Reg Environ Change (2013) 13:477–491
DOI 10.1007/s10113-012-0381-7

ORIGINAL ARTICLE

Potential influences of global warming on future climate and extreme events in Nigeria

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Received: 22 February 2012 / Accepted: 20 November 2012 / Published online: 1 December 2012

Abstract This study investigates future impacts of global warming on climate and extreme climate events in Nigeria, the most populous African country that depends on rain-fed agriculture. Past and future climate simulations from 9 GCMs were downscaled (using a statistical model) and analyzed for the study. The study considers the impacts of two emission scenarios (B1 and A2) on the future climates (2046–2065 and 2081–2100) over ecological zones in Nigeria. The model evaluation shows that the downscaling adds values to the GCMs simulation, and the results capture all the important climatic features over the country. The model projections show that both B1 and A2 scenarios change the future climate over Nigeria. They significantly increase the temperature over all the ecological zones, with greatest warming (between 1 and 4 °C) over the Sudan (short grass) Savanna in March. The warming, which increases the occurrence of extreme temperature and heat wave events over the entire country, enhances the frequency of the extreme rainfall events in the south and southeast and reduces the annual rainfall over the northeast. Since heavy rains and floods are major problems in the south and southeast, and drought is major problem in the northeast, the global warming may further aggravate these environmental problems in future. These could have negative impacts on agriculture and further threaten livelihood and food security in the rapidly growing country. Hence, there is need for further studies on adaptation and mitigation strategies to address the impacts of global warming in Nigeria.

Keywords Global warming · Nigeria · Ecological zone · Climate change

Introduction

There are compelling evidences for climate change at the global level. The evidences are well documented in various scientific journals and reports, including the Intergovernmental Panel on Climate change (IPCC) Fourth Assessment Report (IPCC 2007a). However, the regional distribution of the climate change is not uniform; some regions have experienced greater change than others. The impact of the climate change is severe in Africa, where it has brought serious disturbances in the ecosystems, reduction in water resources and decline in agricultural and food production (IPCC 2007b). The IPCC report projects that by 2020, between 75 and 250 million people will be exposed to an increase in water stress caused by climate change; hence, agricultural production and access to food in many African countries may be further threatened. This will adversely affect food security, aggravate malnutrition, and increase diseases in the continent. However, there is still insufficient knowledge on the local impacts of the global warming, especially the impacts on individual

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countries in Africa. In addition, there are uncertainties on how the global warming will change the frequency and severity of extreme climate events at local levels. Hence, it is necessary to do more in-depth ecological zone-specific studies and analysis in each African country. The focus of the present study is on Nigeria, the most populous African country (with over 140 million populations) that depends on rain-fed agriculture to feed the population; over 70 % of the population are classified poor and 35 % of them live in absolute poverty (IFAD 2009).

Some studies have investigated the impacts of global warming over Nigeria, but most of them used Global Climate Models (GCMs) simulations to project the future climate change over Nigeria (e.g. Adejuwon 2006). Although GCMs are primary tools for simulating past climate and projecting the future climate under different climate forcing scenarios, their typically horizontal resolution (about 200–300 km) makes their results not applicable at local or national scale because they cannot resolve local-scale features (e.g. sea-breeze, mountain-induced flows) that play important roles in regional climate. Therefore, a downscaling technique is required to translate the GCMs results at large-scale to climate information at a local or national scale. There are two major downscaling approaches: dynamical and statistical downscaling methods. Statistical downscaling method uses statistical/empirical equations to represent the relationship between large-scale atmospheric variables (predictors) and local-scale climate variables (predictands). Dynamical downscaling method embeds a regional climate model (RCM) in a GCM to translate the GCMs simulations from a large-scale to a finer spatial scale by simulating the influence of small-scale features. Various studies have commented on the reliability of both approaches in downscaling GCM results to provide climate information at local scales (McGregor 1997 and Takle 1999).

Despite the international modeling efforts to downscale the impact of global warming over different regions and nations of the world, only little information is available over Nigeria. Hewitson and Crane (2006) used statistical downscaling approach to study future climate projections over West Africa, but excluded Nigeria because they had no access to Nigerian station data to train the model (personal communication with Bruce Hewitson). Sylla et al. (2010) used dynamic downscaling approach over West Africa to add spatial detail to the future climate change projection for late twentieth century under the IPCC A1B scenario. Using the same approach and scenario, Abiodun et al. (2012) provide climate change information for near time future (2030–2050) over West Africa. Patricola and Cook (2009, 2010) used dynamical downscaling to provide the impact of climate change under IPCC A2 scenario. It is widely accepted that climate change information appropriate for planning and decision-making should be based on multiple GCMs using different GHG scenarios and downscaling techniques. Hence, the present study uses statistical method to provide climate change information over Nigeria under two IPCC climate change scenarios (B1 and A2).

This study aims to investigate the future impacts of global warming on climate change and extreme climate over Nigeria. The specific objectives of the study are to (1) use the statistical downscaling approach of Hewitson and Crane (2006) in downscaling global climate simulations (past and future with A2 and B1 scenarios) over Nigeria, (2) evaluate capability of the downscaling approach in replicating the past climate over Nigeria, and (3) study the impacts of the global warming on the future changes in climates and the extreme events over each ecological zone in Nigeria. Section “Study site, data, and methodological concept” presents a brief description of Nigerian climate; Section “Results” describes the data and methodology used in the study; Section “Discussions” presents the results and discussions; and Section “Conclusion” gives the concluding remarks.

Study site, data, and methodological concept

Nigeria lies on the south coast of West Africa between latitudes 4°–14°N and longitudes 2°–15°E. It has a total landmass of about 925,796 km^2. The climate of Nigeria varies more than those of any other country in West Africa because of its great length from south to the north (1,100 km) and it covers virtually all the climatic belts of West Africa. The climate is dominated by the influence of three main wind currents: the tropical maritime (TM) air mass, the tropical continental (TC) air mass, and the equatorial easterlies (Ojo 1977). The first air mass (TM) originates from the southern high-pressure belt located off the Namibian coast and along its way picks up moisture from over the Atlantic Ocean and is thus wet. The second air mass (TC) has the high-pressure belt north of the Tropic of Cancer as its origin. This air mass is always dry as a result of little moisture it picks along its way. The first two, TM and TC, meet along a surface called the Inter-Tropical Discontinuity (ITD). The third air mass (equatorial easterlies), an erratic cool air mass, comes from the east and flow in the upper atmosphere along ITD. This air mass penetrates occasionally to actively undercut the TM or TC and give rise to squall lines or dust devils (Iloeje 1981).

Nigerian climate is humid in the south (with annual rainfall over 2,000 mm) and semi-arid in the north (with annual rainfall less than 600 mm). Rainfall commences at the beginning of the rainy season around March/April from the coast (in the south), spreads through the middle belt, reaching its peak between July and September, and eventually gets to the northern part very much later. The reverse holds for the rainfall retreat period (Ojo 1977). The climatic zones of the country can be broadly grouped into three: Sahel (11°–14°N), Savanna (8°–11°N), and the Guinea (4°–8°N) zones (Fig. 1). The ecological zones of the country are usually grouped into seven, namely from south to north: Mangrove, Fresh water swamp, Rainforest, Woodland or Guinea (Tall Grass) savanna, Montane, Sudan (Short Grass) savanna, and Sahel (Marginal) Savanna. Nigerian topography also plays a significant role in the spatial distribution of the climate. The topography features a low-lying coastal plain, covering much of the country in the south region and along basins of River Niger and River Benue, and high mountains inland (Fig. 1). The mountains, which usually trigger deep convective rainfalls, are associated with higher rainfall and lower temperature than the surrounding low land.

For this study, we used observation (station and gridded) and downscaled GCM datasets. The station data, obtained from the Nigerian Meteorological Agency (NIMET), comprise daily temperature (maximum and minimum) and rainfall data from 1971 to 2000 for 40 synoptic weather stations in Nigeria. The geographical locations of the stations, the topography, the climatic zones, and the ecological zones used in the study are shown in Fig. 1. All the stations meet constraints of minimum of 10 years of daily data post-1979 for the statistical downscaling. Quality control check were perform on the station data, including checking for unrealistic rainfall and temperature values, as well as testing each time series for homogeneity. Suspicious data were set to missing values before proceeding with the tests for trends and using the data for the downscaling. To establish the credibility of the station data, after the quality control, we compared some of the results (i.e. mean and trends) from the station data with those from Climatic Research Unit (CRU; Mitchell and Jones 2005) gridded dataset over Nigeria and found a good agreement between the datasets.

The GCMs simulations data were downscaled with a statistical downscaling model (hereafter, SOMD), developed by Hewitson and Crane (2006). Detailed descriptions of the model are given in Hewitson and Crane (2006). The model was used to downscale results of nine GCMs (Table 1) simulations for historical (1971–2000) and future climate (2046–2065 and 2081–2100) each of the 40 stations. The future climate simulations were forced with the IPCC B1 and A2 scenarios. We used these two scenarios because B1 is the lowest IPCC emission scenario and A2 is the moderately high scenario. The downscaling of the future simulation was limited to 2046–2065 and 2081–2100, for which the GCMs daily datasets were available. B1 and A2 simulation data were available for the study. Climate data over each ecological zone were obtained by averaging the stations data within the zone. The station data were gridded to 50-km resolution grid-mesh to obtain the spatial distribution of the climate variables over Nigeria. The climate changes are obtained by computing the differences between the downscaled past and future climate simulations (i.e. future minus past climate).

In the study, extreme temperature event is defined as the 99.5 percentile of the daily maximum temperature in the past climate (1971–2000), while heat wave event is defined as occurrence of the extreme temperature consecutively for 3 days. The extreme rainfall is defined as the 99.5 percentile of the daily rainfall in the past climate (1971–2000). The onset of rainfall season is defined, following Omotosho et al. (2000), as the beginning of the first two rains totaling at least 25 mm within 7 days, followed by 2–3 weeks each with at least 50 % of weekly water requirement, which are 1.6, 3.6, and 4.6 mm in Guinea, Sudan, and Sahel region, respectively. The length of rainfall season is the period between the rainfall onset and cessation dates.

Results

Model evaluation in simulating past climate

The study evaluates the capability of the downscaling model (SOMD) in simulating the past (1971–2000) climate

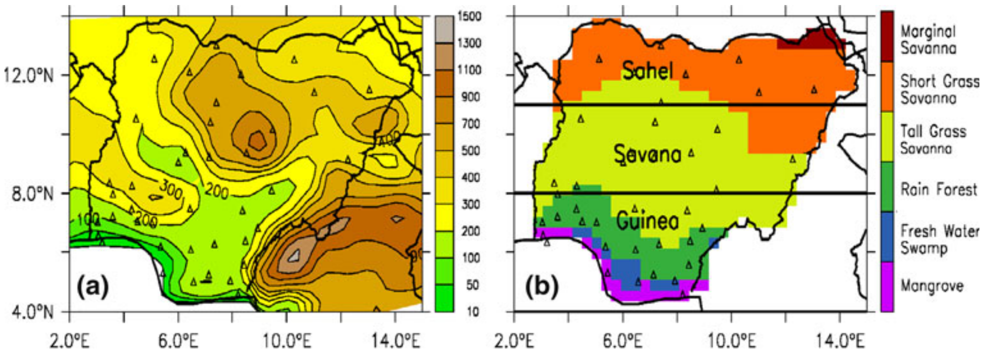


Fig. 1 Study domain showing Nigerian **a** topography (in meters) and **b** ecological zones with regions designated as Guinea, Savanna, and Sahel. The geographical locations of the meteorological stations used in the study are indicated with *triangles*

Table 1 List of general circulation models (GCMs) used in this study

	Modeling group, country	IPCC Model I.D.	Primary reference
1	The Canadian Center for Climate Modeling and Analysis Coupled Global Climate Model, Canada	CCCMA_CGCM3	Flato and Boer (2001)
2	Center National de Recherches Météorologiques Climate Model, France	CNRM_CM3	Cariolle et al. (1990), Déqué et al. (1994), Masson (2003)
3	The Commonwealth Scientific and Industrial Research Organization, Australia	CSIRO_MK3	Gordon et al. (2002)
4	Geophysical Fluid Dynamics Laboratory, USA	GFDL_CM2.0	Gent and McWilliams (1990)
5	Goddard Institute for Space Studies Model, USA	GISS_MODEL_ER	Russell and Lerner (1981)
6	Institut Pierre Simon Laplace, France	IPSL_CM4	Bony and Emmanuel (2001)
7	Meteorological Institute of the University of Bonn (Germany), Institute of KMA (Korea), and Model and Data Group	MIUB_ECHO_G	Roeckner et al. (1996)
8	Max Planck Institute for Meteorology, Germany	MPI_ECHAM5	Roeckner et al. (2003)
9	Meteorological Research Institute, Japan	MRI_CGCM2_3_2a	Yukimoto et al. (2001)

over Nigeria. The evaluation focuses on how well the model reproduces important features in the spatial distribution of temperature and rainfall fields over Nigeria, the seasonality of the climate over the ecological zones, and the horizontal distribution of the extreme climate events over the zones.

The ensemble of the downscaled simulation (from SOMD) reproduces the spatial distribution of temperature and rainfall over Nigeria better than that of the GCMs simulation (Fig. 2). In the temperature and rainfall fields, there are substantial differences between the GCM ensemble and the observation, but there is a very good agreement between the SOMD ensemble and the observation. For example, the GCMs ensemble fails to capture the influence of Jos plateau on both temperature and rainfall fields because the GCMs resolutions are too low to resolve the shape and influence of the plateau. But SOMD ensemble captures the influence as observed, by producing a low temperature and high rainfall over the Plateau. In addition, the GCMs ensemble shows a cold bias of about 3.0 °C in the temperature fields and a dry bias of 3 mm day^{-1} in the rainfall field, but the bias in SOMD ensemble is less than 1.0 °C in the temperature fields and less than 1 mm day^{-1} in the rainfall field. Furthermore, the GCMs ensemble does not reproduce the maximum rainfall along the coastal region, but SOMD ensemble represents it very well. Hence, SOMD adds values to the GCMs simulations and the results agree well with the observation. This confirms the need for downscaling GCMs simulations over Nigeria and shows the reliability of using SOMD for the downscaling.

The downscaled seasonal cycles of the temperature and rainfall over each zone compare well with the observation (Figs. 3, 4). Apparently, the downscaled result of each GCM reproduces seasonality well, but with some biases. The magnitudes of biases vary from one GCM to the other; in general, IPSL results show the highest bias by simulating seasonality (temperature and rainfall) with 3 month ahead of the observed. However, the seasonality of the models ensemble is better than that of individual GCMs. This supports the idea that climate projections from ensemble of multi-models would be more reliable than those from a single model (Rajagopalan et al. 2002; Mylne et al. 2002). However, the ensemble does not reproduce the little dry season (i.e. the local minimum rainfall value in August) over the Mangrove and Rainforest zones, possibly because the vertical motion that plays a crucial role in the occurrence of the little dry season is not a predictor in SOMD (personal communication with Bruce Hewitson). The ensemble also underestimates the rainfall during the peak of the monsoon (July–September) over all the zones. Nevertheless, the level of agreement between the ensemble and observed seasonal temperature and rainfall pattern shows that the downscaling techniques captures the monsoon cycle and the associated rainfall patterns over Nigeria well.

Table 2 presents trends in temperature (maximum and minimum) and rainfall over the country and the four ecological zones in 1971–2000 for downscaled ensemble and observation (station and CRU) data. With temperature, in 1971–2000, the observations (station and CRU) show a statistically significant (at least 95 % confidence level) positive trends for maximum temperature (0.14 and 0.15 °C per decade, respectively) and minimum temperature (0.16 and 0.17 °C per decade, respectively). With station data, the highest trend in maximum temperature occurs over Rainforest (0.023 °C per decade, significant at 99 % confidence level); but with CRU, it occurs over the Mangrove (0.17 °C per decade, significant at 95 % confidence level). The models ensemble shows much lower non-significance positive trends (0.04 °C and 0.03 °C per decade for maximum and minimum temperatures, respectively). Hence, the

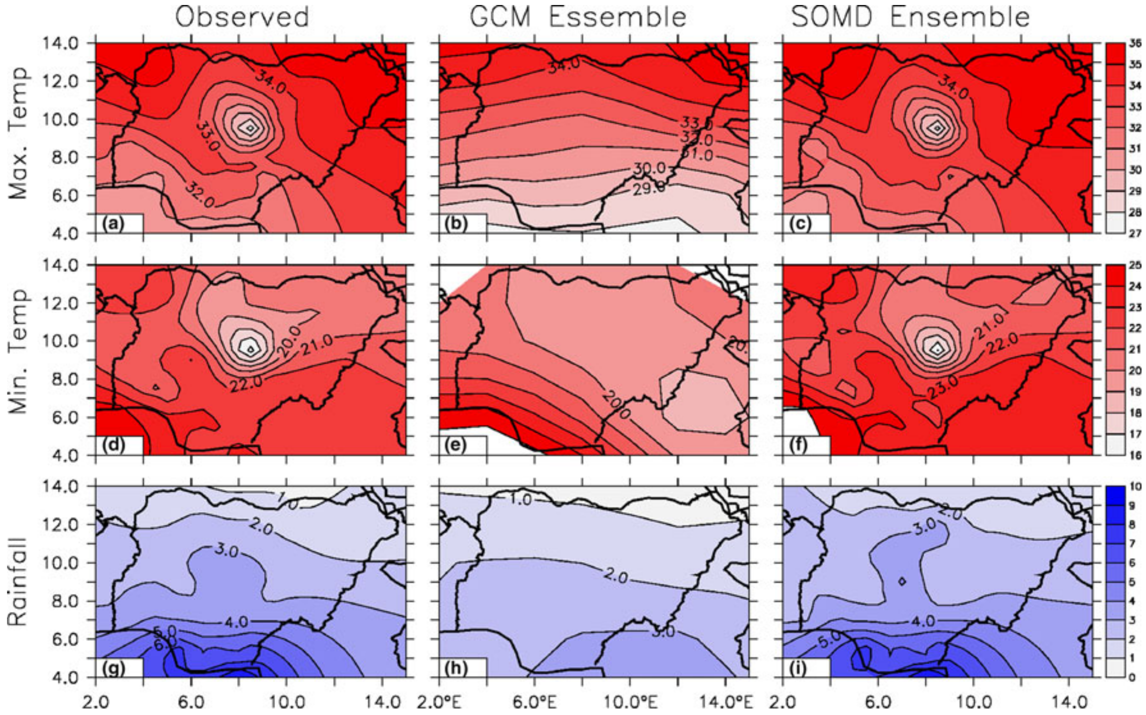


Fig. 2 Spatial distribution of maximum temperature (°C), minimum temperature (°C), and rainfall (mm day^{-1}) as observed, simulated by GCMs, and downscaled by SOMD over Nigeria (1971–2000)

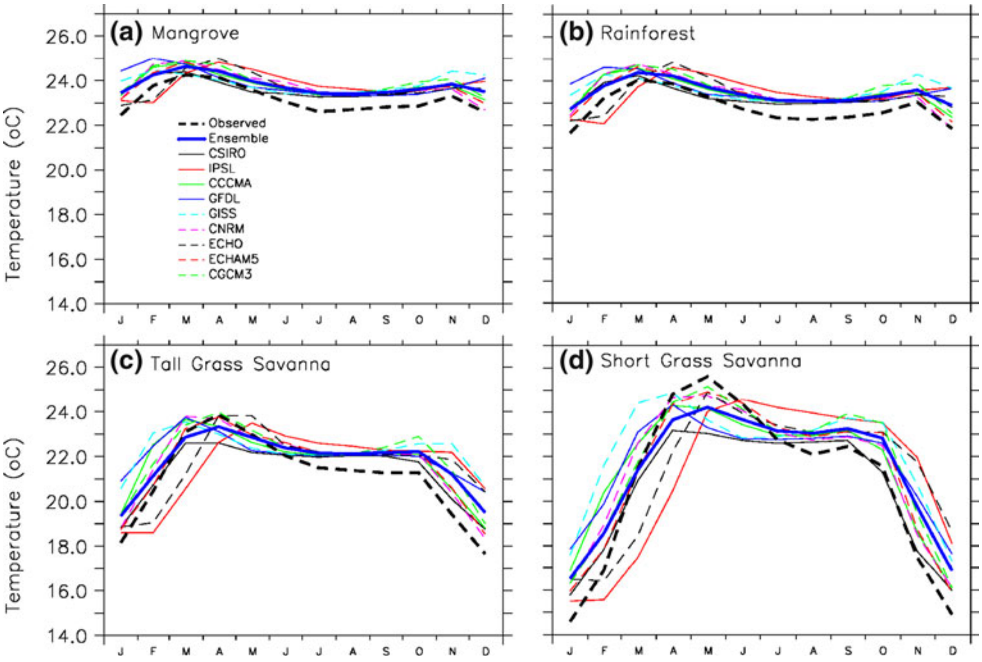


Fig. 3 The seasonal cycle of observed and simulated maximum temperature (°C) over the ecological zones in Nigeria (1971–2000)

ensemble underestimates the temperature trends and highest bias occurs over Mangrove and Rainforest. Observations (station and CRU) show statistically non-significant positive trends for rainfall over Nigeria (4.077 and 1.999 mm year^{-2}, respectively). The models ensemble, on the other hand, show a statistically non-significant negative trend (−3.773 mm per year^{-2}). These results are consistent with that of Oguntunde et al. (2011). This implies that temperature increase in 1971–2000 is significant (i.e. higher that the natural variability), but the change in rainfall is not

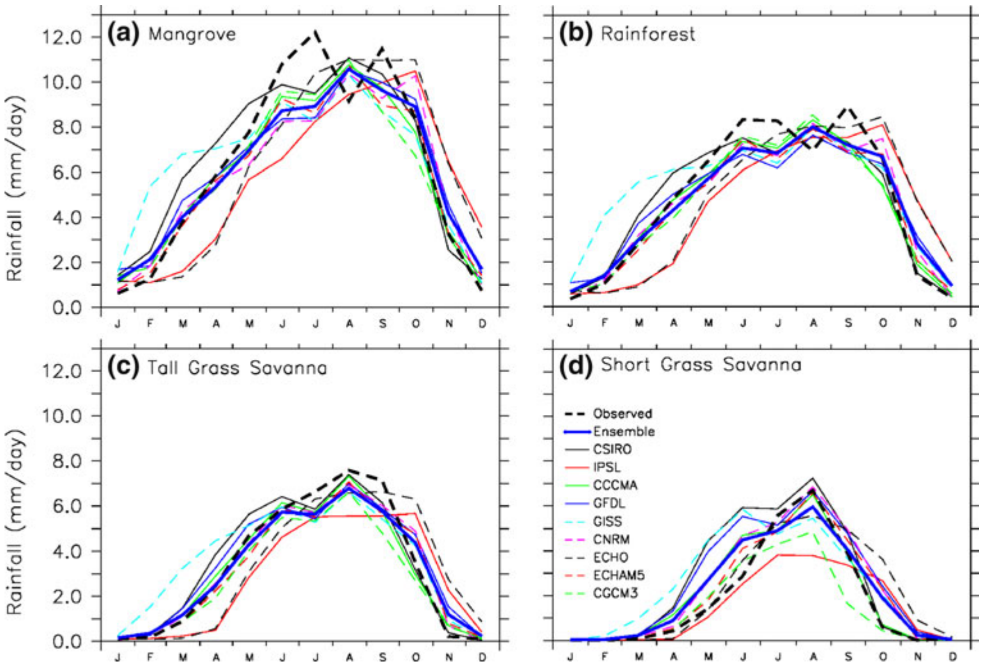


Fig. 4 The seasonal cycle of the observed and simulated rainfall (mm day^{-1}) over the ecological zones in Nigeria (1971–2000)

Table 2 Simulated and observed trends (°C per decade) in maximum and minimum temperature and rainfall in present-day climate: 1971–2000

Parameters	Region/zone	Observation		Model
		Station	CRU	Ensemble
Maximum temperature (°C per decade)	Nigeria	0.14*	0.15*	0.04
	Mangrove	0.23*	0.17*	0.03
	Rainforest	0.27**	0.15	0.04
	Savanna	0.12	0.12	0.03
	Sahel	0.06	0.14	0.06
Minimum temperature (°C per decade)	Nigeria	0.16*	0.17*	0.04
	Mangrove	0.16*	0.17*	0.02
	Rainforest	0.12	0.19*	0.02
	Savanna	−0.07	−0.07	0.00
	Sahel	0.17	0.15	0.06
Rainfall (mm year^{-2})	Nigeria	4.077	1.999	−3.773
	Mangrove	1.951	2.483	−7.396
	Rainforest	4.234	1.762	−4.103
	Savanna	0.966	1.071	−3.373
	Sahel	2.953	0.941	−1.824

Mann–Kendall trend were used for the analysis, after pre-whitening the data to remove auto-correlation. * Denotes 95 % significant level; ** denotes 99 % significant level; and *** denotes 99.9 % significant level

significant (i.e. within the natural variability). Nevertheless, this does not imply that past climate change has not played any role in past precipitation in Nigeria. It might be that the time period (1971–2000) we used in the present study is too short to capture the influence. For example, Oguntunde et al. (2011) found a significant negative trend in rainfall over Nigeria in a longer period (1901–2000).

Projected future changes in climate and extreme events

This section discusses how global warming could change the future temperature (maximum and minimum), rainfall, and frequency of extreme events (i.e. extreme temperature, extreme rainfall intensity, and heat waves) over the ecological zones in Nigeria. The model projections for the two future periods (2046–2065 and 2081–2100) and for the two scenarios (B1 and A2) are discussed. All changes are calculated with respect to the mean of past climate (1971–2000).

Climate changes

In the time series of annual changes in temperature and rainfall (Fig. 5), both B1 and A2 scenarios induce a warmer climate in future, but the future climate is warmer under A2 scenario than under B1 scenario. B1 scenario produces a consistent warming of 0.2 °C per decade from 2000 till late-century (2100), while A2 produces a warming of 0.4 °C per decade from 2000 till mid-century (2046–2065) and a warming of 0.8 °C per decade in late-century (2080–2100) (Fig. 5). By mid-century, the projected annual temperature changes over Nigeria are +1.5 °C and +0.2 °C for B1 and A2 scenarios, respectively. These values are within those shown over Nigeria in the IPCC (2007a) report. The increase in temperature over Nigeria from global scenarios are higher (by 0.2 °C and 0.3 °C, respectively) than the global mean given in the

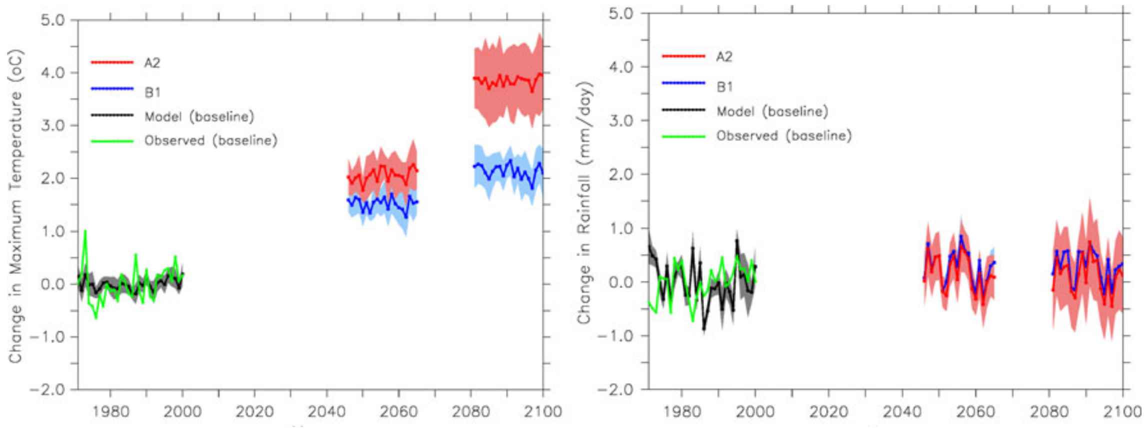


Fig. 5 Time series of changes in maximum temperature (°C) and rainfall (mm day^{-1}) for the past climate and future climate under B1 and A2 scenarios over Nigeria. The *dashes* show the observation; the *lines* represent the models average, while the *shaded* regions are areas of a standard deviation away from the average. Note: GCM daily datasets needed for the statistical downscaling were not available for the missing periods (2001–2039 and 2066–2079)

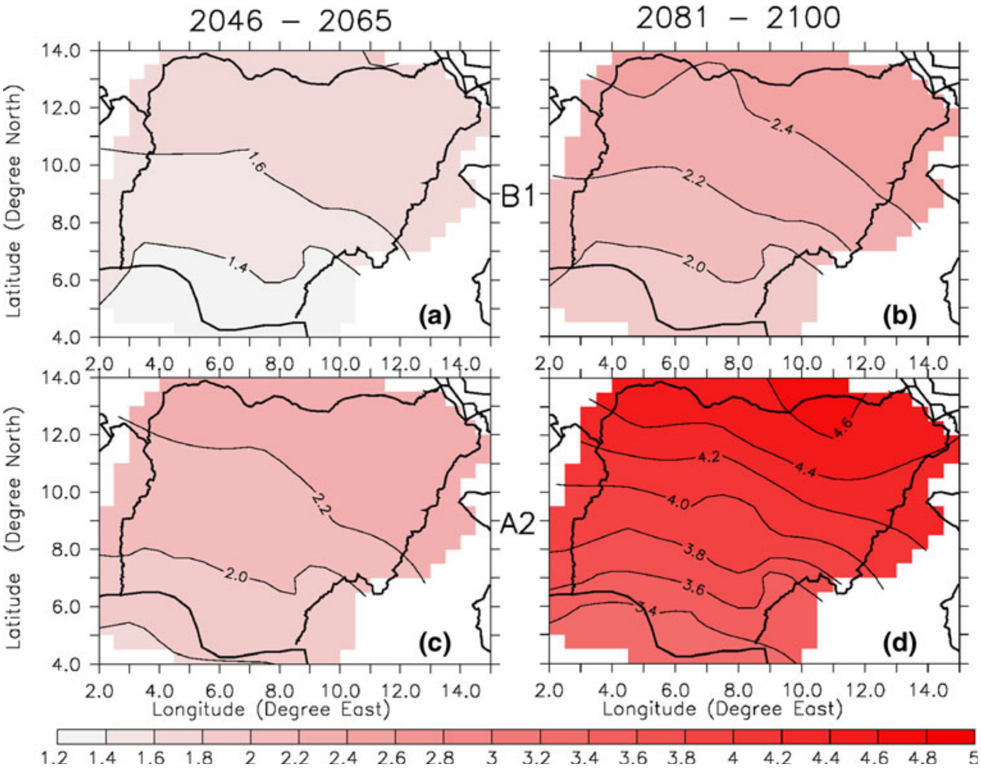
IPCC report. In consistency with the IPCC (2007a) report, the difference between the temperature change in B1 and A2 scenarios becomes wider; it is about 0.5 °C in mid-century and 2.0 °C in the late-century (Fig. 10). There is no specific trend in future rainfall anomalies under both scenarios and projected rainfall changes with both scenarios are similar (Fig. 5b). However, the envelope (i.e. uncertainty) of the rainfall projections is wider in the late-century than in the mid-century, meaning that the uncertainty in the projections is higher in the former than the later.

The spatial distribution of the temperature over Nigeria (Fig. 6) shows positive changes in temperature (warming) over the entire country for both scenarios. However, the warming increases with latitudes, with the lowest warming over the coastal region and the highest at the northeast. The coastal regions receive lower warming than the interior because the cooling effect from the Atlantic Ocean reduces the warming near the coast. Hence, the northern stations are expected to be warmer than the southern stations. At the northeast, B1 scenario produces a temperature increase of 1.8 °C in mid-century (2046–2065) and 2.4 °C in late-century (2081–2100), while A2 scenario produces a temperature increase of 2.2 °C in mid-century (2046–2065) and 4.5 °C in the late-century (2081–2100). This temperature distribution is consistent with those given over Nigeria in the IPCC report. However, it is important to note that the unequal distribution of temperature changes would increase the temperature gradient over the country and that would have dynamical effects on the wind pattern. For instance, it will increase the speed of the southwest monsoon flow, in consistent with stronger Hadley cell circulation under the global warming (Lu et al. 2007). However, a stronger monsoon flow would transport more moisture into the country in summer.

The spatial distribution of the rainfall changes suggests a wetter climate over Nigeria (especially over the southern half) in future (Fig. 7). B1 scenario produces an increase in rainfall over the entire country, with highest increase (about 0.8 mm/day) near the coast and the lowest (about 0.2 mm/day) value at northeast; the rainfall pattern does not change between the mid-century and late-century. A2 scenario produces an increase in rainfall over parts of the country and a decrease in rainfall over the northeast, with possibility for a decrease in rainfall over Jos plateau in the late-century. The model results for both scenarios are consistent with changes in the temperature pattern. The stronger monsoon flow, caused by the stronger temperature gradient, would transport more moisture to produce more rainfall over the country, especially over the coastal region. In addition, with the increase in the temperature (Fig. 5), the capability of the atmosphere to contain moisture increases. Hence, the increase in temperature along the coast would make the atmosphere evaporate more water from the ocean to produce more rainfall over the coastal region. On the other hand, the warmer climate over the semi-arid region (i.e. northeast) would decrease the relative humidity of the atmosphere because evaporation of soil moisture may not be sufficient to meet the extra demand of atmospheric air to reach saturation, thereby reducing the chance of cloud formation and rainfall. In line with this, the northeast would have a drier climate under A2 scenario than under B1 scenario (as shown in Fig. 7) because the temperature is higher under A2 scenario than under the B1.

Nevertheless, Table 3 shows that while the projected changes in the annual temperature over the ecological zones are significant (i.e. higher than the natural variability of the past climate), the changes in annual rainfall are not significant. This is because, in the tropics, the interannual variability of temperature is very low, but the interannual variability of rainfall is very high. However, the global warming increases the annual temperature in Nigeria

Fig. 6 Spatial distribution of the projected changes in maximum temperature (°C) over Nigeria in the future (2046–2065 and 2081–2100) under B1 and A2 scenarios



beyond the threshold of the natural variability of the past climate, but leaves annual rainfall changes within the natural variability of the past climate. Although the rainfall changes may not be significant, they may still enhance or weaken the natural rainfall variability in the future climate. The monthly variation of the increase in temperature (Fig. 8) shows that over Mangrove and Rainforest zones the warming is almost uniform through the year, but over Tall Grass Savanna and Short grass Savanna it is somewhat higher in March (when the arrival of the insolation increases the surface temperature) than in June–August (when arrival of the cool monsoon air lowers the surface temperature). The monthly distribution of the rainfall changes has a similar pattern over all the zones; the maximum increase is in August (Fig. 9). In addition, all the zones show increase in rainfall during the pre-monsoon months (March–May), suggesting earlier onset of rainy season over the zones (as shown Table 3). This is consistent with the projected increase in temperature gradient and the stronger monsoon flow, which brings in moisture faster to initiate the onset of rainy season earlier over the country (Abiodun et al. 2008).

Furthermore, both scenarios show an increase of 4–11 days in the length of the rainy season over the zones in mid-century and late-century. And in most cases, the increase in the length of rainy season is due to the earlier onset of rainfall rather than the late cessation of the rainy season (Table 3). However, the changes in onset dates, cessation, and the length of rainy season are within the natural variability of the past climate. The table also shows significant decreases in the number of days with dry spell over the zones, with the highest decrease over the Tall Grass Savanna; most of the decrease in the dry spell days occurs during the pre-monsoon periods (Fig. 10); this is in agreement with the projected earlier onset of rainfall due to the global warming.

The climate extreme events

The models project an increase in future occurrences of extreme temperature event over all the ecological zones in Nigeria under the two scenarios (B1 and A2). With B1 scenario, the number of days with extreme temperature event increases over the zones (Mangrove, Rainforest, Short Grass Savanna, and Tall Grass Savanna) by about 24, 13, 18, and 22 days per year in 2046–2065, respectively, and by 42, 25, 29, 33 days per year, respectively, in 2081–2100. But with A2, it increases by 40, 24, 27, and 30 days per year, respectively, in the mid-century and by 106, 73, 72, and 71 days per year in the late-century. However, the increase in the extreme temperature is not evenly distributed within the year (Fig. 11). The maximum increase occurs during the pre-monsoon season (March–April, when the arrival of the insolation increases the surface temperature), and the minimum increase occurs during the peak of monsoon period (June–August, when then entire country is under the influence of cool moist air from the Atlantic). The number of days with heat wave also increases. With B1 scenario, heat wave event increases by

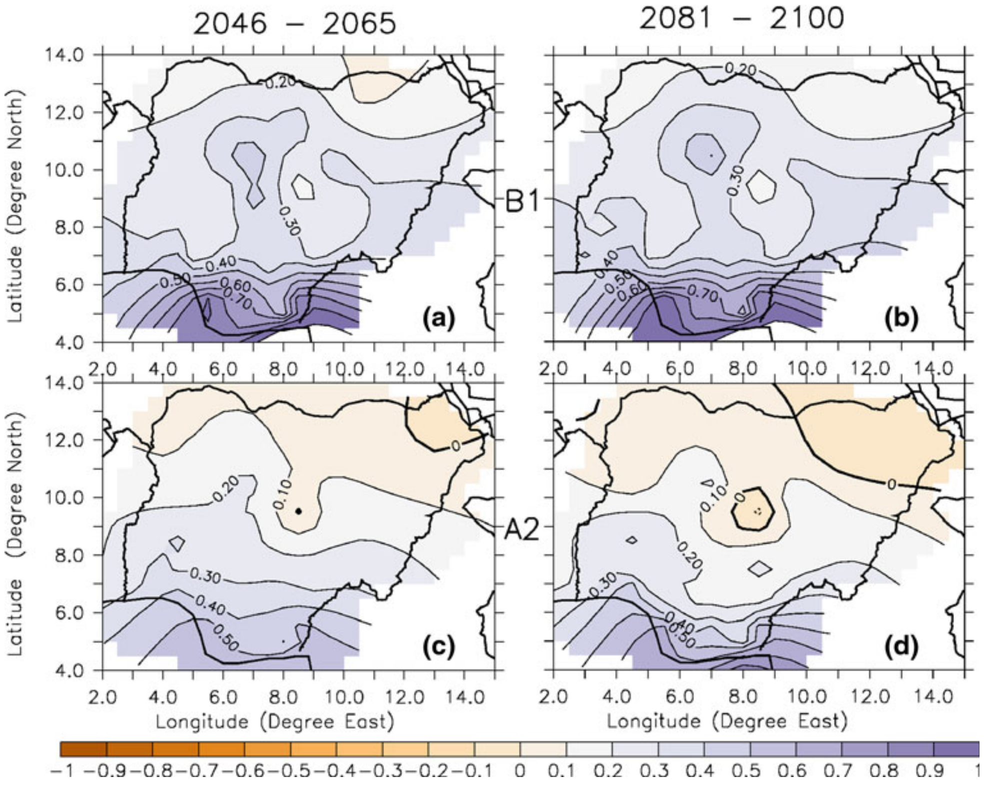


Fig. 7 Spatial distribution of the projected changes in rainfall (mm day-1) over Nigeria in the future (2046–2065 and 2081–2100) under B1 and A2 scenarios

about 3, 1, 3, and 5 days per year in 2031–2060 and by 8, 3, 7, and 10 days per year (over Mangrove, Rainforest, Short Grass Savanna, and Tall Grass Savanna, respectively) in 2081–2100. And with A2 scenario, it increases by 7, 3, 6, and 8 days per year, respectively, in 2046–2081 and by 45, 26 31, and 31 days per year, respectively, in 2081–2100. The annual distribution of the increase is similar to that of extreme temperature, maximum in February-April and minimum in June–August (Fig. 12).

The changes in number of days with extreme rainfall are small, less than 1 day per decade (Table 3); the seasonal distribution of the changes shows that highest increase (1.2 days per decade) over the Mangrove zones in July under B1 scenario in 2081–2100 (Fig. 13). However, the increase in extreme rainfall over Mangrove and Rainforest is expected because with the increase in temperature, the atmosphere would contain more water at saturation and more water would be released during the rainfall events. Note that the above discussion is on climate extremes, which can be quite different from weather extremes; the later can be much higher.

Discussions

This study used statistical downscaling technique that gives a realistic simulation of past climate over Nigeria to downscale the future projection over the country. As with any future climate projection, there are uncertainties in the results of the projection; the measure of the uncertainties is indicated in Figs. 8, 9, 10, 11, 12 and 13. The main sources of uncertainty are due to future greenhouse gas trajectory and their resultant radiative forcing, natural climate variability, inadequacies in GCM formulation, and downscaling from GCMs. Despite these uncertainties, the results of the projection provide some robust messages that can guide policy makers in taking climate change adaptation decisions in Nigeria.

The projection shows an increase in temperature over the whole country in future but with highest warming at the northern regions and indicates that the country could experience more heat wave events during the pre-monsoon period in future. The projection also suggest both increase and decrease in rainfall over the country in future; the southern part is expected to experience the increase in rainfall (and more extreme rainfall events) during wet season, while the northern region is projected to have a decrease in the annual rainfall amount. These projections have a lot of implications for Nigeria, a developing country with over 140 million populations. As the increasing population is expected to puts more pressure on diminishing resources, the projected future climate impacts could escalate environmental problems and further threaten food production in Nigeria. Land degradation as a result of deforestation, flooding, overgrazing, and oil exploration is already severe in many parts in the country.

Table 3 Impacts of global warming on climate change and extreme events over the ecological zones in Nigeria: the simulated mean and standard deviation (σ; natural variability) of the past climate; the projected changes in 2046–2065 and 2081–2100 under B1 and A2 scenarios. Significant changes (i.e. greater than σ) are indicated in bold

Parameters	Ecological zones	Past climate		Changes with B1		Changes with A2	
		Mean	σ	2046–2065	2081–2100	2046–2065	2081–2100
Maximum temperature (°C)	Mangrove	31.7	0.5	**1.4**	**1.9**	**1.8**	**3.4**
	Rainforest	32.0	0.5	**1.4**	**2.0**	**1.9**	**3.5**
	Tall Grass Savanna	32.7	0.7	**1.6**	**2.2**	**2.1**	**3.9**
	Short Grass Savanna	34.8	1.2	**1.9**	**2.5**	**2.3**	**4.4**
Rainfall (mm day^{-1})	Mangrove	6.0	2.6	0.7	0.7	0.5	0.5
	Rainforest	4.5	2.1	0.5	0.5	0.4	0.3
	Tall Grass Savanna	3.2	1.7	0.3	0.3	0.2	0.2
	Short Grass Savanna	2.1	1.4	0.2	0.3	0.1	0.0
Extreme temperature event (days/year)	Mangrove	2.2	0.4	**23.8**	**42.0**	**39.7**	**106.1**
	Rainforest	2.3	0.4	**13.4**	**24.9**	**24.3**	**73.4**
	Tall Grass Savanna	2.5	0.5	**17.6**	**28.8**	**27.0**	**72.8**
	Short Grass Savanna	2.5	0.5	**22.2**	**32.8**	**29.7**	**70.6**
Heat wave event (days/year)	Mangrove	0.0	0.0	**3.0**	**8.3**	**7.4**	**44.8**
	Rainforest	0.0	0.0	**1.1**	**3.4**	**3.1**	**26.2**
	Tall Grass Savanna	0.0	0.0	**2.8**	**6.8**	**5.7**	**30.8**
	Short Grass Savanna	0.0	0.0	**4.8**	**10.2**	**8.0**	**31.1**
Extreme rainfall event (days/year)	Mangrove	0.8	0.2	0.1	0.1	0.0	0.0
	Rainforest	0.7	0.2	0.1	0.1	0.1	0.0
	Tall Grass Savanna	0.5	0.2	0.0	0.1	0.0	0.0
	Short Grass Savanna	0.3	0.2	0.0	0.0	0.0	0.0
Dry spell (days/year)	Mangrove	66.3	4.3	−2.9	−3.3	−1.7	**−4.7**
	Rainforest	88.0	4.5	**−5.1**	**−7.3**	−4.1	**−5.9**
	Tall Grass Savanna	146.7	4.2	**−8.5**	**−8.7**	**−4.3**	**−4.9**
	Short Grass Savanna	205.3	4.3	**−7.9**	**−8.6**	**−4.3**	**−4.8**
Rainfall onset date (Julian day)	Mangrove	57.2	25.6	−5.9	−8.7	−7.4	−7.7
	Rainforest	70.3	23.7	−7.5	−9.4	−8.2	−7.9
	Tall Grass Savanna	112.0	22.9	−10.0	−9.4	−7.1	−4.5
	Short Grass Savanna	151.9	25.5	−11.3	−11.8	−6.9	−2.7
Rainfall cessation date (Julian day)	Mangrove	319.7	13.9	2.1	1.0	1.5	1.3
	Rainforest	315.3	13.0	1.7	1.7	1.1	0.6
	Tall Grass Savanna	295.3	14.9	1.3	1.6	−1.0	0.1
	Short Grass Savanna	268.0	14.2	−0.4	0.2	−1.2	0.7
Length of rainfall season (days/year)	Mangrove	265.6	28.7	5.8	5.7	6.2	6.2
	Rainforest	245.5	27.1	8.7	10.4	8.6	7.9
	Tall Grass Savanna	183.4	27.5	11.1	10.9	6.0	4.8
	Short Grass Savanna	117.2	28.3	10.2	11.4	5.4	4.0

The projected decrease in rainfall in the northern region could aggravate land degradation because drought is a common problem in the north, while the increase in extreme rainfall could worsen heavy rains and floods (which are major problems) in the south and southeast (IFAD 2009). Desertification, drought, and flooding can lead to poor agricultural output, thereby worsening malnutrition among vulnerable subgroups. Furthermore, heavy rainfall in the coastal regions can aggravate epidemic and endemic diseases. For example, cholera epidemics may be aggravated by flooding and fecal contamination of surface and underground water. Malaria, already endemic and accounting for significant morbidity and mortality among pregnant women and children aged less than 5 years, will be further aggravated by increased breeding sites for anopheles species.

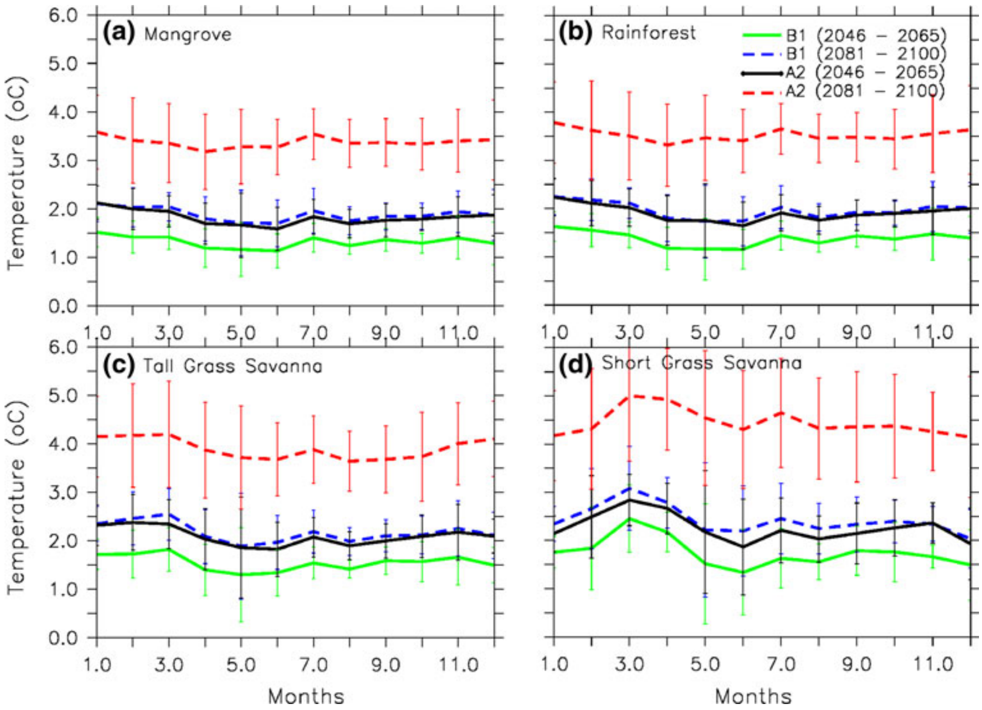


Fig. 8 Seasonal distribution of the projected changes in maximum temperature in future under B1 and A2 scenarios over the ecological zones in Nigeria. The *error bars* show a standard deviation (of the GCMs results) away from the average to indicate the level of inter-model uncertainty

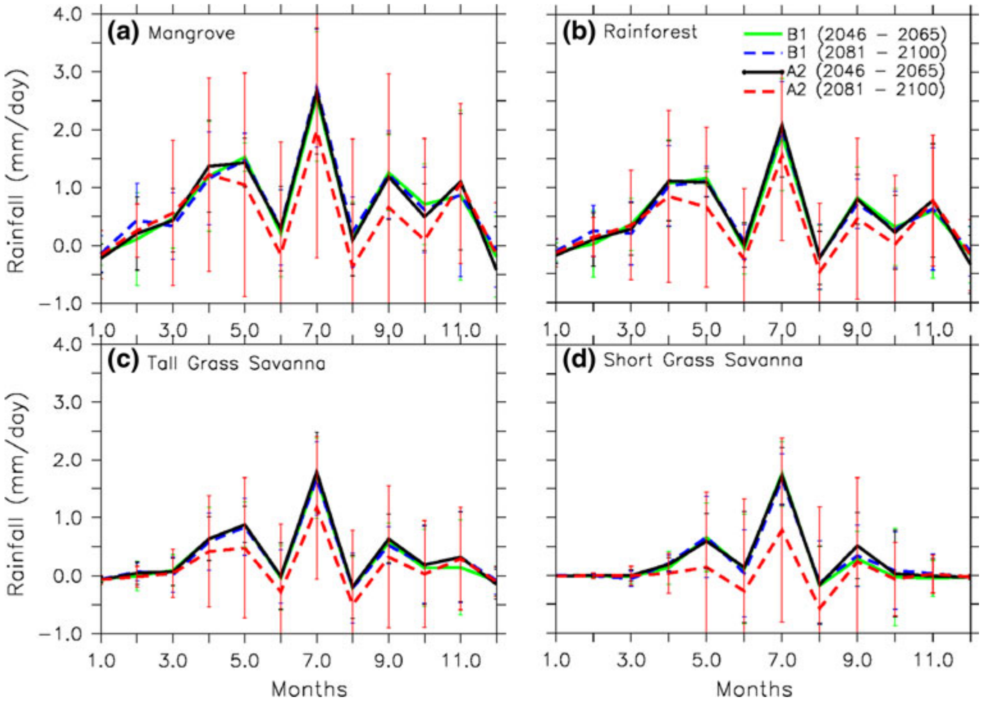


Fig. 9 Seasonal distribution of the projected changes in monthly rainfall in future under B1 and A2 scenarios over the ecological zones in Nigeria. The *error bars* show a standard deviation (of the GCMs results) away from the average to indicate the level of inter-model uncertainty

Hence, Nigeria needs to adequately prepare in handling the negative impacts of the climate change. Government and non-government agencies should create more awareness of the climate change impacts in Nigeria so that private sectors, civil societies, communities, and individuals can be involved in developing adaptation strategies. The awareness can be created through campaigns and information dissemination through radio and television. The campaigns should specially target farmers, who may be mostly affected by the impacts of the climate change. Although the farmers have been practicing various adaptation measures to cope with climate variability in past, such measures may need to be reviewed and improved to withstand the impacts of future climate change.

Necessary control measures to reduce the impact of these on the population should be initiated. For instance,

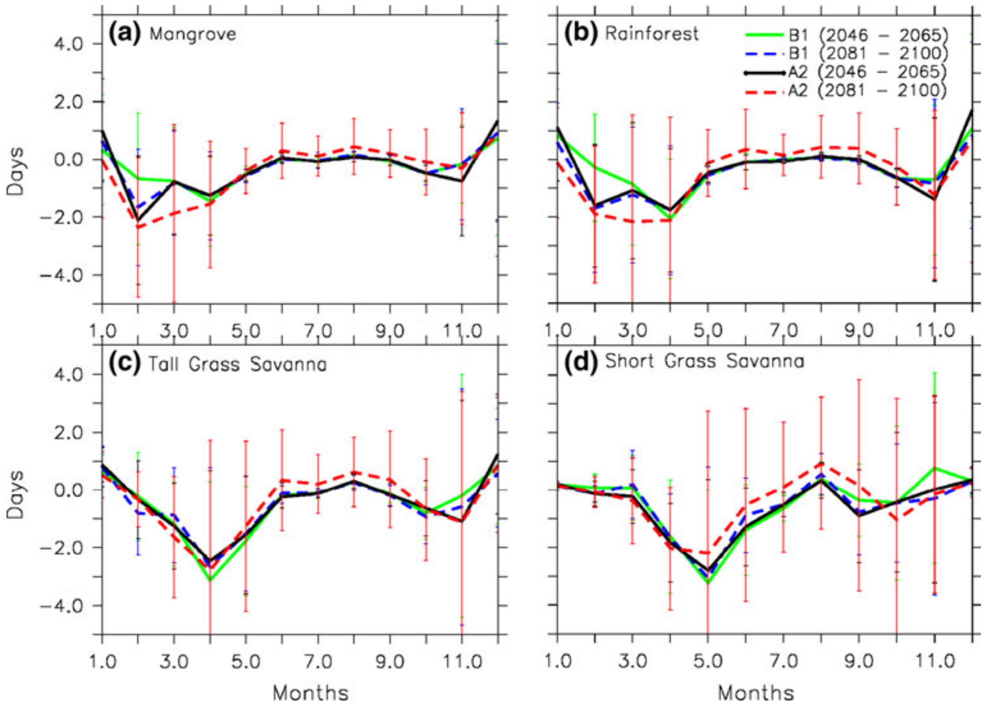


Fig. 10 Seasonal distribution of the projected changes in dry spell in future under B1 and A2 scenarios over the ecological zones in Nigeria. The *error bars* show a standard deviation (of the GCMs results) away from the average to indicate the level of inter-model uncertainty

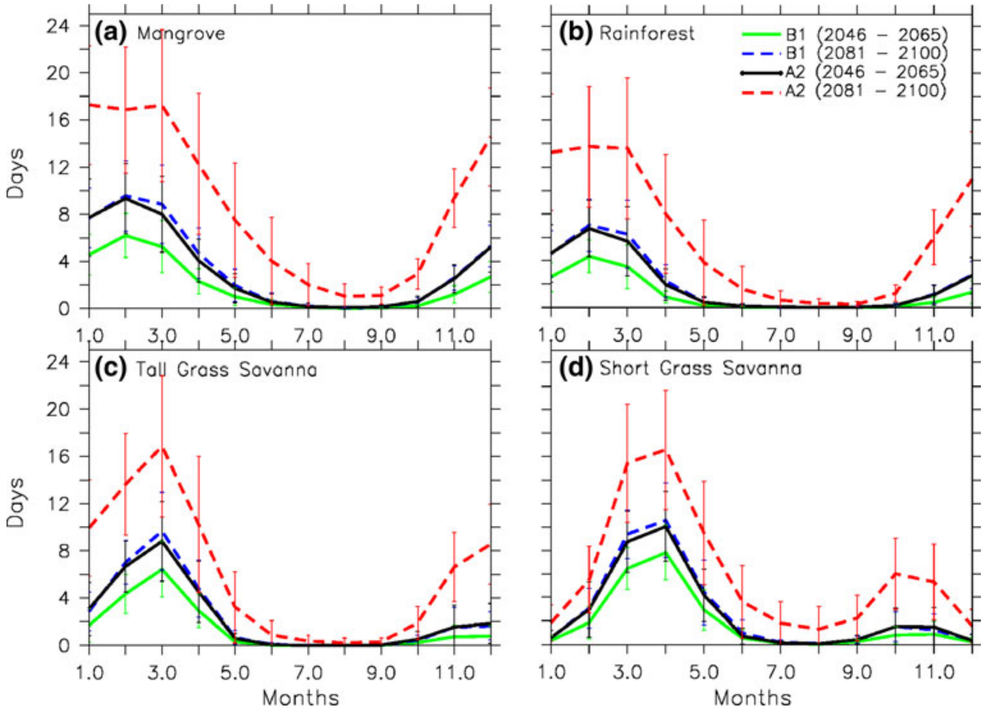


Fig. 11 Seasonal distribution of the projected changes in extreme temperature events in future under B1 and A2 scenarios over the ecological zones in Nigeria. The *error bars* show a standard deviation (of the GCMs results) away from the average to indicate the level of inter-model uncertainty

government needs to do more to track the occurrence of these diseases through improved surveillance activities (i.e. constant monitoring of the occurrence). The Federal government of Nigeria may need to expedite action on relevant policies aimed at combating malaria, especially in the northern parts and coastal regions of the country, such as the provision of long-lasting insecticide treated nets at subsidized rate. Efforts should be made to ensure that Nigerians derives maximum benefits from the Affordable Medicine Facility-malaria (AMF-m) to which the country is a signatory. This facility (through which the malaria drugs are sold at about 20 % of the real cost) allows for affordable anti-malaria drugs.

Furthermore, Nigerian government should work in collaboration with climate researchers in developing, testing, and implementing sustainable climate change adaptation

Fig. 12 Seasonal distribution of the projected changes in heat wave events in future under B1 and A2 scenarios over the ecological zones in Nigeria. The *error bars* show a standard deviation (of the GCMs results) away from the average to indicate the level of inter-model uncertainty

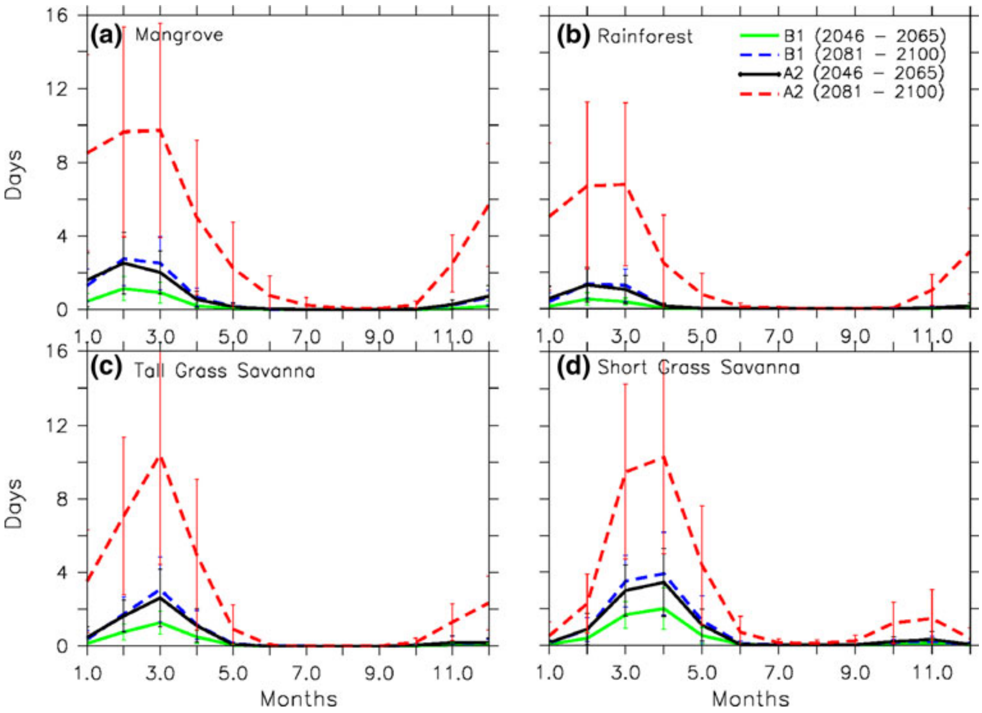
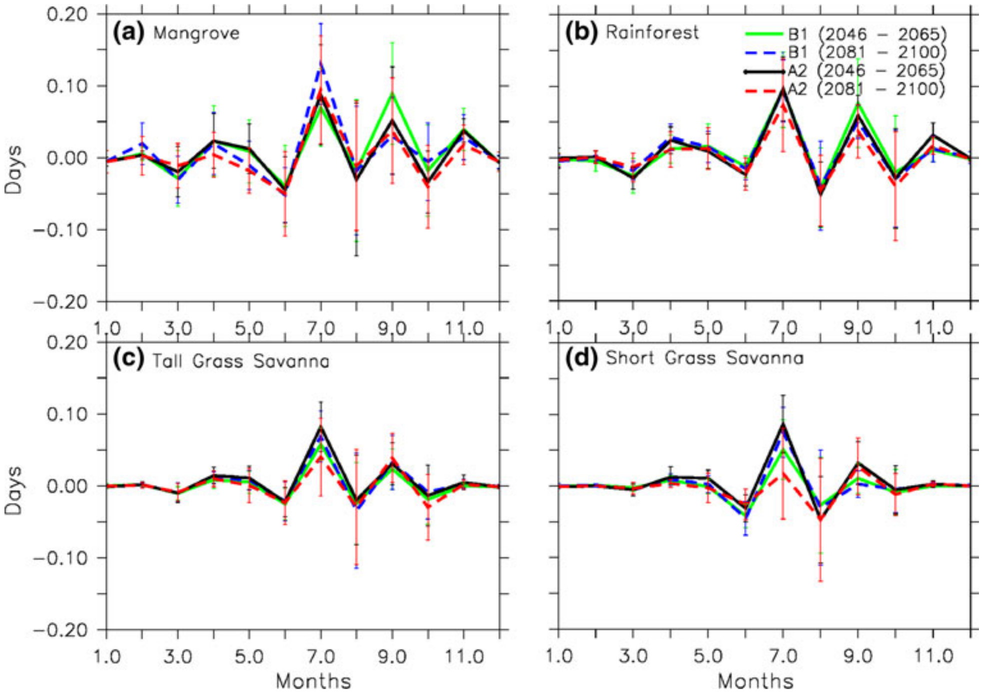


Fig. 13 Seasonal distribution of the projected changes in extreme rainfall events over the ecological zones in Nigeria in future under B1 and A2 scenarios over the ecological zones in Nigeria. The *error bars* show a standard deviation (of the GCMs results) away from the average to indicate the level of inter-model uncertainty



and mitigation measures. While some mitigation measures could reduce the impacts of climate change in a region, it could enhance the impacts in another region. For example, Nigerian government has embarked on large-scale afforestation in Nigeria to mitigate the climate change impacts in the country[1]; meanwhile, Abiodun et.al (2012) recently demonstrated how large-scale afforestation in the middle part of Nigeria could lower the warming in the reforested region but enhance the warming in the northern region. Hence, there is need for more research on using mitigations options (like afforestation) in addressing the problem of climate change in Nigeria. In this regard, the Nigerian government needs to better equip the climate researchers in the country and form partnership with international

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[1] (http://www.punchng.com).

researchers to address the problem of climate change in Nigeria. Finally, steps should be taken to reduce the factors (such as gas flaring, fossil fuel burning, desertification, deforestation etc.,) that contribute to global warming in Nigeria.

Conclusion

This work has studied the impacts of global warming on climate changes and extreme climate events over Nigeria, by using a statistical approach to downscale past and future climate simulations from 9 GCM over the country. The results show that the global warming, under both B1 and A2 scenarios, considerably changes the future climate over Nigeria. It significantly increases the temperature over all the ecological zones; the greatest warming (between 1 and 4 °C) occurs over Short Grass Savanna in the March. The impacts of the warming include an increase in extreme temperature and heat wave events over the zones. The impacts also increase annual rainfall and enhance the occurrence of the extreme rainfall events along the coastal region in Nigeria. Heavy rains and floods are major problems in the south and southeast of Nigeria (IFAD 2009); hence, the projected increase in rainfall and extreme rainfall events may further aggravate these problems in future. On the other hand, there is a tendency for A2 scenario to reduce rainfall over the northeast, a region where drought is a major problem in the present climate. Moreover, the projections show that global warming increases the length of rainy season in future climate by inducing earlier onset of the rainy season. Hence, the shifts in the timing and distribution of rainfall would affect the agricultural practices, crop production, and food security in Nigeria. All these need to be taken into consideration in preparing effective adaptation and mitigation measures for the country.

Acknowledgments The project was supported by grants from Build Nigerian Response to Climate Change (BNRCC) and the International Science Program (ISP, Sweden). Computing facility was provided by the Center for High Performance Computing (CHPC) in South Africa. We appreciate the assistance of Bruce Hewitson and Lisa Coop at Climate System and Analysis Group (CSAG) on the statistical downscaling. We thank the two anonymous reviewers for their constructive comments.

References

Abiodun BJ, Pal JS, Afiesimama EA, Gutowski WJ, Adedoyin A (2008) Simulation of West African monsoon using RegCM3 Part II: impacts of deforestation and desertification. Theor Appl Climatol 93:245–261. doi:10.1007/s00704-007-0333-1

Abiodun BJ, Salami AT, Mathew OJ, Odedokun OD (2012) Potential impacts of afforestation on climate change and extreme events in Nigeria. Clim Dyn. doi:10.1007/s00382-012-1523-9

Adejuwon J (2006) Food security, climate variability and climate change in Sub Saharan West Africa. Washington, DC: AIACC; 2006. AIACC Final Report Project No. AF 23

Bony S, Emmanuel KA (2001) A parameterization of the cloudiness associated with cumulus convection; evaluation using TOGA COARE data. J Atmospheric Sci 58:3158–3183

Cariolle D, Lasserre-Bigory A, Royer JF, Geleyn JF (1990) A general circulation model simulation of the springtime Antarctic ozone decrease and its impact on mid-latitudes. J Geophys Res Atmos 95:1883–1898

Déqué M, Dreveton C, Braun A, Cariolle D (1994) The ARPEGE/IFS atmosphere model: a contribution to the French community climate modeling. Clim Dyn 10:249–266

Flato GM, Boer GJ (2001) Warming asymmetry in climate change simulations. Geophys Res Lett 28:195–198

Gent P, McWilliams JC (1990) Isopycnal mixing in ocean circulation models. J Phys Oceanogr 20:150–155

Gordon HB, Rotstayn LD, McGregor JL, Dix MR, Kowalczyk EA, O'Farrell SP, Waterman LJ, Hirst AC, Wilson SG, Collier MA, Watterson IG, Elliott TI (2002) The CSIRO Mk3 climate system model [Electronic publication]. Aspendale: CSIRO Atmospheric Research. (CSIRO Atmospheric Research technical paper; no. 60), 130 pp. (http://www.dar.csiro.au/publications/gordon_2002a.pdf)

Hewitson BC, Crane RG (2006) Consensus between GCM climate change projections with empirical downscaling: precipitation downscaling over South Africa. Int J Climatol 26(10):1315–1337

IFAD (2009) Enabling poor rural people to overcome poverty. International Fund for Agricultural Development (www.ifad.org/operations/projects/regions/pa/factsheets/ng.pdf)

Iloeje NP (1981) A new geography of Nigeria. New revised edition. Longman, Great Britain

IPCC (2007a) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, Eds., Cambridge University Press, Cambridge, 996 pp

IPCC (2007b) Climate Change 2007: Impacts, Adaptation and Vulnerability. contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, 976 pp

Lu J, Vecchi GA, Reichler T (2007) Expansion of the Hadley cell under global warming. Geophys Res Lett 34:L06805. doi:10.1029/2006GL028443

Masson V (2003) A global database of land surface parameters at 1-km resolution in meteorological and climate models. J Clim 16:1261–1282

McGregor JL (1997) Regional climate modeling. Meteorol Atmos Phys 63:105–117

Mitchell TD, Jones PD (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int J Climatol 25:693–712

Mylne KR, Evans RE, Clark RT (2002) Multi-model multi-analysis ensembles in quasi-operational medium-range forecasting. Q J R Meteorol Soc 128:361–384

Oguntunde PG, Abiodun BJ, Lischeid G (2011) Rainfall trends in Nigeria, 1901–2000. J Hydrol 411:207–218

Ojo O (1977) The climates of West Africa. Heineman, London

Omotosho JB, Balogun AA, Ogunjobi JK (2000) Predicting monthly and seasonal rainfall, onset and cessation of the rainy season in West Africa using only surface data. Int J Clim 20:865–880

Patricola CM, Cook KH (2009) Northern African climate at the end of the twenty-first century: an integrated application of regional and global climate models. Clim Dyn (2010) 35:193–212. doi:10.1007/s00382-009-0623-7

Patricola CM, Cook KH (2010) Sub-Saharan Northern African climate at the end of the twenty-first century: forcing factors and climate change processes, Clim Dyn. doi:10.1007/s00382-010-0907-y

Rajagopalan B, Lall U, Zebiak SE (2002) Categorical climate forecasts through regularization and optimal combination of multiple GCM ensembles. Mon Weather Rev 130:1792–1811

Roeckner E, Arpe K, Bengtsson L, Christoph M, Claussen M, Dümenil L, Esch M, Giorgetta M, Schlese U, Schulzweida U (1996) The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate. Reports of the Max-Planck-Institute, Hamburg, no. 218, 90 pp

Roeckner E, Bäuml G, Bonaventura L, Brokopf R, Esch M, Giorgetta M, Hagemann S, Kirchner I, Kornblueh L, Manzini E, Rhodin A, Schlese U, Schulzweida U, Tompkins A (2003) The atmospheric general circulation model ECHAM5. Part I: model description. Max Planck Institute for Meteorology Rep. 349, 127 pp. [available from MPI for Meteorology, Bundesstr. 53, 20146 Hamburg, Germany]

Russell GL, Lerner JA (1981) A new finite-differencing scheme for tracer transport equation. J Appl Meteorol 20:1483–1498. doi:10.1175/1520450(1981)020<1483:ANFDSF>2.0.CO;2

Sylla MB, Gaye AT, Jenkins GS, Pal JS, Giorgi F (2010) Consistency of projected drought over the Sahel with changes in the monsoon circulation and extremes in a regional climate model projections. J Geophys Res 115:D16108. doi:10.1029/2009JD012983

Takle ES (1999) Project to Intercompare Regional Climate Simulations (PIRCS): description and Initial results. J Geogr Res 104:19443–19462

Yukimoto S et al (2001) The new meteorological research institute coupled GCM (MRI-CGCM2). Model climate and variability. Pap Meteorol Geophys 51:47–88