African Crop Science Journal, Vol. 20, Issue Supplement s2, pp. 213 - 225 ISSN 1021-9730/2012 $4.00
Printed in Uganda.

REGIONAL CLIMATE MODEL PERFORMANCE AND PREDICTION OF SEASONAL RAINFALL AND SURFACE TEMPERATURE OF UGANDA

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ABSTRACT

Knowledge about future climate provides valuable insights into how the challenges posed by climate change and variability can be addressed. This study assessed the skill of the United Kingdom (UK) Regional Climate Model (RCM) PRECIS (Providing REgional Climates for Impacts Studies) in simulating rainfall and temperature over Uganda and also assess future impacts of climate when forced by an ensemble of two Global Climate Models (GCMs) for the period 2070-2100. Results show that the models captured fairly well the large scale flow signals influencing rainfall and temperature patterns over Uganda. Rainfall and temperature patterns were better resolved by the RCM than the GCMs. The rainfall and temperature patterns differed among the three seasons. Rainy season March to May (MAM) is likely to experience increment in both surface temperature (0.9 ^{o}C) and rainfall (0.2 mm day^{-1}). For September to October (SON) rainy season, an opposite trend in the two climate parameters, temperature and rainfall, will be registered with the former increasing by 0.9 ^{o}C and the latter dropping by 0.7 mm day^{-1}. For the dry season, June to August (JJA), both temperature and rainfall are projected to decrease by 0.3 ^{o}C and 0.4 mm day^{-1}, respectively.

Key Words: Ensemble mean, Global Climate Models, surface temperature

RÉSUMÉ

La connaissance du climat de demain fournit un aperçu sur la manière dont les défis posés peuvent être adressés. Cette étude a évalué la compétence du Modèle Climatique Régional (RCM) PRECIS du Royaume Uni (fournissant des climats régionaux pour des études d'impacts) dans la simulation de la pluviométrie et la température en Ouganda et, d'autre part, étudier les impacts des climats une fois forcée par un ensemble de deux Modèles Climatiques à l'échelle de l'Univers (GCMs) pour les périodes 2070-2100. Les résultats montrent que les modèles ont raisonnablement saisi une large échelle du flow des signaux qui influencent la tendance de la pluviométrie et la température en Ouganda. Les tendances de la pluviométrie et la température étaient mieux déterminées par RCM que GCMs. Les tendances de la pluviométrie et la température différaient au cours des trois saisons. La saison pluvieuse Mars à Mai (MAM) connaitra probablement une augmentation de la température (0.9 ^{o}C) et de la pluviométrie (0.2 mm jr^{-1}). Pour la saison de pluie de Septembre à Octobre, une tendance contraire dans les deux paramètres climatiques sera enregistrée avec la même augmentation de 0.9 ^{O}C et une diminution de 0.7 mm jr^{-1} de pluie. Pour la saison sèche de Juin à Août (JJA), les projections montrent une diminution de la température et de la pluie de 0.3 ^{O}C et 0.4 mm jr^{-1}, respectivement.

Mots Clés: Modèles Climatiques du Globe, température de surface

INTRODUCTION

Climate change is among the most pressing environmental development challenges globally (UNCTAD/WTO, 2007). With the expected global temperature increases of 1.4 to 5.8 °C by the end of the twenty first century, Sub-Saharan Africa in general, and Uganda in particular, are vulnerable to the adverse impacts of climate change and variability because their economies are tightly bound to climate (Houghton *et al.*, 2001; IPCC, 2007; Lukwiya, 2009). Agriculture is a major Gross Domestic Product (GDP) contributing sectors of Uganda's economy.

Several studies show that rainfall is likely to increase in humid areas and decline in semi-arid areas across the tropics (Hulme *et al.*, 2001; Hulme *et al.*, 2005; Christensen *et al.*, 2007). However, these studies are based on global Climate Models (GCMs) projections which are not capable of capturing the detailed processes associated with regional/local climate variability and changes that are required for regional and national climate change assessments. Hence, their outputs are not very useful in designing appropriate adaptation and mitigation strategies to reduce the impact of climate change for the small holder farmers in countries such as Uganda.

Dynamical downscaling using high resolution Regional Climate Models (RCMs), is one of the alternative solution available for providing finer spatial and temporal detail than the GCM (Pisnichenko and Tarasova, 2007). The RCMs resolve mesoscale forcings associated with mountains, coastlines, lakes and vegetation characteristics that exert a strong influence on the local climate (Giorgi and Mearns, 1999; Vernekar, 1995; Pal *et al.*, 2000), and are generally nested within a GCM. At its lateral boundaries, the RCM is driven by winds, temperature and humidity variable outputs every 6 hours from the GCM. This is referred to as one-way nesting, since the RCM does not feed information back to the GCM.

The objective of this study was to assess the skill of the ensemble mean output of ECHAM4 and HadAM3P in simulating the climatology of Uganda and, thereafter, use this to project rainfall and surface temperatures over Uganda for the period 2071-2100.

METHODOLOGY

The study area. The study covered the whole of Uganda using weather observing stations located in different parts of the country. Uganda is located between 4° North and 1° South and 29.5° West to 35.5° East (Fig. 1). It has a total area of 241,040 Km^2, a north-south scope of about 650 Km and a maximum east-west scope of about 500 Km. Uganda shares with Kenya and D.R. Congo the same features of equatorial climate with moderate humid and hot climatic conditions throughout the year; this is modified by the elevation of the country . The altitude ranges between 620 m (Albertine Rift) and 5110 m (Mt. Rwenzori), with a mean of 1200 m above sea level. The country receives uni-modal (northern part) and bi-modal (central, western and eastern parts) types of rainfall. The long rains fall between March and May (MAM), while the light/short rains fall between September and November (SON) (State of the Environment Report for Uganda, 1996). The bimodal patterns is influenced by the circulation of air masses associated with the equatorial trough or Inter-tropical Convergence Zone-ITCZ (State of the Environment Report for Uganda, 1996). The dry seasons occur between June and August (JJA) and December and February (DJF) when temperatures are highest. Annual rainfall and temperature range from 500 mm to 2500 mm; and 2 to 26 ^{o}C, respectively (McSweeney, 2008).

Model data. The Hadley Center Atmospheric global Climate Model (HadAM3P) and the European Community Hamburg Model version 4 (ECHAM4) were combined to get the ensemble output GCMs data as well as ERA-40 reanalysis were used to provide initial and boundary conditions for the PRECIS model. The European Centre provides atmospheric data for Medium-Range Weather Forecasts (ECMWF) 40-yr Re-Analysis (ERA-40), including mean monthly rainfall and temperature. These data are available on 2.5° x 2.5° latitude–longitude regular grid globally for the period 1979 to 2001. The data were obtained from the ECMWF Web site (http://data.ecmwf.int/data/) in 2010.

Model description. The RCM used in this study is the PRECIS (Providing Regional Climates for

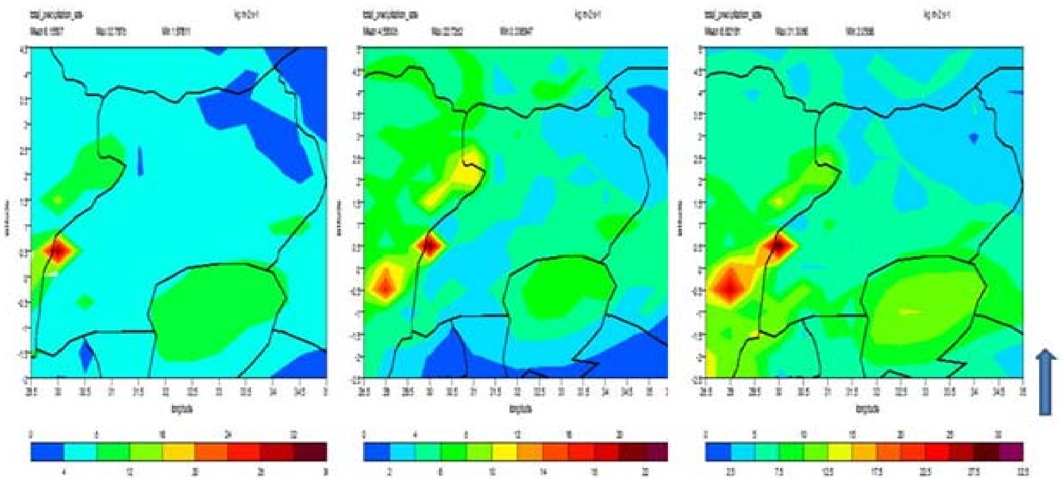
Figure 1. Map of Uganda and selected key features.

Impacts Studies). This is the Hadley Center's current version of the Regional Climate Model (HadRM3P) based on HadAM3P, an improved version of the atmospheric component of the latest Hadley Centre coupled Atmosphere Ocean Global Circulation Model (AOGCM), HadCM3, (Gordon *et al*., 2000). PRECIS has been used with horizontal resolutions of 50 Km with 19 levels in the atmosphere (from the surface to 30 Km in the stratosphere) and four levels in the soil. The RCM uses the same formulation of the climate system as in the GCM which helps to ensure that the RCM provides high-resolution regional climate change projections generally consistent with the continental scale climate change projected by the GCM. The HadRM3P model ran the ensemble GCMs outputs downscaling them at 50-Km horizontal resolution for the present climate (1961–1990) using ERA-40 Re-analysis for base-line lateral boundary conditions (LBCs) and for future scenarios 2071–2100) using the A2 special report on emissions scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC) and ECHAM4 and HadAM3P (Omondi, 2010).

RESULTS

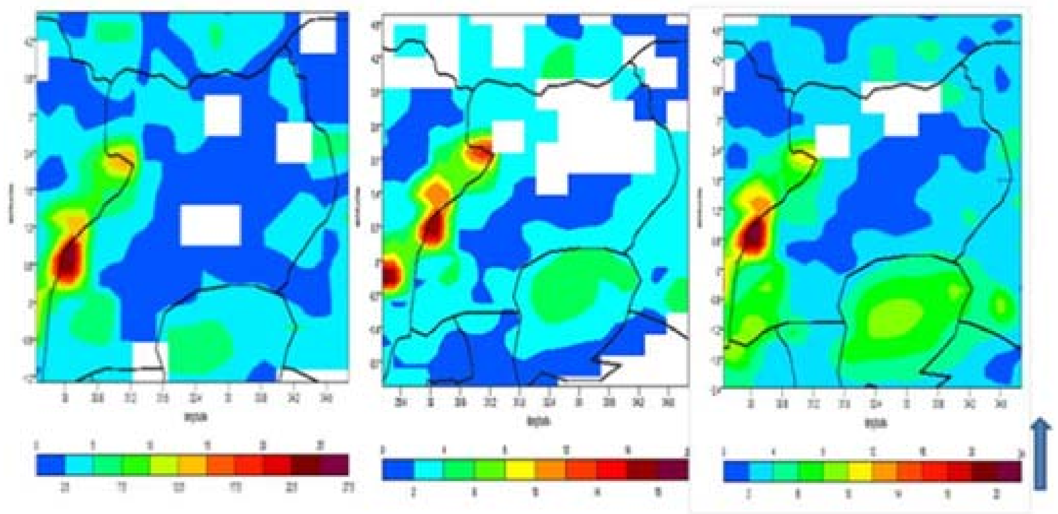
Performance of the RCM. Figures 2 and 3 show the simulated rainfall climatology (1961-1990) of Uganda and the model bias. The model reproduced fairly well the rainfall around the cattle corridor and badly the rainfall around Mt Rwenzori and over Lake Victoria. The model bias is relatively higher during SON compared to other seasons.

Simulated surface temperature and the model bias is depicted in Figures 4 and 5. Areas with relatively high bias included the highlands of south-western, Mt Elgon region, Lake Albert and Lake Victoria (Fig. 1).



(a) March – May (MAM) (b) June – August (JJA) (c) September – November (SON)

Figure 2. Seasonal RCM rainfall climatology (1961-1990) over Uganda (mm day^{-1}).

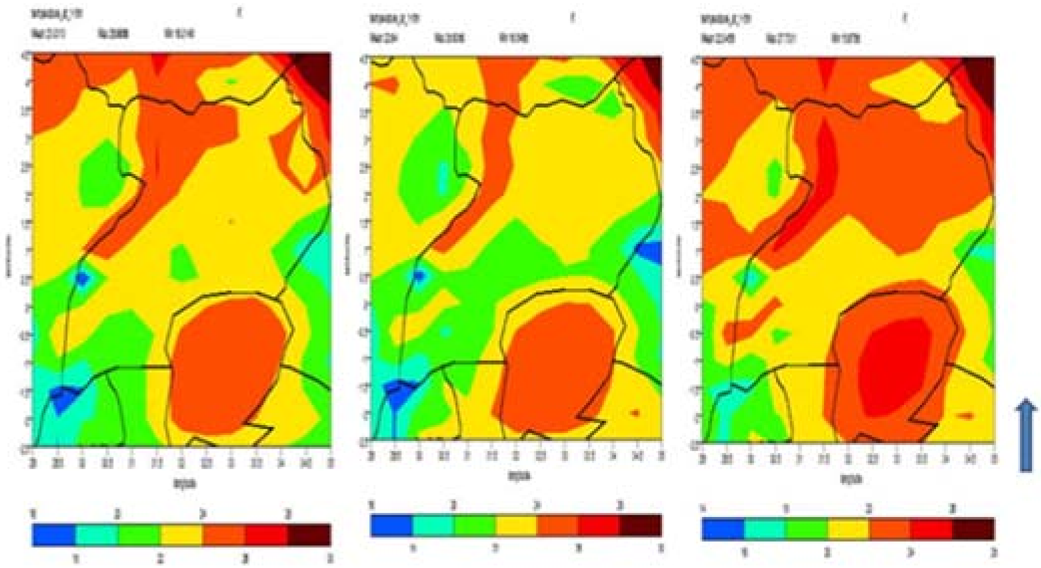


(a) March – May (MAM) (b) June – August (JJA) (c) September – November (SON)

Figure 3. Seasonal model bias from mean rainfall climatology (1961-1990) over Uganda (mm day^{-1}).

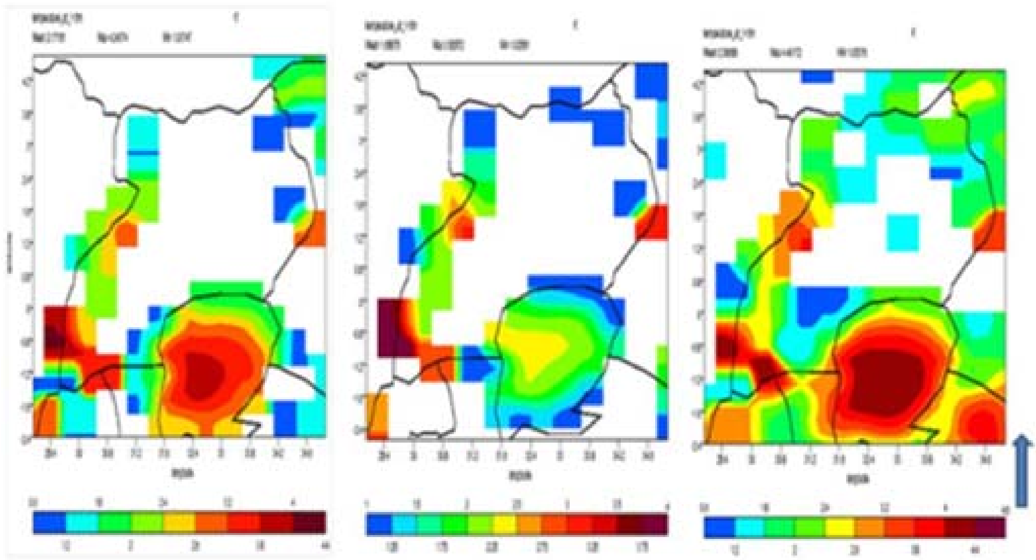
Figure 5 shows the observed and simulated mean annual cycle for a number of stations across Uganda. The bimodal regime common in most rainfall stations in Uganda is reasonably simulated for several zones. The model simulated the seasonality of rainfall climatology fairly well compared with station data. However, the model over-estimated rainfall in northern and central Uganda. It under-estimated rainfall for the first season in south-western Uganda and over-estimated it for the dry and second season in western Uganda.

Figures 7a and b show the performance of the model for the maximum and minimum temperature respectively. As for rainfall, simulated and observed temperature followed the same trend. The difference between observed and simulated was relatively smaller for the minimum



(a) March – May (MAM) (b) June – August (JJA) (c) September – November (SON)

Figure 4. Temperature climatology (1961-1990) over Uganda (°C).



(a) March – May (MAM) (b) June – August (JJA) (c) September – November (SON)

Figure 5. Seasonal model bias from mean temperature (°C) climatology (1961-1990) over Uganda.

temperature compared to the maximum temperature.

Projected rainfall over Uganda (2071-2100). Seasonal model projections of future rainfall for the 2071-2100 periods for Uganda from different ensemble mean datasets are presented in Figure 8. During MAM and SON seasons, several parts of the country are projected to be wet, with rainfall ranging between 4-8 mm day^{-1}, with small patches of relatively dry areas (0-4 mm day^{-1}). The Lake Victoria and the area near D.R. Congo (Rwenzori)

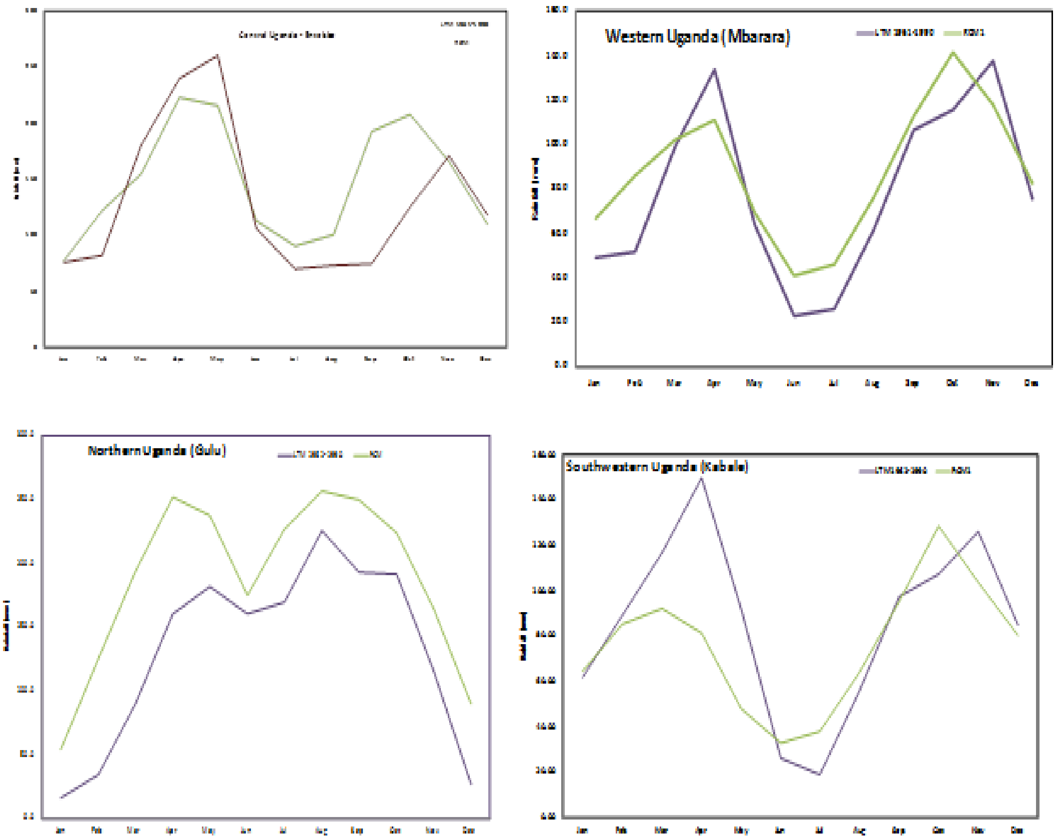


Figure 6. Simulated mean annual cycle of both observed and model rainfall in some parts of Uganda.

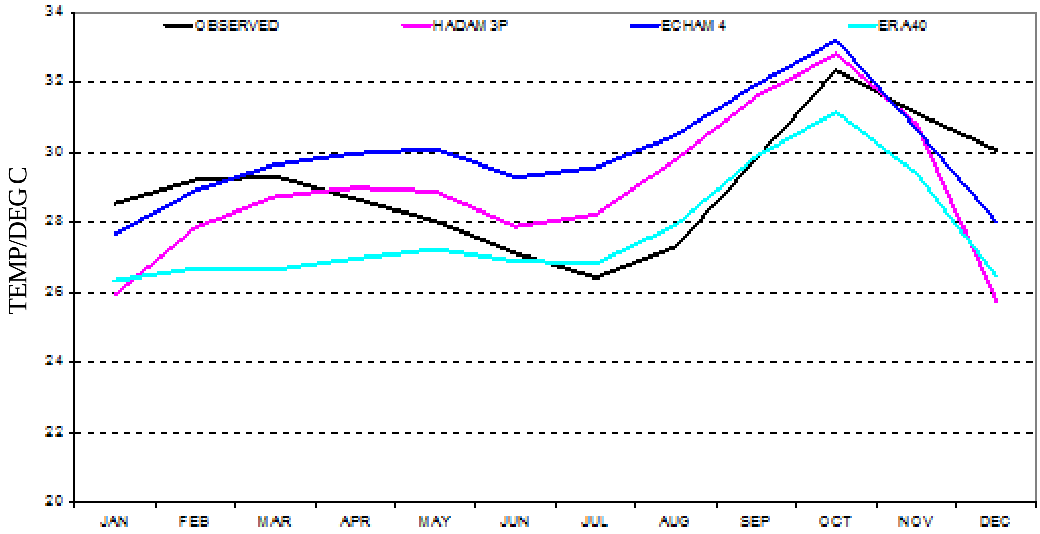
(Fig. 1) are likely to receive high rainfall ranging from 10-16 mm day^{-1}. During JJA, a big portion of the cattle corridor, the Lake Albert area and south-western part of the Lake Victoria are likely to receive 0-4 mm day^{-1}. The north-western part of the country and other areas bordering Kenya and DRC are likely to receive rainfall of 4-8 mm day^{-1}.

The model projected an increase in mean rainfall in the future 2071-2100, during the MAM season compared to the climatological period (1961-1990) for almost the entire country. The mean rainfall amount for MAM is projected to increase by 0.2 mm day^{-1}. It projected a reduction in rainfall of about 0.4 mm day^{-1} in JJA and 0.7 mm day^{-1} in SON (Table 1). For all the seasons, both maximum and minimum rainfall amount show a decreasing trend with biggest drop during rainy seasons- MAM (32.8 to 21.3 mm day^{-1}) and SON (31.3 to 19.3 mm day^{-1}). The lowest drop was registered under JJA (22.7 to 17.1 mm day^{-1}).

Projected temperature over Uganda (2071-2100). The model projections for surface mean, maximum and minimum temperatures are presented in Figure 9. The mean surface temperature is projected to increase for all seasons with both rainy seasons MAM and SON registering higher increases of 0.9 °C; while 0.3 °C recorded for JJA. During MAM and SON, a big portion of the northern parts of the country is likely to remain hot; while the Mt Elgon and South-western region (Fig. 1) are likely to be cool throughout the year.

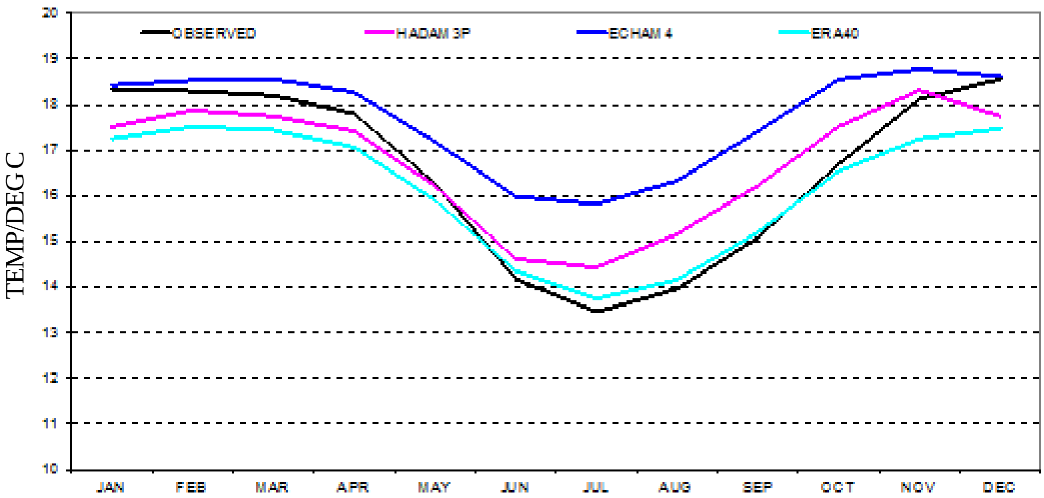
Generally, the maximum and minimum surface temperatures are projected to increase for both rainy seasons MAM and SON. The maximum for MAM is projected to increase by 1 °C and by 0.7 °C for SON, while the minimum for MAM is projected to increase by 1.6 °C and by 1.4 °C for SON. For the dry season-JJA, the maximum is projected to decrease slightly by 0.1 °C while the minimum will increase by 0.6 °C.

(a)



Annual cycle for simulated and observed maximum temperature

(b)

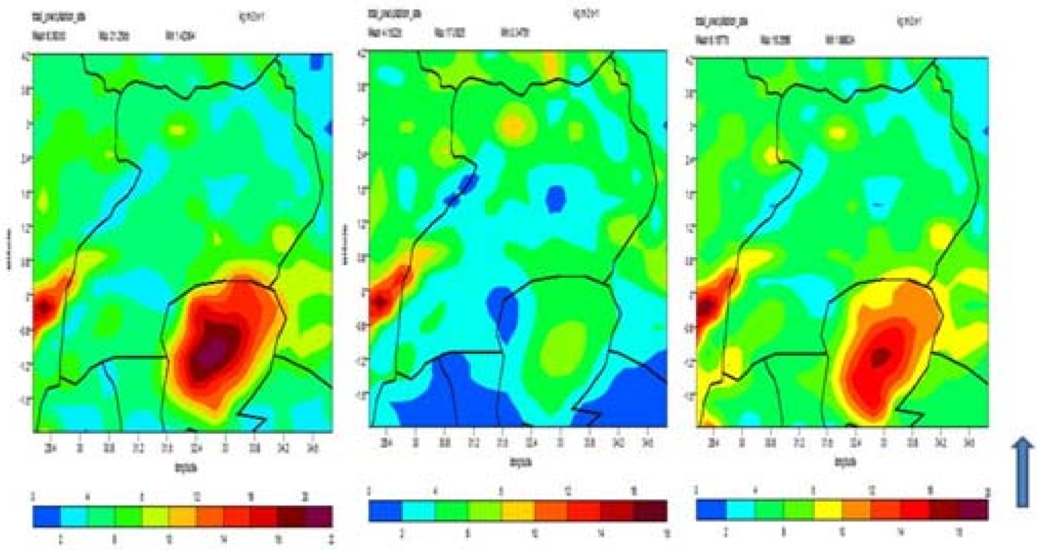


Annual cycle for simulated and observed minimum temperature

Figure 7. Observed and simulated annual cycle of RCM mean (a) maximum and (b) minimum projected rainfall over Uganda (2071-2100).

DISCUSSION

Performance of the model. Although the ensemble model was robust in simulating the two parameters (Figs.1- 6), and more especially temperature, relatively high bias were observed on the highlands and water bodies. This can be attributed to the model physics (physical processes captured by the model and boundary conditions), topography and land-surface processes, and lack of quantitative data over these features. Climatological parameters of highland areas are principally not governed by synoptic-scale circulation but by local scale



(a) March – May (MAM) (b) June – August (JJA) (c) September – November (SON)

Figure 8. Projected rainfall (mm/day) (2071-2100) over Uganda.

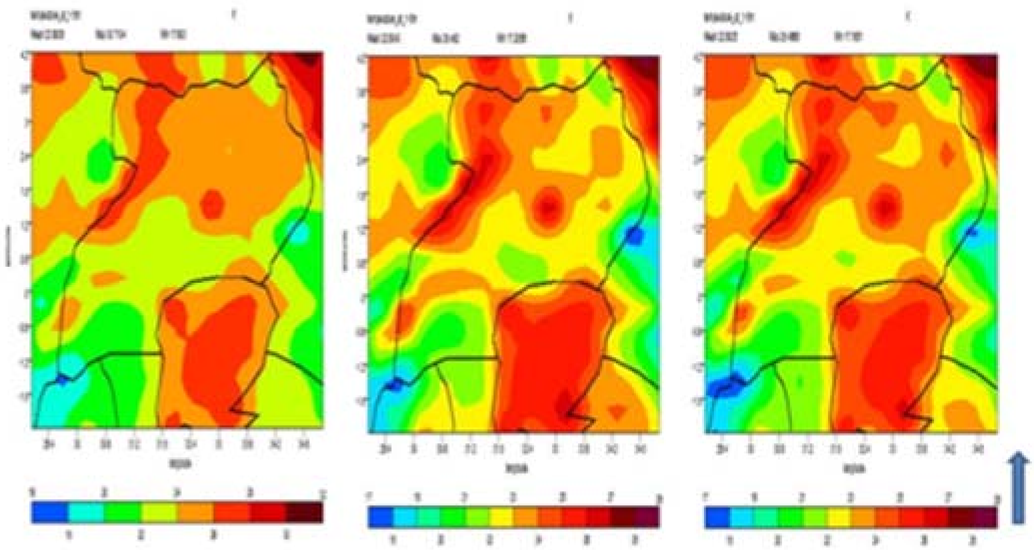
TABLE 1. Comparative seasonal rainfall statistics 1961-1990 and 2071-2100 over Uganda

Season	1961-1990			2071-2100		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum
MAM	6.2	32.8	2.0	6.4	21.3	1.4
JJA	4.6	22.7	0.3	4.2	17.1	0.4
SON	6.9	31.3	2.1	6.2	19.3	1.7

MAM = March-May, JJA = June to August; SON = September to October

conditions, such as topography, distance from the sea, elevation, convergence and the uplift of air masses (Seth *et al.*, 2006; Thorton *et al.*, 2010). Aktar *et al.* (2009) and McGregor (1997) observed that regional models tend to over-estimate rainfall over the mountain areas and underestimation of temperature with respect to Climate Research Unit (CRU) data the observed global data used usually used for comparisons. Similar observations were made by several other scholars (Indeje *et al.*, 2000; Giorgi *et al.*, 2004; Solman *et al.*, 2008; van de Steeg, 2009) over simulation of warm bias over Lake Victoria and other inland large water bodies of East Africa.

The models tend to under-estimate the total rainfall during the long-rain season (Fig. 6). Thus, biases in climate model reproduction of the season cycles of the atmospheric predictors used in downscaling tend to have significant impacts on simulated rainfall (Charles *et al.*, 2007). Shongwe *et al.* (2010) pointed out the difficulty in predicting long rains with the existing uncertainties in patterns, which were higher than the short rain season. Perhaps, this depends on the methods used (Barsugli *et al.*, 2009). Charles *et al.* (2007) pointed out that ECHAM4 significantly over-estimates observed rainfall compared with HadAM3P, yet it should be observed that the present study used these two models. Furthermore, the simulated climate over several decades may be quite different given slightly different initial climate conditions in the



(a) March – May (MAM) (b) June – August (JJA) (c) September – November (SON)

Figure 9. Projected seasonal temperature (°C) over 2071-2100 in Uganda.

TABLE 2. Comparative seasonal temperature (°C) statistics 1961-1990 and 2071-2100 over Uganda

Season	1961-1990			2071-2100		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum
MAM	23.0	29.7	16.0	23.9	30.7	17.6
JJA	22.6	28.6	16.6	22.9	28.5	17.2
SON	22.0	27.7	15.7	22.9	28.4	17.1

model (Barsugli *et al.*, 2009), and the influence of the *El Niño* Southern Oscillation (ENSO) phenomenon. The latter is known to be among the major causes of uncertainties in climate projections for east Africa's rainfall since the seasonal weather in the region is highly influenced by this phenomenon (Dore, 2005) which masks the important role of other oceans; particularly the Indian Ocean. Hemming *et al.* (2010) suggests that computer resources limitations in understanding of small-scale climate processes induced uncertainties in future projections, may be the major challenge in the next 50 years.

Projection of future climate in Uganda. In comparison with the 1961-1990 period, the projected mean daily rainfall of 2071-2100 is likely to increase during MAM, and decrease for all other seasons; while the mean daily temperature will likely increase by a range of 0.5 to 0.9°C. Very little variations are expected for the minimum daily rainfall compared with the maximum daily rainfall. MAM season will have the highest variation (hotter) in terms of maximum (1°C) and minimum temperature (1.6°C); followed by SON for the minimum temperature (1.4°C) and lastly JJA season for the minimum temperature (0.6°C), which also recorded lesser maximum temperature in the future period in comparison to 1961-1990 period. This insinuates that Uganda may not reach the expected global temperature increase of up to 5.8°C reported for instance by Houghton *et al.* (2001).

Model simulations agree with the earlier studies (Byrnes, 1990; Taylor and Howard, 1999; Indeje *et al.*, 2000), which pointed out that the MAM season will receive rainfall increment, with a relatively high amount near Lake Victoria and the highlands. These projections are also in agreement with McSweeny *et al.* (2008) who projected rainfall increases of 7 to 11 % not only during MAM, but also for other seasons of up to 15% by 2090s, though the study was at global scale. However, a similar study carried out in areas close to Uganda-Kenya and Eritrea by Ward and Lasage (2009), downscaling ECHAM5 at regional level, projected an increase in rainfall in the March-May season, with less rainfall towards the end of the season in May. SON the second rain season received, for the period 1961-1990, the highest mean rainfall of up to 6.9 mm day^{-1}, but with maximum 31.3 mm day^{-1} and minimum 2.1 mm day^{-1}. This season accounts for about the quarter of the total annual rainfall over Uganda (Indeje *et al.*, 2000) and is uniformly well distributed. The dominance of large-scale weather systems may be responsible for the spatial homogeneity of rainfall during this season (Indeje *et al.*, 2000). The model projected a change in rainfall patterns over the country. McSweeney *et al.* (2008) also projected the highest rainfall to be in the SON season. On the other hand, Hepworth and Goulden (2008) projected the shift of MAM long rains to SON season extending this short rain season with increased rainfall projected for December, January and February (DJF) a normally short season. In addition, the simulated declines of mean and maximum rainfall during JJA with an increase in the minimum rainfall, compared with the past trend is in agreement with Ward and Lasage (2009) study whose projections showed decline over the May month which eventually extending up towards the end of the year. Shongwe *et al.* (2010) projected increased wetness trend over much of east Africa for both seasons with higher rainfall over the Great Lakes Region and much of Uganda. Model outputs variance is mainly due to difference in methods used in the different studies and the fact that rainfall structures change greatly over space and time (Wilby *et al.*, 1998; Wood *et al.*, 2004; Louw, 2007; Ruane and Roads, 2007; Rockel and Geyer, 2008), and the influence of *El Niño* Southern Oscillation (ENSO) phenomenon.

In terms of temperature, the study projected increased temperatures over all seasons, in agreement with other studies such as McSweeney (2008). The JJA season, which is the dry season, is likely to have the highest daily temperatures compared with the other two seasons, with minimum temperatures simulated up to 16.5 ^{o}C, and maximum 26.6 ^{o}C. Projected rates of warming are greatest in the coolest season, JJA season, increasing by 1.5 to 5.4 °C by the 2090s (McSweeney *et al.*, 2008; McSweeney *et al.*, 2010). This is followed by the MAM season, which is surprisingly highly simulated compared with its normal range with minimum temperature up to 16 ^{o}C and maximum of 29.7 ^{o}C. These are, however, most concentrated in the northern region. These results contradict Indeje *et al.'s* (2000) observations that of drier conditions than normal in the northern parts of Uganda during the JJA season. Surprisingly, higher simulations of temperatures during the MAM season can still be attributed to the extension to the month of March of the high temperatures of the December, January and February (DJF) period. Such changes, coupled with the erratic onset and cessation of rainfall seasons, have been noticed over the recent past along with increasing frequency of droughts which has made Uganda more vulnerable to climate change (NAPA, 2007). Oxfam (2008) reported that all seasons were likely to become warm to extremely warm because temperatures will increase, though it would be noticed more over the next decade. Other studies predicted mean annual temperature increase by 1.0 to 3.1°C by the 2060s, and 1.4 to 4.9 °C by the 2090s (McSweeney *et al.*, 2008; McSweeney *et al.*, 2010). This corroborates well with Ward and Lasage (2009) who projected temperature increment over the east African region. However, the projected increment is relatively lower than Hepworth and Goulden (2008) projected temperature rise of 1.5 ^{o}C over the next 20 years and a 4.3 ^{o}C by 2080s.

CONCLUSION

In light of the above results, it is concluded that the ensemble mean of ECHAM4 and HadAM3P reproduce well the surface temperature of Uganda. This study demonstrates that temperatures are going to be considerably warmer over most parts of Uganda for 2071-2100 period. The MAM season is projected to receive enhanced mean rainfall and temperature. Model simulations for SON point to a likely increase in temperature and a decrease in rainfall amount. For the dry season, JJA, both temperature and rainfall are projected to decrease. There is need to assess the effect of projected climate change and variability on the distribution of major crops of Uganda.

ACKNOWLEDGEMENT

We are grateful to the Regional Universities Forum for Capacity Building in Agriculture (RUFORUM) for funding this research, Makerere University, Ministry of Water and Environment- Climate Change Unit, the IGAD Climate Prediction and Applications Centre (ICPAC), Nairobi, for the training and provision of computer facilities during this research study.

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