (j <sub>x</sub> ,xi <sub>y</sub> )
Vertical levels	: 18
Cumulus convection	: Grell (Grell, 1993)
Planetary boundary layer	: Holtslag <i>et al.</i> (1990), Bretherton <i>et al.</i> (2004)
Microphysics	: SUBEX (Pal <i>et al.</i> 2000)
Land Surface Processes	: CLM3.5 (Steiner <i>et al.</i> 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), Flesch 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

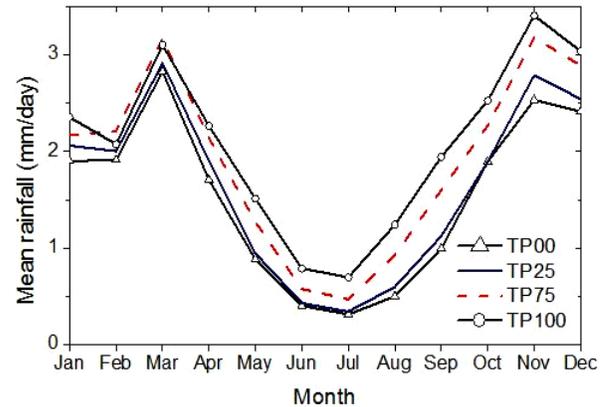
and Jones, 2005 (previous version)). CRU TS3.10 (CRU TS 3.10.01 for precipitation) is a monthly gridded climatology of station data for the period 1901-2009 at a resolution of 0.5 degree. This is because the African rain-gauge data observed during the post-independence era of 1970's through to recent years has many spatial and temporal discontinuities over large sections of east Africa (Schreck and Semaazi, 2004). The wind, relative humidity and temperature used to determine and evaluate moisture transport are those of ERA-interim, gridded at 0.75 degree resolution (Dee *et al.*, 2011). The first year of the model output was dropped as part of the model spin-up. Analyses were then done over the period 2000-2008.

#### 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.

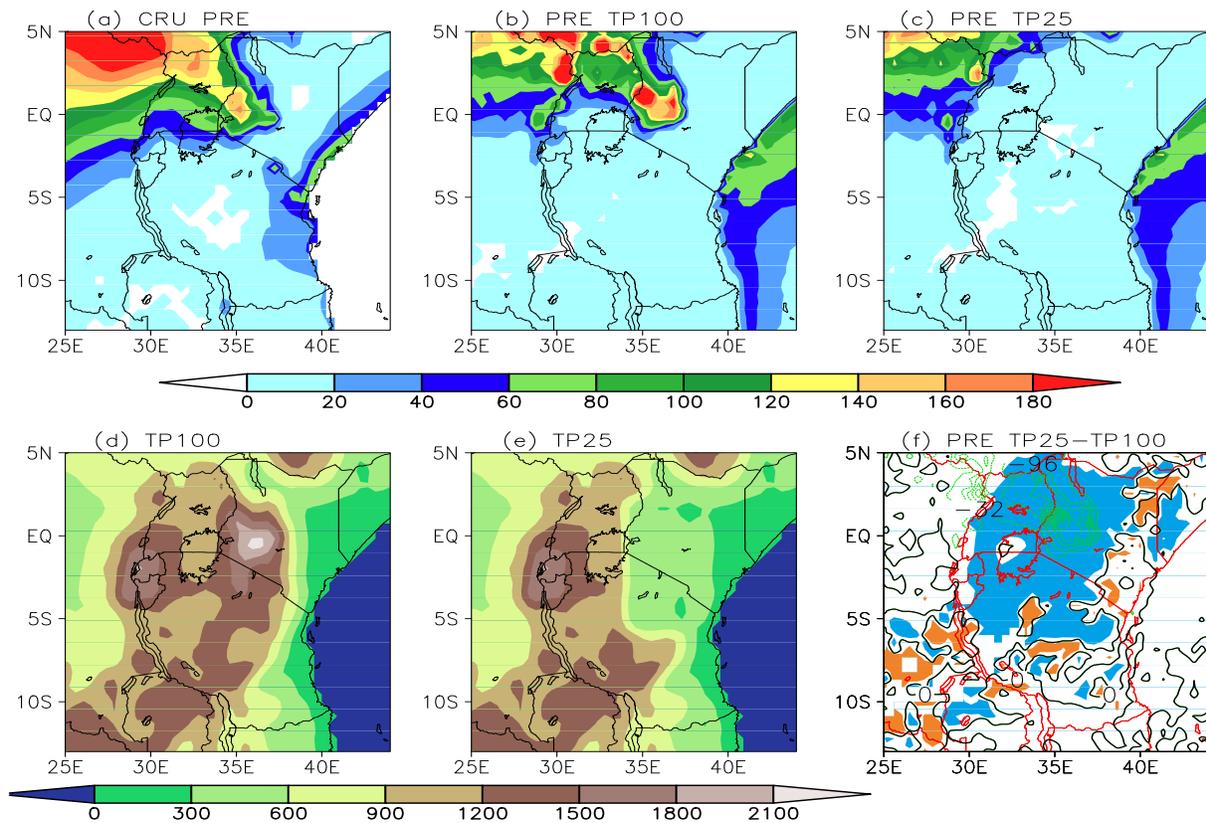


**Fig. 2.** The mean annual cycle of precipitation (in mm/day) for the period 2000-2008, averaged over longitudes 28° E - 42° E and latitudes 12° S - 5° N. TP100 is due to the simulation with actual topography (control experiment), TP75, TP25 and TP00 represent simulations with topography reduced to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

##### 4.2. 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).



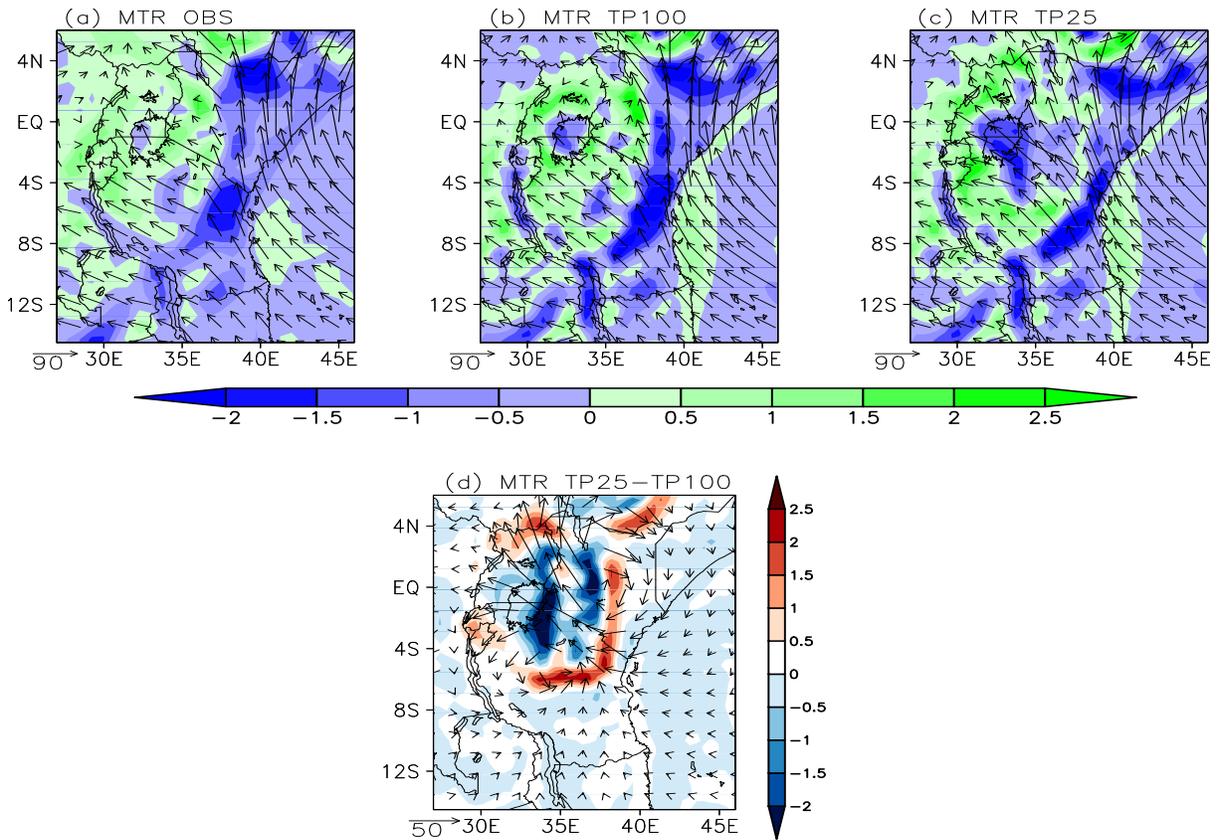
**Figs. 3(a-f).** Climatology of JJA rainfall (in mm) over the period 2000-2008 (a) CRU observed rainfall over land, (b) Simulated using actual topography (TP100), (c) Simulated using topography reduced to 25% (TP25), (d) Actual topography (TP100), (e) Topography over KTU reduced to 25% (TP25), (f) Rainfall difference [(c) minus (b)], with contours (green) at 32mm interval and the thick (black) contours represent regions over which the rainfall difference is zero. The shaded regions in (f) are significant at 95% confidence level

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).

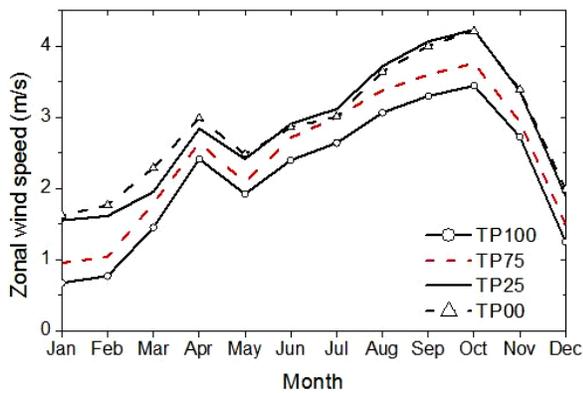
#### 4.3. Wind and moisture transport

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)]



**Fig. 5.** The mean annual cycle of the zonal wind magnitude (in  $ms^{-1}$ ) for the period 2000-2008, averaged over longitudes  $28^{\circ} E - 42^{\circ} E$ , and latitudes  $12^{\circ} S - 5^{\circ} N$ . 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

**TABLE 2**

**Statistics of the model simulated mean JJA rainfall (mm) over east Africa, averaged over  $28^{\circ} E - 42^{\circ} E$ ,  $12^{\circ} S - 5^{\circ} N$  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 (mm)	B*CRU (mm)	B*TP100 (mm)	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%

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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