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The effect of climate change on solar radiation in Nigeria

Olayinka S. Ohunakin [a,*], Muyiwa S. Adaramola [b], Olanrewaju M. Oyewola [c], Olaniran J. Matthew [d], Richard O. Fagbenle [e]

[a] *Mechanical Engineering Department, Covenant University, P.M.B 1023, Ota, Ogun State, Nigeria*
[b] *Department of Ecology and Natural Resource Management, Norwegian University of Life Science, Ås, Norway*
[c] *Department of Mechanical Engineering, University of Ibadan, Oyo State, Nigeria*
[d] *Institute of Ecology and Environmental Studies, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria*
[e] *Department of Mechanical Engineering, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria*

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Abstract

In this study, global solar radiation over Nigeria was simulated under an enhanced atmospheric CO_2 level using the International Centre for Theoretical Physics (ICTP) Regional Climate Model version 3 (RegCM3) for the period 1981 to 2100 with ECHAM5 GCM as the lateral boundary conditions. The simulated seasonal global solar radiation bias for the RegCM3 with NIMET and NASA observed datasets in the control period are of similar magnitudes and showed a mixture of persistent positive and negative biases ranging between −10% and 30%. The model generally underestimates solar radiation (biases −10% to −30%) across the whole country in most of the months. In addition, it overestimates radiation (biases +2–30%) over the northern region of the country. Alongside the present climate (1981–2010), three future periods were considered viz: period 1 (2011–2040), period 2 (2041–2070) and period 3 (2071–2100) for the potential future changes. The seasonal potential future changes in period 1 (i.e. potential future changes with respect to 2040) showed a reduction in the range of 0% (North) to 3.27% (South) whereas more reduction in global solar radiation is observed in period 2 (i.e. 2041–2070 minus present climate) having general decrease ranging from 0.11% to 3.39% with the least value in April (Middle-belt) and the largest in the South zone (March). Potential future changes in period 3 (i.e. 2071–2100 minus present climate) is generally characterized with mixed increase and decrease in global solar radiation across the country than the previous two periods (1 and 2). For the annual potential future changes, RegCM3 model predicted a decrease in solar radiation towards the end of the century with more reduction found in the South zone and the least in the North region. Furthermore, future changes in global solar radiation across the zones in all the periods are however found to be insignificant at $p \leqslant 0.01$.

Keywords: Climate change; Global solar radiation; Regional climate model; General circulation model

1. Introduction

Solar radiation (a renewable energy resource) has direct impact on energy generation in addition to agriculture and water resources. The energy resource was observed to be affected by climate changes induced by CO_2 emissions (Pan et al., 2004). With enormous solar potential across Nigeria, a moderate seasonal effect of climate change can have significant socio-economic impacts; change of solar radiation in future climate is thus of considerable interest (Pan et al., 2004). High resolution reliable projections of 21st century climate change are of great importance to

* Corresponding author. Tel.: +234 8050961739.
E-mail address: olayinka.ohunakin@covenantuniversity.edu.ng (O.S. Ohunakin).

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assess related impacts on renewable energy resources (directly on solar energy and indirectly on wind and hydro power), human activities and natural ecosystem over the country. African countries are shown to be among the most vulnerable to climatic changes expected for the next decades of the 21st century due to increasing concentrations of atmospheric greenhouse gases (IPCC, 2007; Mariotti et al., 2011). Furthermore, among African regions, West Africa is found as one of the world most exposed to the negative effects of climate variability (Tchotchou and Kamga, 2010). In Nigeria, Climate change is the latest challenge to sustainable human development and is leading to more frequent and more severe climate-related impacts that may deter efforts to achieve the country's development objectives, including the targets of the Nigeria Vision 20:2020 and the Millennium Development Goals (MDGs) NEST and Tegler, 2011; NASPA-CCN, 2011; the challenges being multifaceted (social, economic, environmental), its impact on infrastructure will be significant because infrastructure provides a critical platform for the effective functioning of the Nigerian economy (NEST and Tegler, 2011). Climate change is also expected to negatively affect the already limited electrical power supply through impacts on the existing hydroelectric and thermal generation; service interruption is also expected to result from damage to transmission lines and substation equipment impacted by sea level rise, flash floods, and other extreme weather events (NASPA-CCN, 2011).

Climate change was discussed in (Li et al., 2012) to have effect on weather parameters (wind speed, solar radiation, precipitation, mean temperature, maximum and minimum temperatures etc.) that constitute the renewable resources. Several authors have also shown that potential climatic changes due to increased atmospheric greenhouse gases might affect the availability of renewable resources in West Africa in the future. However, changes (increase or decrease) in resource potentials resulting from climate change consequences may affect power generation from renewable energy resources and can consequently affect the potential contribution to future electricity output. There is also the tendency of a reduction or increase in magnitude of the several weather parameters (global solar radiation, dry-bulb temperature (mean, maximum and minimum), relative humidity, precipitation, and wind speeds) that contribute to building comforts (through heat gain and loss in buildings) in the advent of a changing climate (Ohunakin et al., 2013).

However, study of the physical mechanisms underlying climate variability and the quantification of the relative contributions of each of the driving factors, require long time series of observations. The long range of observed data is a disability in West Africa because of the relatively few observation stations, and most times, poor quality of available data; these necessitate the use of climate models whose outputs constitute consistent datasets of atmospheric variables. Climate models (global and regional circulation models) are thus the primary tools that aid in our understanding of the many processes that govern the climate systems (Pal et al., 2007). A number of simulations have been carried out using Global Circulation Models (GCMs). Climate models with GCMs have been found to have difficulties reproducing various atmospheric variables of interest and thus generating unrealistic outputs (some examples are in the results as given in the following: Community Climate Model version 3-CCM3 in the work of (Jenkins and Mikovitz, 2003); Laboratoire de Météorologie Dynamique (LMD) GCM and also the Centre for Ocean-Land-Atmosphere (COLA) GCM as reviewed in the work of (Tchotchou and Kamga, 2010).

In (Anyah and Semazzi, 2007), regional climate modelling is presently one of the fundamental techniques used to downscale global (large scale) climate information for regional applications. The Regional Climate Models (RCMs) have proven to be very essential tools for regional climate downscaling through the detailed representation of regional climate variability when nested within global analyses of observations or the GCM outputs, needed for the initial and time dependent lateral boundary conditions (e.g. previous work as listed in (Anyah and Semazzi, 2007); they have higher spatial resolution and can potentially better simulate finer structures of circulation and precipitation distribution by taking into account steep topography and resolving orographic features, such as isolated reliefs, lakes, coastlines and sharp gradients in vegetation, temperature, and soil moisture (Semazzi et al., 1993). Several studies demonstrated to determine the sensitivities of RCMs to dynamic configuration and the physical parameterizations proved RCMs to have better performance than GCMs with even drastic reduction in errors associated with large scale simulations (Anyah and Semazzi, 2007; Kgatuke et al., 2008). In (Mariotti et al., 2011), the RCM solution is determined by a dynamical equilibrium between the information being derived from the lateral boundary conditions and that produced by the internal model dynamics and physics. As a result, more realistic output regimes can be expected by adapting the model physics to the region of interest (Tchotchou and Kamga, 2010). RCMs are also expected to be dynamically configured and customized in their simulation for sensitivity of climates over different domains/regions for their optimum performance (Anyah and Semazzi, 2007; Giorgi et al., 1993; Seth and Giorgi, 1998; Sun et al., 1999; Denis and Laprise, 2002; Giorgi and Mearns, 1999). In line with this assertion, several works were carried out, many on mid-latitude climates and very few covering some regions and sub-regions of Africa as discussed in literatures.

Several versions of RCMs exist including the International Centre for Theoretical Physics (ICTP) Regional Climate Model versions 2, 2.5, 3, 4 and respectively tagged as RegCM2, RegCM2.5, RegCM3 and RegCM4 (most recent version and model still under evaluation) etc. In (Sylla et al., 2010), the performance of

RegCM3 model was tested over the entire African continent and surrounding ocean regions; the model was able to reproduce the dynamics of different African circulation features. However, (Mariotti et al., 2011) extended the work of (Sylla et al., 2010) by examining the relationship of the climate change signal produced by the RCM and that of the driving global model (ECHAM5-AOGCM). In (Kgatuke et al., 2008), the internal variability of RCM through nesting the RCM within Atmospheric General Circulation Model (AGCM) over South Africa was investigated. A mesoscale climate model was developed to study the influence of sea surface temperature (SST) anomalies on West African monsoon system by (Vizy and Cook, 2002), while a high resolution RCM was used to simulate the intraseasonal variability of rainfall in West Africa in the work of (Gallee et al., 2004). In a study carried out by (Anyah and Semazzi, 2007), the performance of RegCM3 in representing the climatology, intraseasonal and interannual variability of rainfall during the short rains season was evaluated. In (Afiesimama et al., 2006), the mean state and the interannual variability of the West African climate as simulated by the RegCM3 over the period 1979 through 1990 was evaluated. RegCM3 simulations had been validated over West African region and Nigeria, and found to be good resources for climate change studies (Afiesimama et al., 2006; Abiodun et al., 2008, 2012a,b) particularly where and when the surface observed data is not available. This thus call for the application of this model in this work.

As observed in literature, several applications of RCM carried out in Africa, centred mostly on precipitation and agriculture. However, the effect of enhanced CO_2 simulation over the United States showed a trend of decreased seasonal mean daily global radiation availability in the range of 0–20% using RegCM2 nested in HadCM2-GCM in the work of (Pan et al., 2004). General decrease in average wind power availability was also simulated over the United States under an enhance CO_2 scenario using a General Circulation Model (GCM) and atmospheric regional model results in Segal et al. (2001).

Many regional climate modelling applications have often involved shorter model integration periods (a few months to a season). These do not provide sufficient scope for evaluating the downscaling ability of RCMs over a wide spectrum of climate regimes as observed in (Anyah and Semazzi, 2007). However, the work of (Mariotti et al., 2011), over all-Africa domain with RegCM3 driven by the European Centre for Medium Range Weather Forecasts Hamburg-Atmosphere-Ocean Global Circulation Model (ECHAM5-AOGCM) under the A1B greenhouse gas forcing scenario of (IPCC, 2007) for the period 1980-2100 through the Coordinated Regional Climate Downscaling Experiment (CORDEX) project, was downscaled in this work over Nigeria domain. This is done to provide a more comprehensive evaluation of climate change influence on solar radiation through a thorough examination of climate change signal of the RCM and that of the driving global model. The spread of solar radiation among other renewable energy resources in Nigeria has indicated that all regions in Nigeria have adequate solar radiation that can support one form of application to the other (primarily due to the country's positioning on the equator); hence, in order to predict the future of solar irradiance fields needed for long range planning of solar energy use (including small and large scale solar electricity generations, and other solar energy applications), there is need for the quantification of the potential changes of solar radiation in the enhanced CO_2 climate over Nigeria. This work can thus provide useful information for future analogous energy studies needed for (i) renewable energy systems design, (ii) future building energy consumption in Nigeria, (iii) building comfort (orientation and cooling load calculations), (iv) rivers and streams' level (effect on hydro power), (v) drought and impact on agricultural outputs etc.

2. Methodologies and data

2.1. RegCM3 regional model description

The present work uses the ICTP RegCM3 developed at the Earth System Physics (ESP) section of the Abdus Salam International Centre for Theoretical Physics (ICTP). It is a three-dimensional primitive equation atmospheric model and an evolution of the NCAR-RegCM2 model originally developed by (Giorgi et al., 1993a,b) and augmented by (Sun et al., 1999). The model uses terrain-following (σ–p) vertical coordinate system and the model dynamics is based on the hydrostatic primitive equation dynamical core of the NCAR/PSU Mesoscale Model version 5 MM5 (Grell, 1994). It uses a sub-grid explicit moisture scheme for large-scale precipitation parameterization (SUBEX) as developed by (Pal et al., 2000), which includes variation at the sub-grid scale of clouds, cloud water accretion and evaporation of raindrops; the parameterization of cumulus convection is based on the Grell convective scheme of (Grell, 1994), while also applying the (Fritsch and Chappell, 1980) closure assumption, which was chosen after extensive testing of the different schemes (Sylla et al., 2010). Radiative transfer scheme is represented by the NCAR CCM3 package (Kiehl et al., 1996); land-atmosphere interactions are parameterized using the biosphere-atmosphere transfer scheme (BATS) Dickinson et al., 1993 and ocean fluxes are described by Zeng scheme in (Zeng et al., 1998) alongside with the MIT-Emanuel convection scheme (Emanuel, 1991). The model uses the (Holtslag et al., 1990) planetary boundary layer scheme, which gives non-local diffusion resulting from counter-gradient fluxes produced by large-scale eddies in an unstable, well-mixed atmosphere. RegCM3 has options to interface with a variety of reanalysis and GCM boundary conditions to provide a full suite of simulation options. Comprehensive description of RegCM3 and the main model components are discussed in (Pal et al., 2007).

2.2. ECHAM5 general circulation model description

ECHAM5 is the 5th generation of ECHAM Global Climate Model (GCM) developed by the Max Planck Institute for Meteorology in Hamburg. It evolves originally from the spectral weather prediction model of the European Centre for Medium Range Weather Forecasts (ECMWF), which can be configured to resolve the atmosphere up to 10 hPa for tropospheric studies, or up to 0.01 hPa for middle atmosphere studies (http://www.ess.co.at/METEO/models.html). The model was configured at a triangular spectral truncation 42 (T42), and as a result the resolution is about 2.8° lat x lon with 19 vertical layers. The atmospheric component of ECHAM5, has a horizontal resolution of T63, corresponding to a grid resolution of 1.875° × 1.875°, and 31 vertical hybrid levels. The oceanic component (MPI-OM) of the coupled model is a primitive equation z-coordinate model with an integrated sea ice model (Im et al., 2011).

2.3. Observation data used for model validation

The performance of RegCM3 output was evaluated using ground observed (gauged) data from the WMO-Regional Meteorological Research Institute, Lagos, Nigeria (widely referred to as the Nigerian Meteorological Agency (NIMET)) REMP, 2005 and satellite-based observations from NASA Surface Meteorology and Solar Energy (SSE) SSE Release. The spatial coverage for NASA dataset extends over all land areas. The datasets include global solar radiation and mean temperature observations taken across all the geopolitical zones of the country. The spatial horizontal scale and the number of grid points for both NIMET and NASA data were chosen to be identical to that of the model data as utilized in Ohunakin et al. (2015). The station data which falls within each grid point were used. Where more than one station is found within a grid point or no station within a grid but the surrounding grid points have data, the average of the neighbouring stations were used. Otherwise, no data value was assumed (Ohunakin et al., 2015).

The records of the observed cloud cover ranging between 1981 and 2009 were obtained from the Global Gridded Climatology surface datasets of the Climate Research Unit (CRU), University of East Anglia, United Kingdom. This dataset has been used in a number of applications in applied climatology, including high-resolution climate model evaluation over West Africa [e.g. (Afiesimama et al., 2006; Abiodun et al., 2012a; Christensen et al., 1997)]. The data was re-gridded (to make the scale similar to that of the model) and processed to examine the effects of cloud cover on the variations in seasonal solar radiation over the study. It must be noted that the output parameters in the RegCM3 do not include the cloud cover.

2.4. Simulation

For the simulation, the initial and time-dependent meteorological lateral boundary conditions for the mother domain simulation are interpolated at 6-hourly intervals from an ECHAM5/MPI-OM A1B scenario simulation with the use of the same model configuration as used in the work of (Mariotti et al., 2011) i.e. a domain at 50 km horizontal grid spacing and 18 vertical sigma levels. The integration spans the 120-year period 1981–2100; the first 30 years covering present-day conditions is the RegCM3 forced by lateral boundary conditions from the ECHAM5 present climate (reference period: 1981–2010). The remaining 90 years (2011–2100) are forced by the ECHAM5 enhanced CO_2 climate scenario and are used to simulate future climate changes with respect to the present day conditions (referred to as the scenario periods).

2.5. Data analysis

Analysis of the data outputs in Network Common Data Format (NetCDF) from RegCM3 were carried out using FERRET gridded-data analysis tool installed on Linux-based computer operating system. FERRET software is publicly available at http://www.ferret.noaa.gov/Ferret; it was developed by the Thermal Modelling and Analysis Project (TMAP) at Pacific Marine Environmental Laboratory (PMEL), National Oceanic and Atmospheric Administration (NOAA) in Seattle, Washington, United States of America, to analyse the outputs of its numerical ocean models and compare them with gridded observational data. Model data sets are often multi-gigabyte in size with mixed 3- and 4-dimensional variables defined on staggered grids (Hankin et al., 2007).

The performance of numerical weather prediction or climate models is evaluated by skill scores based on root mean squared error or related correlation and determination coefficients [e.g. (Murphy and Epstein, 1989; Murphy, 1995; Bergant et al., 2007)]. Such measures are based on the comparison of grid-point values for observations and model results; they could be biased even if the grid-points where the observed and modelled variance is small, and are included. In this work, data were treated using appropriate statistical techniques such as means, standard deviation, normalised anomalies (σ': standard deviation for model divided by observed standard deviation), correlation coefficient (r), root mean square error (RMSE) and percentage change in means as expressed in (Ohunakin et al., 2015). These are expressed as shown in Eqs. (1)–(5):

$$\bar{f} = \frac{1}{N}\sum_i f_n; \quad \bar{r} = \frac{1}{N}\sum_i r_n \tag{1}$$

$$\sigma_f = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(f_n - \bar{f})^2}; \quad \sigma_r = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(r_n - \bar{r})^2} \tag{2}$$

$$\sigma' = \frac{\text{model(simulated)standard deviation}}{\text{observation standard deviation}} \tag{3}$$

$$R = \frac{\frac{1}{N}\sum_{n=1}^{N}(f_n - \bar{f})(r_n - \bar{r})}{\sigma_f \sigma_r} \tag{4}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}[(f_n - \bar{f})]^2} \tag{5}$$

where f and r which denote test field (model) and reference field (observation) respectively, are two N-dimensional variables; σ_f and σ_r are the respective standard deviations.

3. Results and discussion

3.1. Control period

Figs. 1 and 2 show the seasonal global solar radiation bias for the RegCM3 compared with observations from NIMET (Fig. 1) and NASA (Fig. 2) in which the RegCM3 was driven by ECHAM5. Data range of 1981–2010 was selected with NIMET whereas for NASA, the possible range of dataset that exist is 1983–2010 (NASA SSE dataset commenced in 1983). For CRU observational dataset, the cloud cover obtained were from 1981–2009. The country is further divided latitudinally into three major zones namely: South (4°N–8°N), Middle-belt (8°N–11°N) and North (11°N–14°N) in line with the prevailing synoptic pattern over the country; this classification follows that in Abiodun et al., (SSE Release). It can be observed from Fig. 1 that the magnitude of the simulated global solar radiation showed a mixture of persistent positive and negative biases with approximate range between −30% and +30% throughout the simulated domain. Negative biases (approximately −10% to −30%) are found to be more dominant across the whole country in February, May, June, July, August, September, October, November and December in the South zone and most part of the Middle-belt. The North region and the month of January (for all regions) is typically characterized with positive biases in the range of 2–30%; these regions are characterized by desert climate from the Sahara. Other than in February, the model exhibits positive biases in the South coast over the Atlantic Ocean. This thus reflects that RegCM3 does not properly model the coastal stratus clouds.

Fig. 2 has more negative biases for the simulated global radiation with magnitudes ranging from −2% to −30% across the whole country throughout the simulated domain; this may be attributed to the wider coverage of data readings across the country by NASA observation than the NIMET readings (characterized by limited gauge stations and coupled with some days of none readings). This under-prediction is within the typical average biases

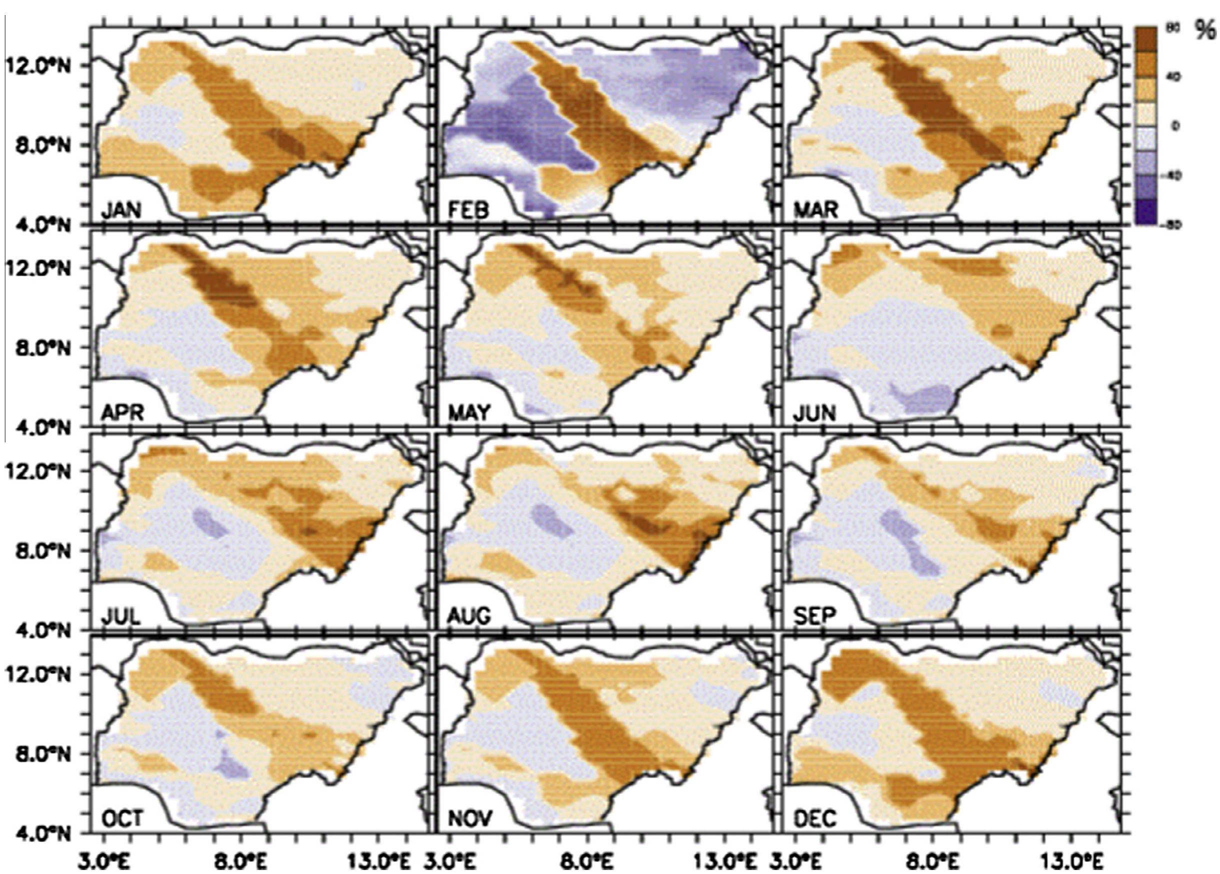

Fig. 1. Biases of the global solar radiation for the RegCM3 driven by ECHAM5 compared with NIMET observation for the period 1981–2010.

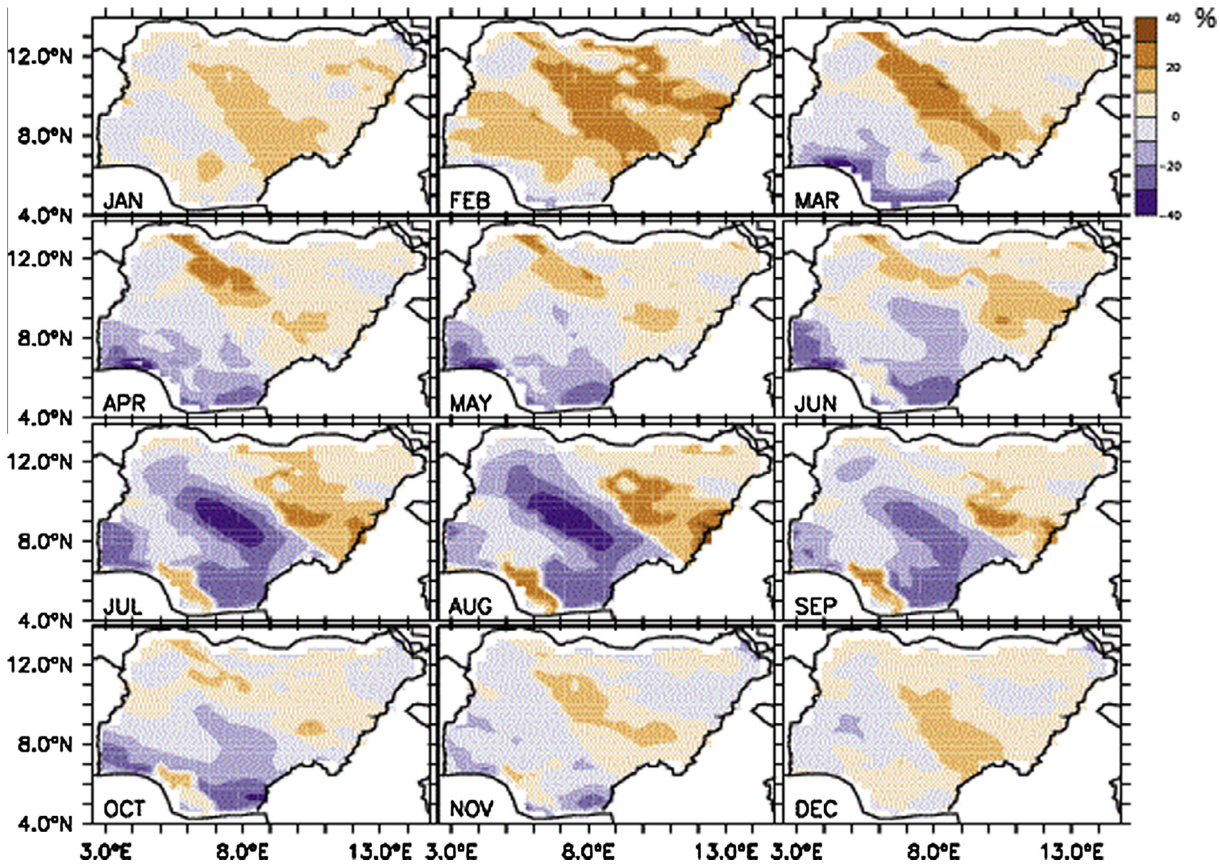

Fig. 2. Biases of the global solar radiation for the RegCM3 driven by ECHAM5 compared with NASA observation for the period 1981–2010.

in global solar radiation as expressed in the work of (Pan et al., 2004).

3.2. Cloud cover and present climatology for solar radiation in Nigeria

Clouds, cover about 60% of the Earth's surface (Rossow and Schiffer, 1999; Vardavas and Taylor, 2011) and have been recognized to strongly affect the radiation budget of the Earth atmosphere system. They are also found to modulate the global albedo, temperature distribution and the general circulation of the atmosphere and are the most important regulators of the Earth's climate (Pyrina et al., 2013). It has been shown in Pyrina et al. (2013) that the Earth's climate is sensitive to cloud distributions and cloud radiative properties associated with anthropogenic forcings arising from changes in greenhouse gases and aerosols; they are highly variable and small changes in the properties can significantly affect climate.

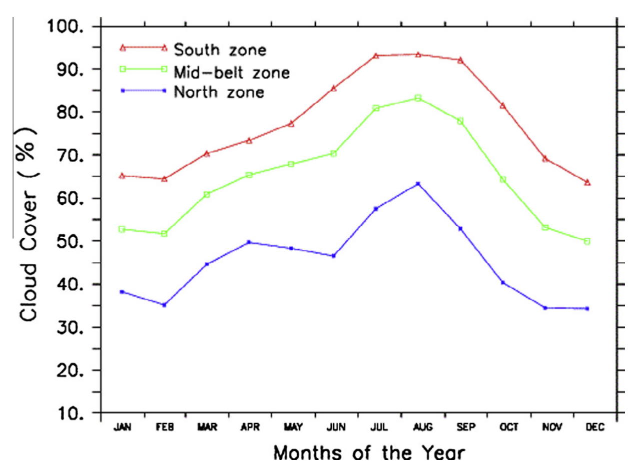

Fig. 3. Observed monthly mean cloud cover (%) over different zones of Nigeria (1981–2009).

Fig. 3 depicts the line plot of the cloud cover over Nigeria between 1981 and 2009. It can be observed that cloudiness decreases northward with more cloudiness occuring in the south region followed by the middle-belt and north zone of the country. The peak values of cloud cover in all the zones exist in the months of July, August and September and having average values 95%, 80% and 65% in the south, middle-belt and north regions respectively as shown in Fig. 4. These months coincide with the periods of heavy rains across the country; the heaviest rainfall occurs in the south-west and south-east of West Africa (Afiesimama et al., 2006; Udo, 1978). Since the climate of West Africa is dominated by monsoon (a large scale circulation characterized by a seasonal reversal of winds due to the continent-maritime temperature contrast (Afiesimama et al., 2006), the higher cloud cover noticed

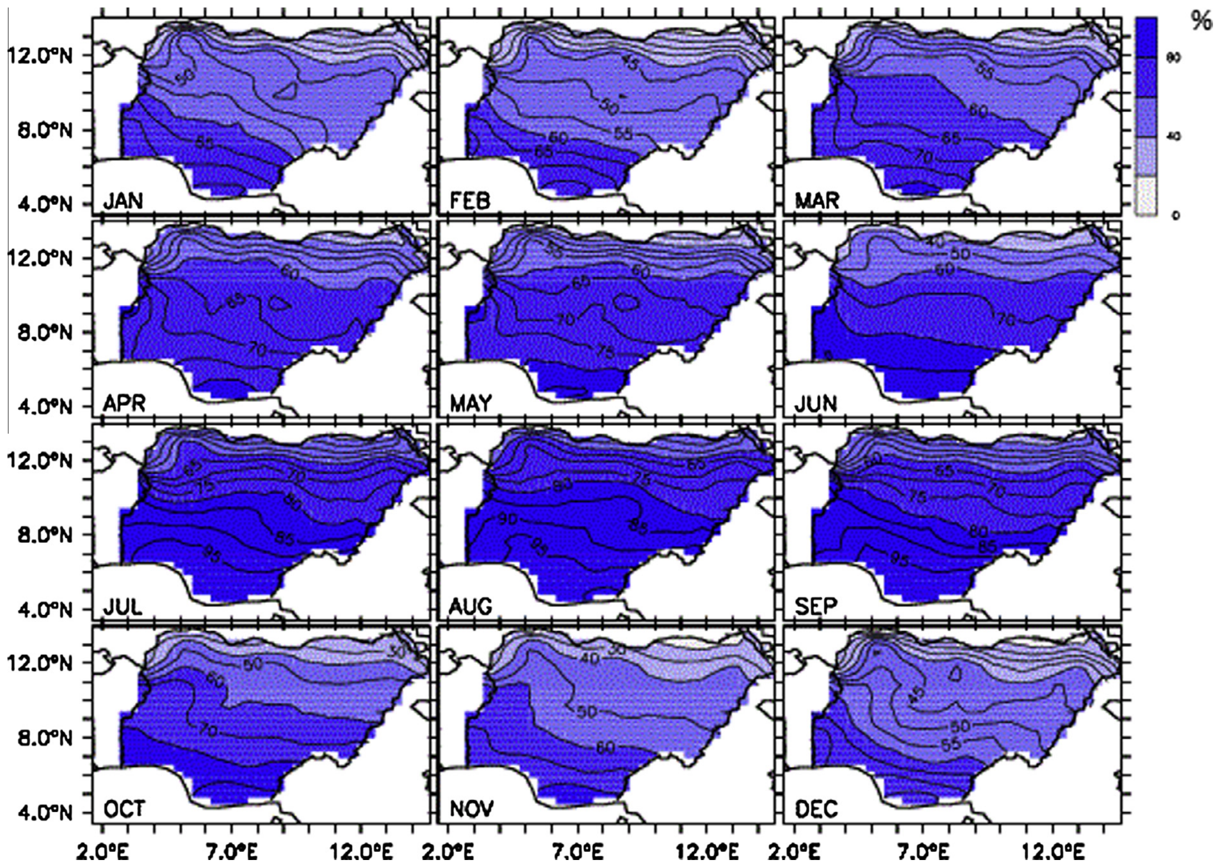

Fig. 4. The spatial plot of observed mean variations in seasonal cloud cover (%) over Nigeria (1981–2009).

over the south part of Nigeria, may be connected to the heavy precipitation that results from the movement of rain bearing south-westerly winds (primary source for West African rainfall) from the ocean (Gulf of Guinea) towards the land, thus bringing about a change in moisture content of the atmosphere. In (Vizy and Cook, 2002), higher evaporation rates over the warm SST anomalies of the gulf increase the water vapour content in the lower troposphere. Hence, most part of the regions are thus under this influence of the south-westerly winds during the period April to September; earlier visit may be experienced in March in the south zone. The south-westerly winds further extends northwards to cover the middle-belt and north areas, though with a weak wind strength (winds from the gulf decreases in response to the weakening of the land-sea temperature gradient between the gulf and the Sahara (Afiesimama et al., 2006), resulting in the continued northward decrease in rainfall over the zone, bringing about a reduction in cloud cover as observed in Figs. 3 and 4. Minimum values in cloud cover are observed during the dry season (November to March) across the zones and was also found to decrease northward.

The spatial distributions of average seasonal cycle of simulated global solar radiation (RegCM3) over Nigeria between 1981 and 2010, is shown in Fig. 5. Values of the global solar radiation, range between 160 and 280 W/m^2 throughout the seasons (rainy and dry) with the model. Global solar radiation was observed to have the highest values during the late dry and early rainy season (March/April) as 280 W/m^2 in the North. General increase in radiation across the zones are also noticed during this dry period (November–March); this period was found to reflect the season of clear sky when values of cloud cover are minimum as indicated in Figs. 3 and 4. However, least values of global solar radiation are obtained during the rainy period of May/June (coinciding to the period of rainy cloudy sky) in the South, with RegCM3 having 160 W/m^2; reduction in radiation values is further observed across the zones in July, August and September during the heavy rainy months. This decrease in global solar radiation may be as a result of cloud scattering (reflection) and absorption of radiation, since the period of reduction occur when cloud covers are highest (Figs. 3 and 4).

In (Ohunakin et al., 2013), the clearness index (K_T), which indicates the level of availability of solar radiation and weather condition at a particular location on the earth's surface) for a south location, varies from 0.271 in August and 0.438 in November, thereby making the site to be heavily overcast since $K_T < 0.4$ Iqbal, 1980. This observed trend was found to be common with locations in the southern part of Nigeria (Adaramola, 2012) as indicated in Figs. 3 and 4. According to (Adaramola, 2012), diffuse radiation increases linearly with global solar radiation when the weather is heavily overcast. In (Iqbal, 1980), for partly

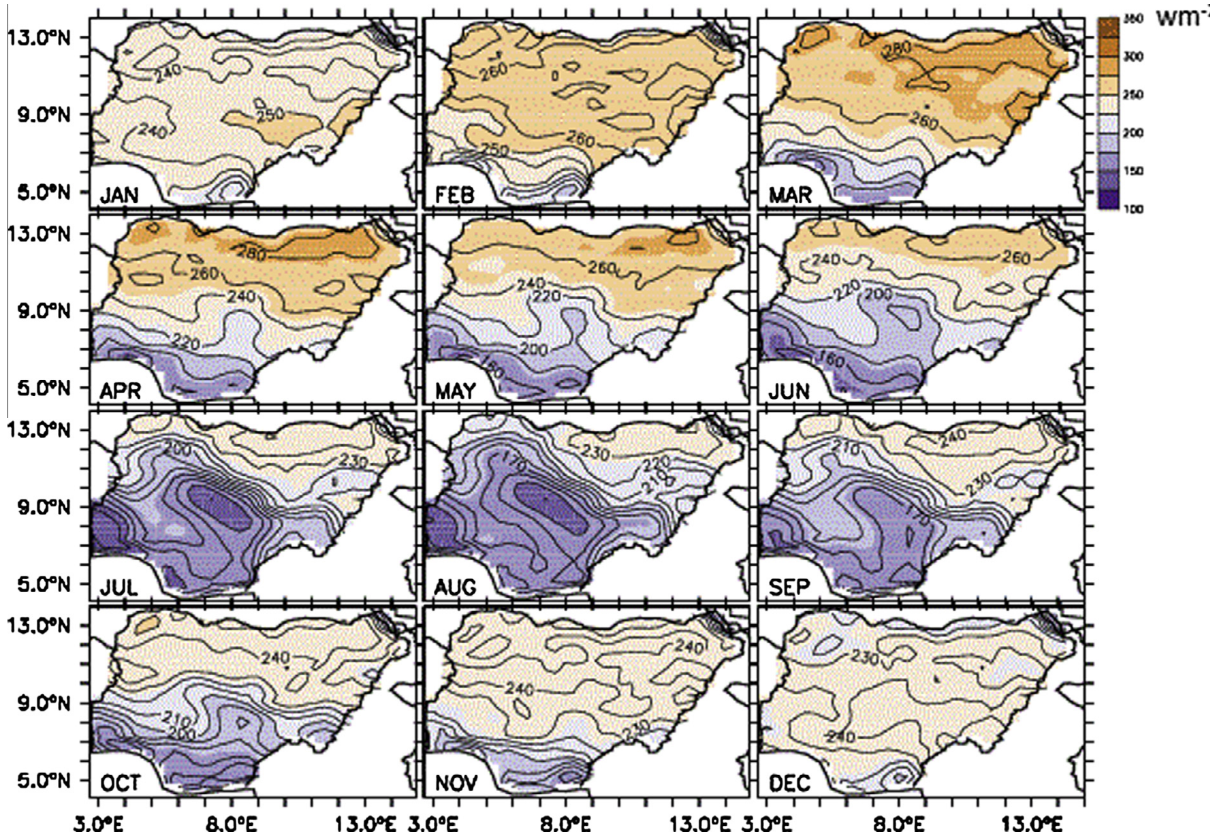

Fig. 5. Simulated seasonal mean solar radiation (W/m^2) for RegCM3 over Nigeria (1981–2010).

overcast weather condition ($0.4 < K_T < 0.6$), the diffuse component of the global solar radiation increases temporarily with increase in global radiation and then decreases as the partly cloudy skies become clearer. This may be attributed to the prevailing high moisture content and heavy cloud during the raining season in Nigeria and dust and forest fire smoke during the dry season (Fagbenle, 1992; Maduekwe and Chendo, 1997).

3.3. Impacts of global warming on the future climate of solar radiation in Nigeria

3.3.1. Future climate change

The summary of the future change in climate for global solar radiation and mean temperature parameters over Nigeria under an enhanced CO_2 scenario (elevated greenhouse gases (GHG)) by the RegCM3 climate model is given in Table 1. For the control period (present-day climate: 1981–2010), global solar radiation has the highest value in the North zone with 244 W/m^2 and decreases down latitude with the minimum in the South (210 W/m^2).

In future period 1 (2011–2040), the model predict the least solar radiation over the South zone and increases progressively up north (South: 209 W/m^2; Middle-belt: 228 W/m^2; North: 243 W/m^2). Similarly, RegCM3 predicted a reduction in solar radiation across the zones in period 1 with more reduction in the Middle-belt zone (Table 1). The potential future change is found to be: −0.99 (0.47% reduction), −1.16 (0.5% reduction) and −1.12 (0.46% reduction) in the South, Middle-belt and North zones respectively. Hence, with the model, more cloudiness is predicted in the future thus making the diffuse component of the global radiation to increase (Iqbal, 1980).

In future period 2 (2041–2070), there is also a reduction in solar radiation reaching the surface across the three zones; more decrease in solar insolation is found in the South in this period (0.74%) than in period 1 (0.47%) whereas in the Middle-belt and North zones reduction is less in period 2 than 1. These indicate more cloudiness over the South zone, which thin out to give rise to a clear sky over the Middle-belt and North zones in period 2; this increase in cloudiness may be attributed to the movement of the south-westerly winds from the gulf that weaken in strength northwards. The South zone is the industrial hub of the country and shelters the major hydrocarbon and cement productions taking place in Nigeria. It is also more densely populated than the other zones; higher population growth and more socio-economic activities leading to more industrial activities is expected in the South zone in the future. More emissions of GHGs are thus inevitable in this zone than the North and Mid-belt. Solar radiation is also found to decrease towards the end of the century as indicated in future period 3 (2071-2100); less reduction is however noticed towards the end of the 21st century (period 3) when compared to periods 1 and 2. In addition, in period 3, more reduction in solar radiation is found at

Table 1
Simulated present (1980–2010), future periods (2011–2040, 2041–2070, 2071–2100) and future change in solar radiation (Wm^{-2}) over Nigeria.

		Global solar radiation (W/m^2)			Maximum temperature (°C)			Mean temperature (°C)		
		South	Middle-belt	North	South	Middle-belt	North	South	Middle-belt	North
Present	Mean	210	230	244	26.2	26.5	27.2	25.4	25.4	25.6
	σ	2.4	2.9	3.2	0.4	0.5	0.5	0.4	2.3	2.4
Future period 1	Mean	210	228	243	26.9	27.2	27.9	26.1	26.1	26.8
	σ	3.1	3.7	3.6	0.4	0.5	0.6	0.4	0.5	0.5
	Future change	−0.9	−1.2	−1.1	0.7	0.7	0.7	0.7	1.1	1.2
	% change	−0.5	−0.5	−0.5	2.5	2.6	2.7	2.6	4.4	4.5
Future period 2	Mean	208	229	243	28.1	28.5	29.3	27.3	27.4	28.2
	σ	2.6	2.7	2.8	0.7	0.8	0.9	0.7	0.8	0.9
	Future change	−1.5	−0.9	−0.8	1.9	2.0	2.1	1.9	2.4	2.5
	% change	−0.7	−0.4	−0.4	7.2	7.6	7.8	7.4	9.7	9.9
Future period 3	Mean	210	229	244	29.4	29.9	30.7	28.6	28.9	29.6
	σ	3.1	2.3	2.8	0.6	0.7	0.8	0.6	0.7	0.7
	Future change	−1.1	−0.3	−0.2	3.2	3.4	3.5	3.2	3.8	3.9
	% change	−0.5	−0.1	−0.1	12.2	12.9	12.9	12.6	15.3	15.3

σ = Standard deviation.

the South (0.49%), and this becomes less further upward with the least in the North (0.07%).

Although, with statistical analysis, the future changes in global solar radiation across the zones in all the periods are insignificant (absolute value of future variation is less than standard deviation) over the country. Hence in all the periods, global solar radiation showed no particular significant trend. Global warming is changing the monsoonal flow into the southern region of Nigeria between periods 1 and 2 and this is responsible for the increasing clouds and decreasing solar irradiance. The cloudiness are further decreased in time as warming continues.

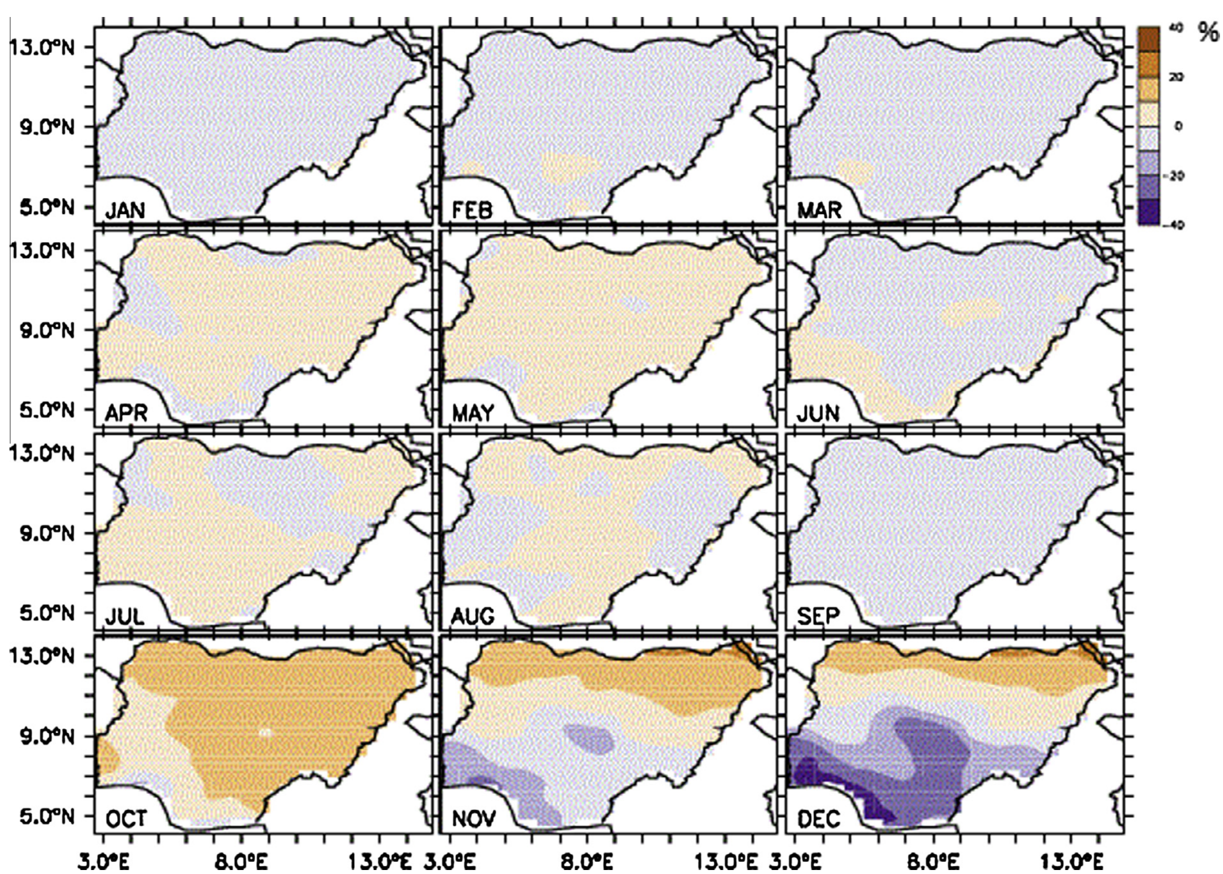

Fig. 6. Potential future change during period 1 (2011–2040).

The maximum and mean temperatures by RegCM3 (Table 1) suggests that the southern parts of the country warm less than the northern regions: South (26.2 °C), Middle-belt (26.5 °C) and North (27.2 °C). The model in period 1 suggested a warmer future with increasing change from the South (2.49% and 2.62%) to the North zone (2.74% and 4.50%) for the maximum and mean temperatures respectively; this is in support of the findings in the separate works of (Abiodun et al., 2012a) and (Lawal, 2010). However, the percentage change is observed to be increasing, from period 1 to 3 for the maximum and mean temperatures respectively (Table 1). This indicates an increase in warming over the years to 2100.

The influence of relatively cool moist air from the ocean and the increased cloud cover over the coastal region as discussed by (Grell, 1994; Sylla et al., 2010) may be responsible for the smaller warming over the South zone. Increasing magnitude of warming observed from the South zone to North may be attributed to decreasing cloud cover northward due to the weakening in strength of the movement of the south-westerly winds up north (Figs. 3 and 4). In addition, future changes between periods 1, 2 and 3 being greater than their respective standard deviations for the maximum and mean temperatures across the zones (Table 1) is an indication of a consistent significant change in temperature over the country, resulting from global warming by RegCM3.

3.3.2. Potential future changes on solar radiation

Figs. 6–8 present the differences in the monthly mean global solar radiation between the enhanced CO_2 scenario and the present climate i.e. (enhanced CO_2 scenario at 2040, 2070 and 2100 less the present climate). The present climate is taken as 1980-2010. In Fig. 6 which presented the seasonal potential future changes with respect to 2040 (period 1), a general reduction in global solar radiation can be observed in most of the months in the country, with decreases in the range of 0–3.27% across the whole zones. The reduction in solar radiation is observed to rise southward with the least decrease in the North zone (0%) in April and the largest reduction in the South (3.27%) in March; this reduction in the South zone is attributed to the influence of relatively cool moist air from the ocean and the increased cloud cover over the coastal region (Sylla et al., 2010), due to the movement of the south-westerly winds from the gulf of Guinea. The months of April, July and August have noticeable increase in global solar radiation above the present climate in the South and Middle-belt zones, whereas months of May and November are characterized with increase across all the zones; these months are expected to witness clear skies.

The potential future change in global solar radiation as shown in period 2 (i.e. 2041–2070 minus present climate) in Fig. 7 is characterized with a general reduction in global solar radiation that is more pronounced than in Fig. 6 in

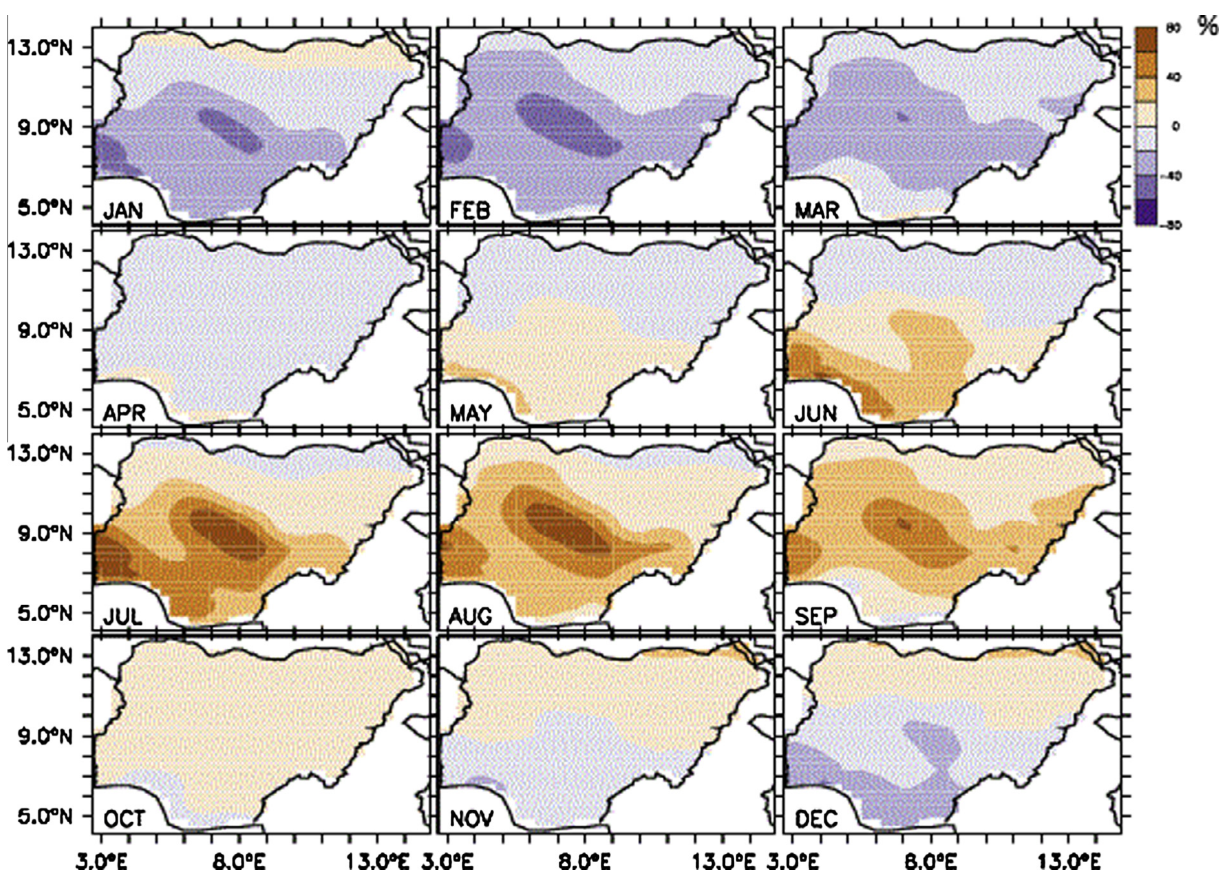

Fig. 7. Potential future change during period 2 (2041–2070).

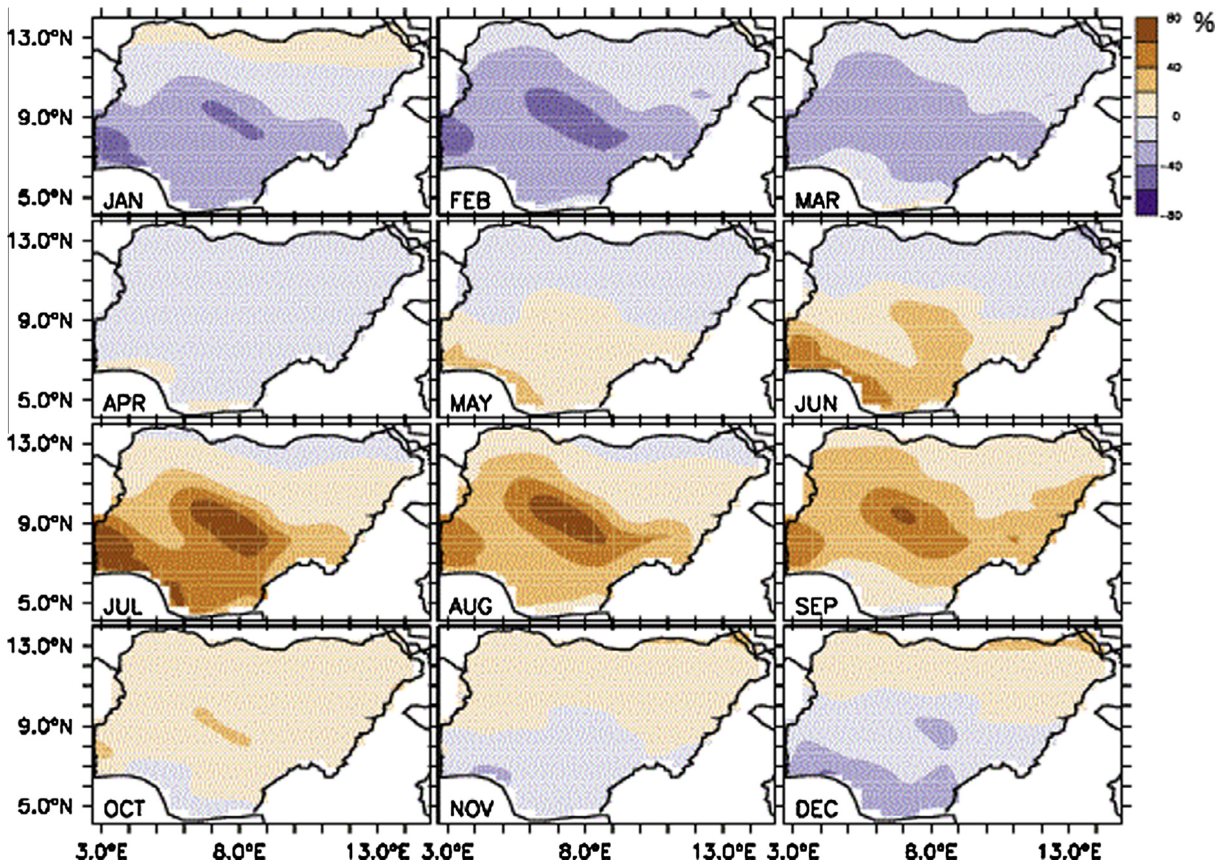

Fig. 8. Potential future change during period 3 (2071–2100).

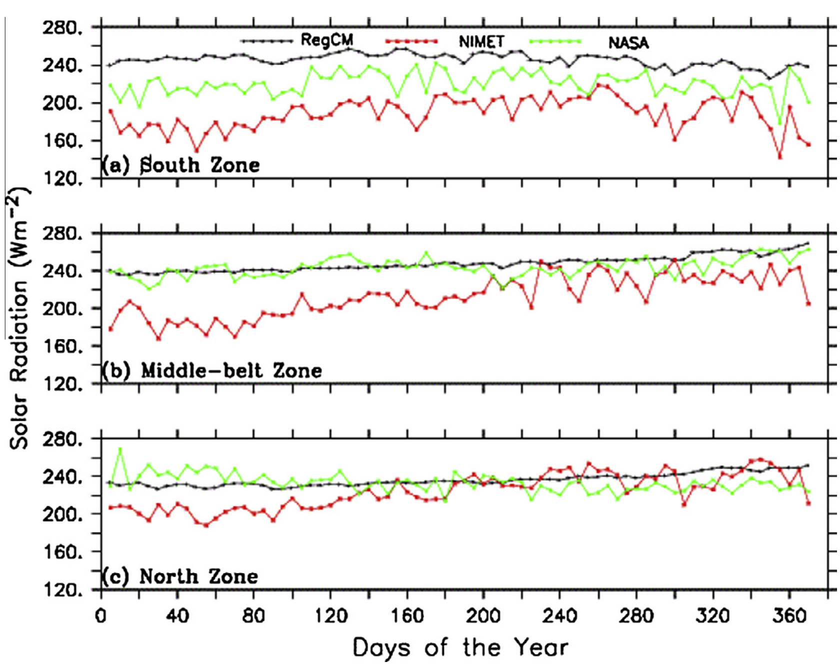

Fig. 9. Simulated (RegCM3) and observed (NIMET and NASA) mean daily variation of solar radiation (1981–2010) over the three climatic zones of Nigeria.

all the zones across the country. The month of March experienced the highest reduction in all the zones while decrease in global solar radiation is also observed in January, April, July, September, November and December in all zones. General increase in dust and forest smoke or aerosol deposits can be deduced during the dry season as concluded in the work of (Fagbenle, 1992) and (Maduekwe and Chendo, 1997) while cloudiness can be attributed to the heavy rainy months (April–September) due to the movement of the south-westerly winds from the gulf of Guinea. The general reduction ranges from 0.11% to 3.39% with the least in April (Middle-belt) and the largest in the South zone in March (3.39%). The large reduction in the South zone can be attributed to the influence of relatively cool moist air from the ocean and the increased cloud cover over the coastal region (Grell, 1994; Lawal, 2010).

Period 3 which indicates the late 21st century potential change of global solar radiation over Nigeria (2071–2100 less the present climate) is shown in Fig. 8. Period 3 is generally characterized with mixed increase and decrease in global solar radiation across the country than the previous two periods (1 and 2). Increase in global solar radiation is common in the rainy season (April–September) than the dry season especially in the Middle-belt and North zones, thus indicating a situation of clear sky whereas reduction is seen to depict the South during the rainy season as observed in (Sylla et al., 2010). All the zones witnessed a general increase in solar radiation in May and June. Reduction in solar radiation is very evident in the dry periods with more spread in the Middle-belt and North zones than the South. This may be attributed to the general increase in dust and forest smoke or aerosol deposits during the dry season as concluded in the work of (Fagbenle, 1992) and (Maduekwe and Chendo, 1997). In general, increase in global solar radiation is found to be more in period 3 (0.06–3.61%) than in periods 1 and 2 whereas general reduction is found to be less in period 3 (0.18–2.40%) than periods 1 and 2.

3.3.3. Seasonal variation of global solar radiation for the present and future projections over Nigeria

Comparison of the seasonal variation of global solar radiation for the daily simulated (RegCM3) model and observed (NIMET and NASA) over Nigeria between 1981 and 2010, is shown in Fig. 9. Correlations for the solar radiation R is 0.6, 0.61 and 0.58 for the South, Middle-belt and North region respectively with NIMET observation while R obtained for the NASA observation is 0.8, 0.81 and 0.71 for the South, Middle-belt and North zone respectively at $p \leqslant 0.01$, thus reflecting that the daily simulated seasonal variation gave a better performance with the NASA observation than NIMET. The model best performance is found at the Middle-belt followed by the South and the least in the North with both the NIMET and NASA observations.

The simulated seasonal variation of global solar radiation over the three climatic zones is shown in Fig. 10. General decrease in daily global solar radiation can be observed in the South zone. Clear sky is found to be prominent during the rainy period with higher solar radiation experience in all the climatologies as averaged for the zone. The dry season in the zone is found to experience reduction in global solar radiation which may be the result of dust and forest smoke or aerosol deposit (Fagbenle, 1992; Maduekwe and Chendo, 1997). Reduction in global solar radiation is also observed to increase with years; global solar radiation in 1989–1998 (baseline year) > 2021–2030 > 2031–2040 > 2041–2050 and having the potential future changes given as -1.49 (0.7%), −3.49 (1.7%) and −22.56 (10.7%) respectively with the baseline year. As observed in (Pal et al., 2000; Lawal, 2010), the influence of relatively cool moist air from the ocean and the

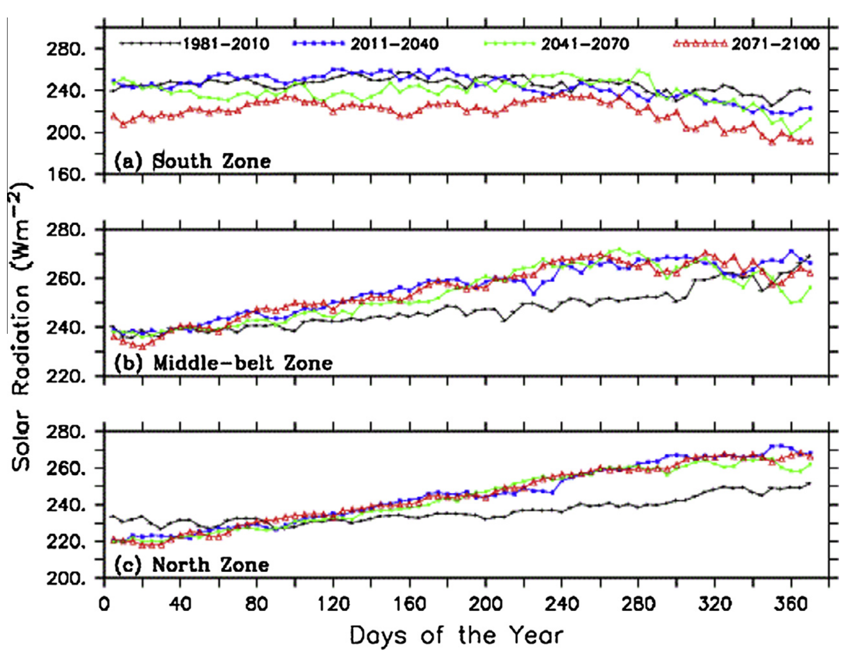

Fig. 10. Simulated present (1981–2010) and future (2011–2040; 2041–2070; 2071–2100) mean daily variation of solar radiation over the three climatic zones of Nigeria.

increased cloud cover over the coastal region may be responsible for the large reduction noticed in the South zone due to the movement of the south-westerly winds from the ocean.

In the Middle-belt zone, the rate of reduction in the daily mean global solar radiation with the different climatologies as predicted by RegCM3 follows similar trend, and less in magnitude than in the South zone. Potential future changes of the periods (2021–2030; 2031–2040; 2041–2050) with the baseline year are found to be 0.13 (0.06%), −3.28 (−1.4%) and −1.19 (−0.52%). The different climatologies (2021–2030; 2031–2040; 2041–2050) as computed for the North zone follow similar trend with the Middle-belt; general reductions are also observed in the region (North) in all the periods as −0.33 (0.13%), −2.81 (1.16%) and −1.30 (0.54%).

4. Conclusion

Basic findings of the effect of climate change on solar radiation in Nigeria as simulated by the International Centre for Theoretical Physics (ICTP) Regional Climate Model version 3 (RegCM3) driven by ECHAM5 GCM are concluded below:

1. The simulated seasonal global solar radiation bias for the RegCM3 with NIMET and NASA observations in the control period (1981–2010) are of similar magnitudes and showed a mixture of persistent positive and negative biases ranging between −30% and +30%. Negative biases (approximately −10% to −30%) are found to be more dominant across the whole country in most of the months. The North region of the country being characterized by the desert climate is typically depicted with positive biases in the range of 2–30%.
2. The influence of relatively cool moist air from the ocean and the increased cloud cover over the coastal region due to the movement of the south-westerly winds from the ocean is also observed to be responsible for the positive biases in global solar irradiance exhibited by the model in the south coast over the Atlantic Ocean.
3. Increasing cloudiness is predicted for the future and this is believed to be responsible for the decrease in the global solar irradiance. However, information about changes in aerosol properties from the climate runs was not available. This information is thus needed from future climate model runs to better assess changes in the solar irradiance and its components of direct and diffuse fluxes. The model further indicates future warming to the end of the 21st century.
4. RegCM3 further gave a consistent significant change in temperature over the country resulting from global warming while future changes in global solar radiation across the zones was reduced. However, then note that the differences in solar fluxes were insignificant. RegCM3 predicted a reduction in solar radiation across the zones in all the periods; less reduction in global solar radiation is observed in the late 21st century across the zones than in the early century (periods 1 and 2).

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