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Simulation of West African monsoon using the RegCM3. Part I: Model validation and interannual variability

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With 9 Figures

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Summary

The West African monsoon oscillates each year with remarkable regularity but the interannual variability associated with the monsoon is not fully understood although much progress has been made in recent years. This study examines and evaluates the mean state and the interannual variability of the West African climate as simulated by the International Centre for Theoretical Physics (ICTP) Regional Climate Model version 3 (RegCM3) over the period 1979 through 1990 using the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data as lateral boundary conditions.

Our analysis shows that the averaged rainfall over the region is well represented by the model and demonstrates considerable skill in reproducing the extreme rainfall regimes.

There is however a tendency to overestimate rainfall amounts along the Guinean coast, particularly around mountainous areas, and to underestimate it over the Soudano-Sahel. The increased rainfall along the coast is due to an enhanced low-level convergence of the moist southwesterly winds along the coast leading to a reduction of the moisture content in the atmosphere. The decrease over the Soudano-Sahel could be associated with the weakening of the land–sea temperature gradient and hence the decrease in the low level southerly flows. The spatial and temporal variations in temperature are well captured by the model except for slightly cold bias over the coastal region due to an overestimation of precipitation.

1. Introduction

The climate of West Africa is dominated by the monsoon, a large-scale circulation characterized by a seasonal reversal of winds due primarily to the continent-maritime temperature contrast. The zone separating the tropical continental airmass of northern origin (Saharan region) from the tropical maritime airmass of Atlantic region is referred to as the intertropical discontinuity (ITD), which is often called the intertropical convergence zone (ITCZ) when it occurs over the ocean.

The climatological significance of the ITD lies in its position, which is associated with the south–north motion of the rain bearing maritime airmass. This is evidenced by the surface movement of the zone and the consequent distribution of rainfall over the West African region. Within the main tropical maritime airmass is embedded a number of rainfall producing systems such as easterly waves, squall lines and two tropospheric jets (African easterly jet (AEJ) centred approximately at 700 hPa and the tropical easterly jet (TEJ) centred at about 200 hPa). The intensity of these systems influences not only the amount of rainfall but also its seasonal distribution over West Africa.

Although the monsoon returns with remarkable regularity each summer, the seasonal amount of rainfall shows a large interannual variability. Since the region depends on rainfall for agriculture, even a moderate decrease in monsoon rainfall or shift in the north–south extent can have significant socio-economic impacts. Therefore, an understanding of the interannual variability of the monsoons is important, not only for the people that live in this region, but also due to the possible consequences for the earth's climate system. For example, studies have also shown that most intense hurricanes that hit the eastern coasts of the United States form from African easterly waves (AEW) (Adedoyin, 1989, 1997, 2000).

The rainfall pattern over West Africa has been documented in many studies such as Kidson (1977) and Nicholson (1981). In addition, many studies have examined the interannual variability of West African rainfall. For example, Hastenrath (1984) and Mohr (2004) looked at interannual variability of the sub-Saharan region, while Lamb (1978), Lough (1986), Nicholson (1981, 1993) and Rowell et al. (1995) concentrated on West African rainfall spatial patterns. In this study, we investigate how the RegCM3 performs in simulating the basic features of West African climate.

Over the past 30 years, the region has experienced a downward trend in rain amounts during its critical period (May–October) (Nicholson et al., 2000). The reasons for this reduced rainfall are still unclear. West African climate variability has been shown to be related to anomalous Atlantic or global sea surface temperature (SST) anomalies, and the interdecadal trend in Northern and Southern Hemisphere SST anomalies (Lamb, 1978; Palmer, 1986; Rowell et al., 1995). Furthermore, model studies indicate that land-use change can reduce rain amounts in West Africa (Charney, 1975; Xue and Shukla, 1993; Zheng and Eltahir, 1998; Wang and Eltahir, 2000). We address some of the various processes and interactions that affect the monsoon in a companion paper (Part II).

Anomalous atmospheric circulation has also been associated with negative precipitation anomalies during the main rainy season (Lamb and Peppler, 1992; Newell and Kidson, 1984). In addition, Rowell et al. (1995) analyzed the variability of summer rainfall over North Africa using a general circulation model (GCM). They distinguished three main sources of variability: (a) SST forcing, (b) internal atmospheric variability, and (c) soil moisture feedback. In addition to climate variability and land-use change, there is the potential for changes in the mean climatic state of West Africa from anthropogenic greenhouse forcing (e.g. Jenkins et al., 2002).

Climatic variability strongly influences fluctuations in West African food production particularly in the Soudano-Sahel and semi-arid areas of the region. In particular, rainfall is the most important limiting factor in agriculture and water resources, and one of the most variable climate elements in West Africa. Therefore, characteristics of this climatic variable must be well understood in order to formulate better policies and strategies to promote sustainable food production and adequate water resources. Regional climate models are useful tools for understanding rainfall variability and how external forcings can impact the regional climate of West Africa (Jenkins, 1997; Fulakeza and Druyan, 2000). However, before any conclusions can be drawn from climate model sensitivity studies, one must assess a given model's ability to simulate the mean state and the intraseasonal and interannual variabilities of the West African climate, in particular the wet season.

This study examines the ability of the ICTP RegCM3 to capture the mean climate characteristics of the West African climate system with particular emphasis on the rainy season. Although various versions of the RegCM have been applied to many regions around the world, it has yet to be determined how the model performs in monsoon climates.

2. Description of the numerical model and experiments

2.1 Model description

The present study uses the ICTP RegCM3. As the model is well documented in Pal et al. (2005), only a brief description is provided here.

The dynamical component of the RegCM3 is derived from the NCAR-Pennsylvania State

University (PSU) Mesoscale model Version 5 (MM5; Grell et al., 1994).

RegCM3 offers multiple convection parameterisations. Preliminary experiments over West Africa demonstrate that the Grell (1993) mass-flux based cumulus convection scheme with the Fritsch and Chappell (1980) closure assumption gives a superior reproduction of the observed distribution and magnitude of meteorological variables (not shown). According to the Fritsch and Chappell (1980) closure assumption, convection intensity is based on the rate of convective destabilisation according to a given timescale (assumed to be 30 minutes in this study). We use the subgrid explicit moisture and cloud scheme (SUBEX) developed by Pal et al. (2000) that includes variation at the subgrid scale of clouds, cloudwater accretion and evaporation of raindrops. The land surface processes are based on the Biosphere–Atmosphere Transfer Scheme (BATS) (Dickinson et al., 1993) and the surface ocean processes are based on the Zheng et al. (1998) scheme. The model uses the Holtslag et al. (1990) planetary boundary layer scheme, which gives non-local diffusion resulting from countergradient fluxes produced by large-scale eddies in an unstable, well-mixed atmosphere. The radiative transfer is according to the package used in the NCAR Community Climate Model version 3 (Kiehl et al., 1996).

2.2 Experiment design

The model's domain and topography are depicted in Fig. 1a. There are 85 gridpoints in the north–south direction, 80 gridpoints in the east–west and 14 in the vertical with a horizontal spacing of 90-km and a model top of 70-hPa. A Mercator projection centred at 7.5° N, 5.0° E is utilised. Most of the prominent topographic features in the domain such as the Jos Plateau (Nigeria), Cameroon Mountains (Cameroon), Fouta Djalon Highlands (Guinea) are captured well.

The choice of a domain larger than the West African region is to have lateral boundaries far from the region of interest. This is important to reduce the influence of the time-dependent inflow/outflow boundary conditions over West Africa. In addition, such a large domain was designed to capture the important aspects of extra-tropical systems that appear to influence the West African climate.

The landuse types are specified according to the United States Geological Survey GTOPO30 Global 30 arc second elevation data and Global Land Change Characterization (Loveland et al., 2000). Figure 1b shows the model's surface vegetation types using the BATS classification. Generally speaking, between 5° and 20° N, there are three landuse zones that contain a predominant land cover type. The zone north of 15° N consists

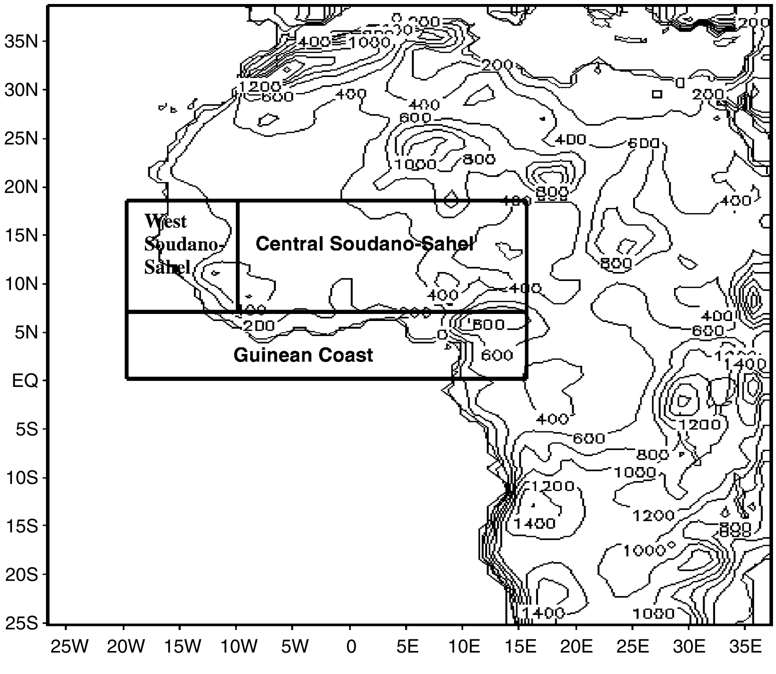

Fig. 1a. Model domain and topography represented by the 90-km grid. (Contour interval is 200 m). Also, subdivision of West African land area into 3 zones

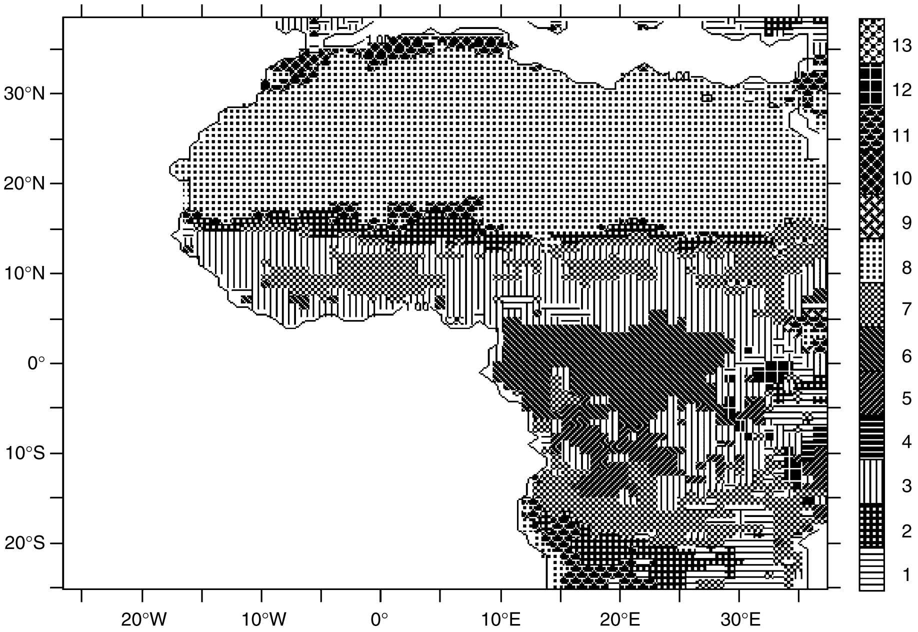

Fig. 1b. Model landuse. 1 – Crop/mixed farming; 2 – Short grass; 3 – Forest/Field mosaic; 4 – Mixed woodland; 5 – Deciduous broad leaf trees; 6 – Evergreen broadleaf tree; 7 – Tall grass; 8 – Desert; 9 – Deciduous shrub; 10 – Evergreen shrub; 11 – Semi desert; 12 – Inland water; 13 – Bog or Mash

of semi-desert and desert. Between 15° and 10° N, the land cover is principally Savanna. In the coastal zone, particularly west of 5° E, evergreen broadleaf forest naturally occurs. The GLCC/BATS land cover classifications in the figure make no distinction between degraded and old-growth broadleaf forest, and the text will refer to this zone containing both broadleaf forest and woody Savanna as forest.

The model integration is performed for 1979 through 1990 using atmospheric boundary conditions from the NCEP/NCAR – Reanalysis version 2 6-h hourly datasets (Kalnay et al., 1996). The sea surface temperatures (SSTs) are specified according to the Optimum Interpolation Sea Surface Temperature weekly data (Reynolds et al., 2002) obtained from the National Ocean and Atmospheric Administration. The first two years of the simulation are disregarded for model spin-up considerations.

It should be noted that the quality of the NCEP/NCAR reanalysis data over Africa and surrounding oceans might contain significant errors as relatively little observational data is assimilated into the product. Unfortunately, it is impossible to completely avoid this problem and it is, therefore, likely to have some impact on the performance of the RegCM3 (Liang et al., 2001). However, GCM simulations of the climate systems are likely to contain larger errors (Pan et al., 2001b). Therefore, the results obtained in this paper represent the minimum level of uncertainty associated with RegCM3 simulations of interannual variability when forced at the lateral boundaries.

The study focuses on the period 1981–1990 because there was anomalously low rainfall over the West Africa during the 1980s (Nicholson, 1993). In some individual years of the 1980s, rainfall was below the long-term means nearly everywhere. In 1983, for example, rainfall was below the long-term mean at 80% of the stations (Nicholson, 1993). In the light of this, it is important to examine rainfall variability during this decade and particularly the observed very dry conditions in 1983 using model simulation as it may provide a better understanding of the principal factors controlling the interannual variability of rainfall.

3. Observational datasets

We assess the performance of the RegCM3 using the Climate Research Unit (CRU) precipitation and temperature data constructed on a 0.5° lat-long grid (Mitchell et al., 2003). The spatial coverage extends over all land areas, including oceanic islands. The CRU dataset has been used in a number of applications in applied climatology, including high-resolution climate model evaluation (e.g. Christensen et al., 1997).

We also assess the RegCM3 (and CRU) performance using West Africa stations daily and monthly rainfall and wind accumulations from 437 stations. The daily data obtained from Climate System Analysis Group (CSAG), University of Cape Town, South Africa are acquired under the Assessments of Impacts and Adaptations to Climate Change (AIACC) Project (AF07) and the monthly data are from National Meteorological Agencies and African Centre of Meteorological Applications for Development (ACMAD). These datasets have been screened for quality and consistency, and some stations have been excluded from the analysis due to inadequate data.

4. Results and discussion

This section examines climatic variables for a 10-year (1981–1990) period from a 12-year (1979–1990) simulation described in Sect. 3.

The region of interest lies approximately between latitudes 4° N and 20° N and between longitudes 18° W and 15° E. To have a better examination of the West African climatic patterns, the region has been subdivided into three zones (see Fig. 1a): Guinean Coast (GC), West Soudano-Sahel (WS) and Central Soudano-Sahel (CS).

Before evaluating RegCM3's ability to capture interannual variability over West Africa, the degree to which the model captures the spatial pattern must be examined. A more precise understanding of the spatial distribution of the climatic variables in the model to observations will enable us to appreciate extreme temperature or precipitation regimes.

4.1 Spatial precipitation and temperature distributions

4.1.1 Precipitation field

The mean annual distribution of precipitation in West Africa is generally zonal and the amount of rainfall generally decreases inland from the coast. The heaviest rainfall occurs in the southwest and southeast of West Africa (Udo, 1978; Nicholson, 2003). The CRU dataset and the RegCM3 simulation depict these two maxima in Fig. 2 (a, b). The rainfall maximum over the coastal areas of the Guinea Republic, Guinea (Bissau), Sierra Leone and Liberia has a value of 7 mm/day in the CRU. The maximum rainfall over the same region in the model simulation reached a value of 10 mm/day. Similarly over western Cameroon where another peak is found, the CRU climatology depicts 7 mm/day while the simulated value is higher at 13 mm/day. The reason for the higher precipitation over these regions in the model simulations may be connected to the low level convergence seen in the model simulations as the surface southwesterly winds move from the ocean towards land. In addition, the CRU climatology may underestimate the observed values over mountainous regions due to the sparse data density in these regions. Despite these discrepancies, the RegCM3 is able to capture these regions of higher rainfall as discussed by Nicholson (2003)

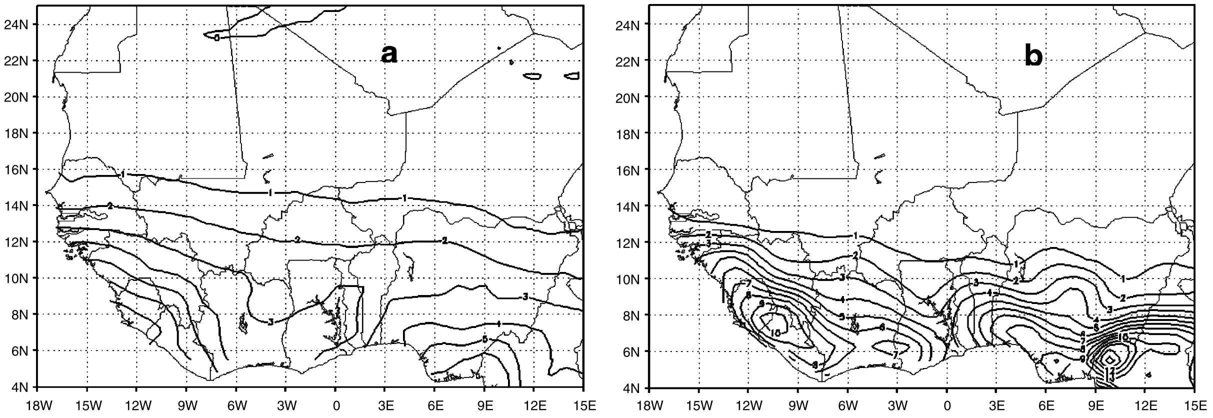

Fig. 2. Mean annual precipitation (mm/day) distribution over West Africa (land only) (**a**) CRU observations; (**b**) model simulation with 9-point smoothing

over West Africa. In both the CRU data and RegCM3 simulations, rainfall decreases from these relatively large amounts in a more zonal pattern to values of 3–4 mm/day over the Savanna, and values of 1–2 mm/day in the semi-arid and arid areas. However, the values obtained from the model simulations over the Soudano-Sahel are lower than observed.

The influence of orography is evident in the pattern of rainfall. For example, the annual rainfall increases rapidly from the lowlands along the western and southern sides of the Cameroon Mountains (~6° N, 12° E) and decreases towards the lowlands in Cameroon. The amount also increases rapidly inland from the coast of Guinea (Bissau), the Guinea Republic and northwestern Liberia, because of the orographic influence of the Fouta Djalon highlands (~10° N, 13° W). The Jos Plateau (~10° N, 7.5° E), which the RegCM3 depicts with an amount of about 4 mm/day, for example stands out as having higher annual totals of precipitation than the average for its latitude. This is not well represented by the CRU climatology partly because of the smoothness of its analysis over the region from the lack of contributing stations. Over the coastlands of southeast Ghana, Togo and western Benin Republic, both the model simulations and observations show rainfall as markedly lower than in other parts of the coasts or over areas on the same latitude. Adefolalu (1974) has argued that this anomalously low rainfall is a result of the rain bearing southwesterly winds becoming parallel to the adjacent coast particularly in August.

Other regional climate modelling studies have had difficulty obtaining results over tropical Africa as good as this simulation. For example, Jenkins (1997) and Sun et al. (1999b) running the RegCM2 over West Africa and East Africa respectively find significant underestimates in rainfall. In their model simulations, they implement the Anthes-Kuo (1987) scheme to represent convection. In this scheme, cumulus convection is largely determined by deep moisture convergence; however, moisture convergence is shallow and weak over most tropical Africa. In these simulations, we implement the Grell (1991) convection scheme implementing the Fritsch and Chappell (1980) closure assumption. This appears to be an improvement over the Anthes-Kuo parameterisation, despite the region precipitation biases.

4.1.2 Temperature field

Temperatures are usually high throughout the year in West Africa and the distribution of the mean annual temperatures also shows approximately a zonal pattern (Fig. 3a, b) that increases inland from the coast. The spatial temperature pattern indicates lowest values over the mountains and highest values over the desert. The model temperature values are generally in agreement with the CRU dataset. In both fields, the peak temperature value of about 30 °C lies over the Soudano-Sahel. However, over the coast where the RegCM3 tends to underestimate, temperature differences of around 1–2 °C can be seen between the CRU dataset and model simulation.

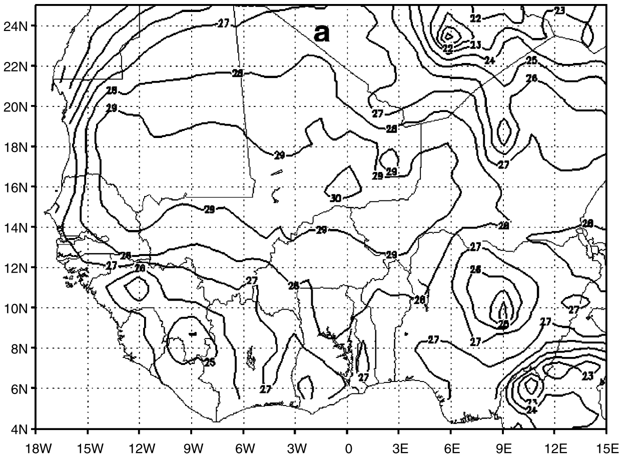

Fig. 3. Mean annual surface air temperature (°C) distribution over West Africa (land only) (**a**) CRU observations; (**b**) model simulation

In general, the RegCM3 accurately simulates regional temperatures from the point of view of land surface characteristics over West Africa as different patterns are depicted from topographic regions through vegetations types to desert areas.

4.2 Monthly variability

Here we investigate the monthly variations of the RegCM3 simulated climate for each of the subregions including the entire West Africa as defined in Fig. 1a.

4.2.1 Precipitation

For precipitation, both the observations and RegCM3 simulations provide a bell-shaped pattern with a peak in August over West Africa (Fig. 4a). During the monsoon retreat in October and November, the model has a tendency to overestimate precipitation. This overestimate, results in mean difference of about 0.5 mm/day over the year.

Analysis of the sub-regions, demonstrates that although the model accurately simulated the distribution of rainfall over the whole of West Africa, it has deficiencies in simulating the regional differences (Fig. 4b–d). The Guinean coast region has two peaks, one around June/July and a second in September, with a relative minimum rainfall in August (Fig. 4b). The dry season occurs between November and February. The rainfall minimum in August is likely connected with the relative stability that exists over the coastal area as a result of lower sea surface temperature and divergence of specific humidity during this period (Adefolalu, 1974; Adegoke and Lamptey, 2000). Although there is a tendency for the model to overpredict precipitation in this region, it accurately simulates the periods of dry and wet conditions throughout the year.

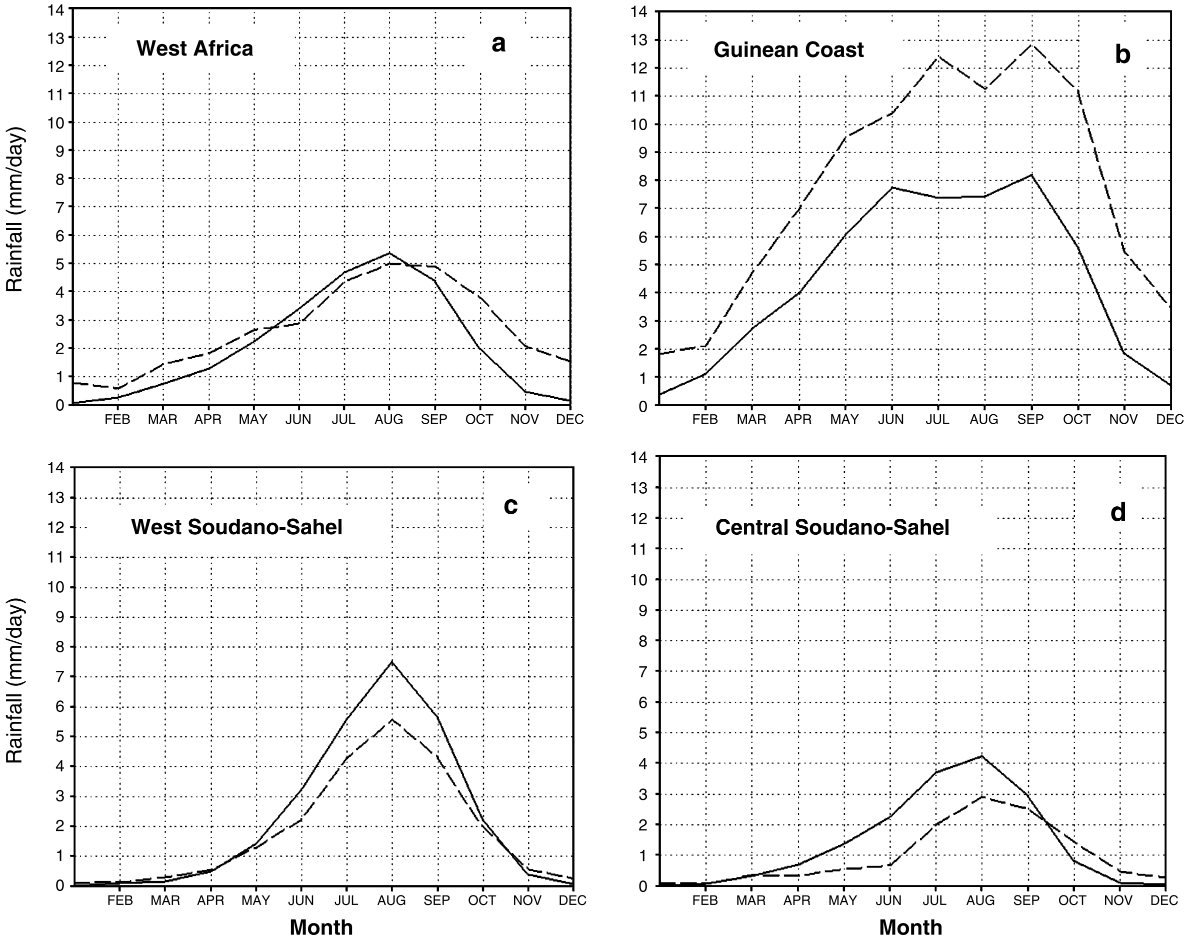

Fig. 4. Monthly mean precipitation (mm/day) pattern over West Africa and the three subdivided zones for 1981–1990. (solid line —— Observation and dashed lines --- model simulation)

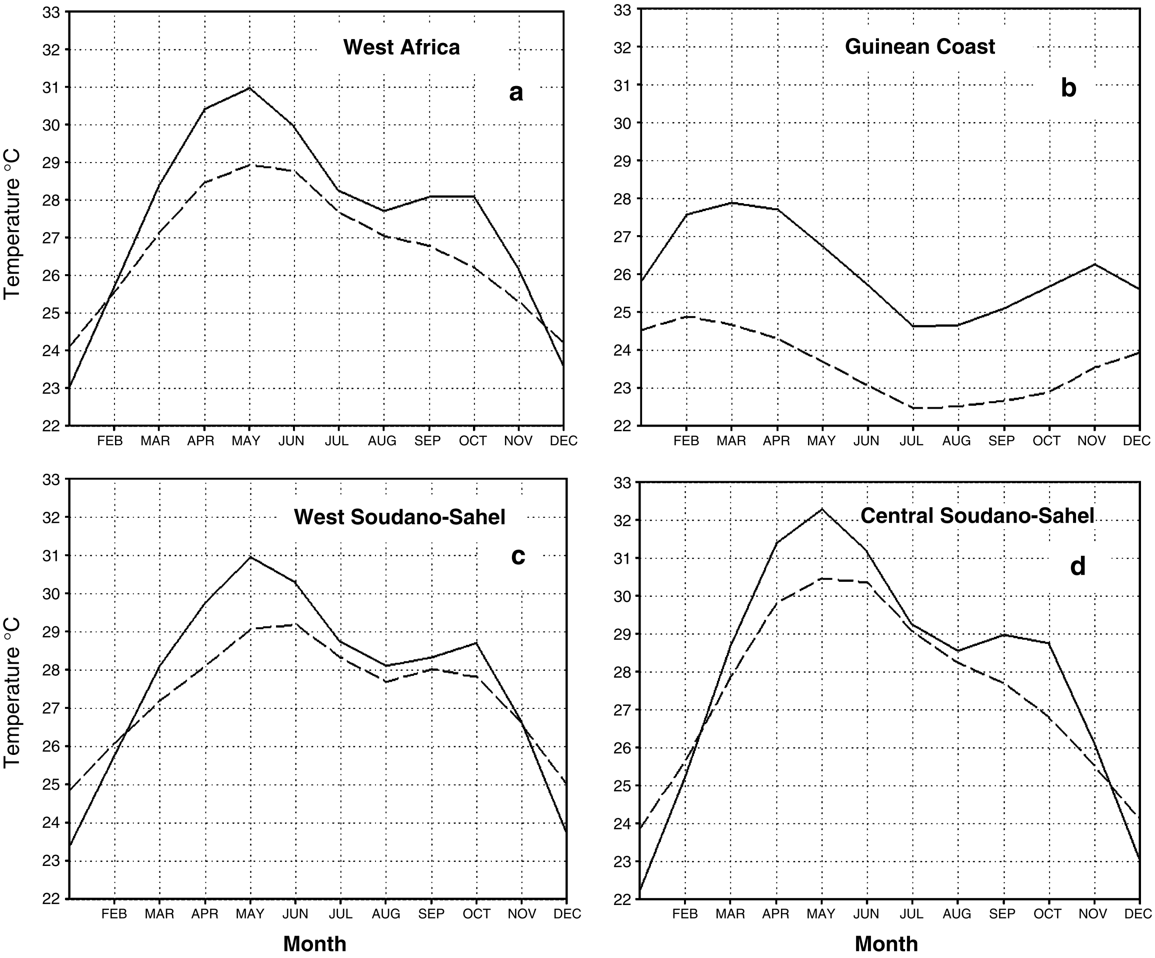

Fig. 5. Monthly mean surface air temperature (°C) pattern over West Africa and the three subdivided zones for 1981–1990. (solid line —— Observation and dashed lines --- model simulation)

Over West Soudano-Sahel, the patterns of both the observations and model results are similar in many respects with a single peak precipitation in August just after the time of high sun (Fig. 4c). However, the mean August precipitation amount in the simulation is underestimated by about 2 mm/day compared to the observations. A similar feature is depicted over the Central Soudano-Sahel although the difference in August amount is much less (Fig. 4d).

4.2.2 Temperature

Over all of West Africa, the seasonal mean surface air temperature pattern exhibits a bimodal characteristic (Fig. 5a). The peak in temperature associated with the first mode occurs in May prior to the monsoon onset and the peak of the second mode usually occurs in October as the monsoon retreats. The RegCM3 simulation captures this pattern; however the maxima are underestimated by approximately 2 °C. The lack of secondary peak in October is likely to be due to the simulated slower than observed retreat of the monsoon. Considering the zones, the Guinean coast experiences its maximum in March shortly before the first rains (Fig. 5b). The model's overestimate of precipitation in the region appears linked to a cool bias of about 3 °C. In the two Sahelian zones, the model agrees more favourable with the pattern of observations (Fig. 5c, d). In general, the model simulation is slightly warmer during the winter months except over Guinean coast where the cold bias persists.

4.2.3 Wind field

The performance of the model over the Soudano-Sahel requires further examination of the dynamics of the monsoon, particularly to ascertain

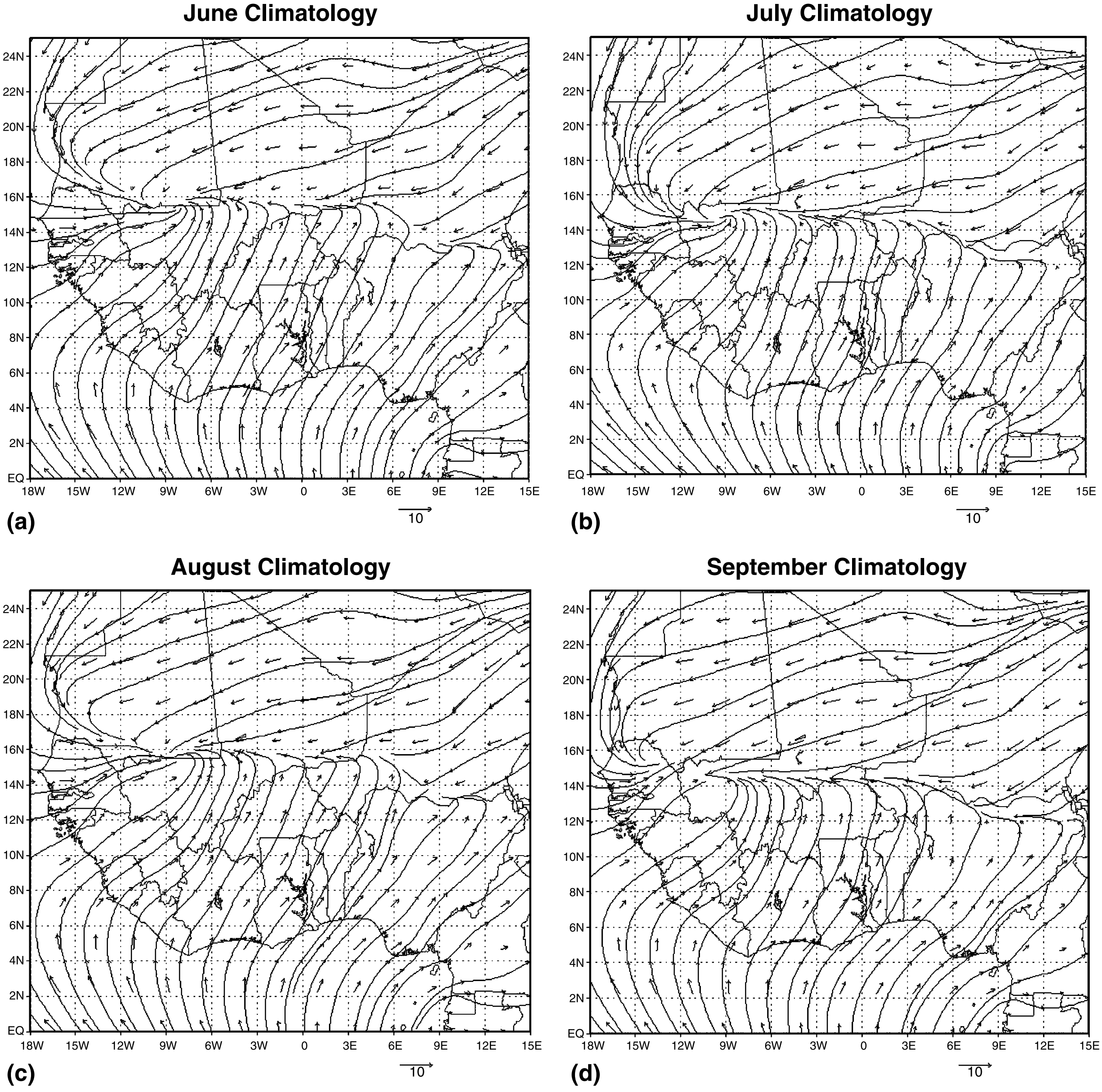

Fig. 6. Mean surface flow patterns over West Africa for 1981–1990

the role of the ITD in the rainfall distribution of that region. Therefore, we analyse the wind patterns during each month of the rainy season (June–September), but without any corresponding observational data (Fig. 6). The attempt here is to examine the factors responsible for the rainfall underestimation over the Soudano-Sahel region via the wind distribution.

The southwesterly wind is a primary moisture source for West African rainfall. Therefore, the northward extent of these winds during the rainy season, in part, can determine the amount and distribution of rainfall over the region. During the period June–September, most parts of the region are under the influence of the rain bearing southwesterly winds. Although, interannual rainfall variability may depend on more than just the ITD position (see Grist and Nicholson, 2001), it is pertinent to see if the southwesterly winds penetrate inland to as far as 20° N in August when the northernmost position of the surface southwesterly wind occurs (Dhonneur, 1971; Kidson, 1977). Thus, an examination of the mean southwesterly wind field during the wet season is

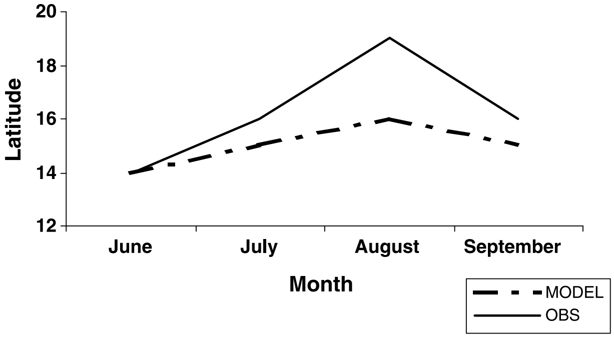

Fig. 7. Mean ITD position during the wet season over West Africa for 1981–1990

crucial to our understanding in the modulation of the interannual variability. The meeting point of the southwesterly winds and those of the northeasterly wind defines the position of the ITD.

Figure 6 shows the RegCM3 simulated monthly surface wind flow pattern over West Africa for June–September. By June, the southwesterly winds extended northwards to cover the semi-arid areas, although the wind strength is weak in those areas as shown in Fig. 6a. In July, these southwesterly winds move further northward, keeping the ITD at a mean position of 15° N (Fig. 6b). This is in near agreement with the observed surface position of ITD at 16° N by the findings of Dhonneur (1971). However, the August surface position of ITD reaching latitude 16° N from the model is rather low compared with observational dataset, which places it at latitude 19° N (Fig. 7).

This southward displacement may explain in part why the model tends to underestimate rainfall over the Soudano-Sahel region compared to the station observations. The low rainfall over the Soudano-Sahel in the model could also be due the SST forcing among other factors as earlier discussed through the findings of Vizy and Cook (2002). They argued that when an idealized north to south SSTA gradient is added in the tropical Atlantic, strong north to south height gradients in the middle levels appear. This limits the northward excursion of the rainbelt in West Africa and the Sahelian area could experience drier conditions due to the additive effect (subsidence anomalies and latitudinal blocking).

In September, as shown in Fig. 6d, the model result depicts the maritime airmass with the associate southwesterly winds beginning a retreat southwards placing the ITD at latitude 15° N, and thus reproducing the intraseasonal oscillation of the monsoon. The seasonal meridional component of the winds (not shown) indicates stronger flow from the Gulf of Guinea towards the coast, which becomes comparatively weaker along the Guinean coast.

4.3 Interannual variability

4.3.1 Precipitation

Figure 8 presents the time series of June–September rainfall anomalies for West Africa, and the sub-regions (delineated in Fig. 1a). These time series show "wet" and "dry" periods for both the RegCM3 and the CRU observations.

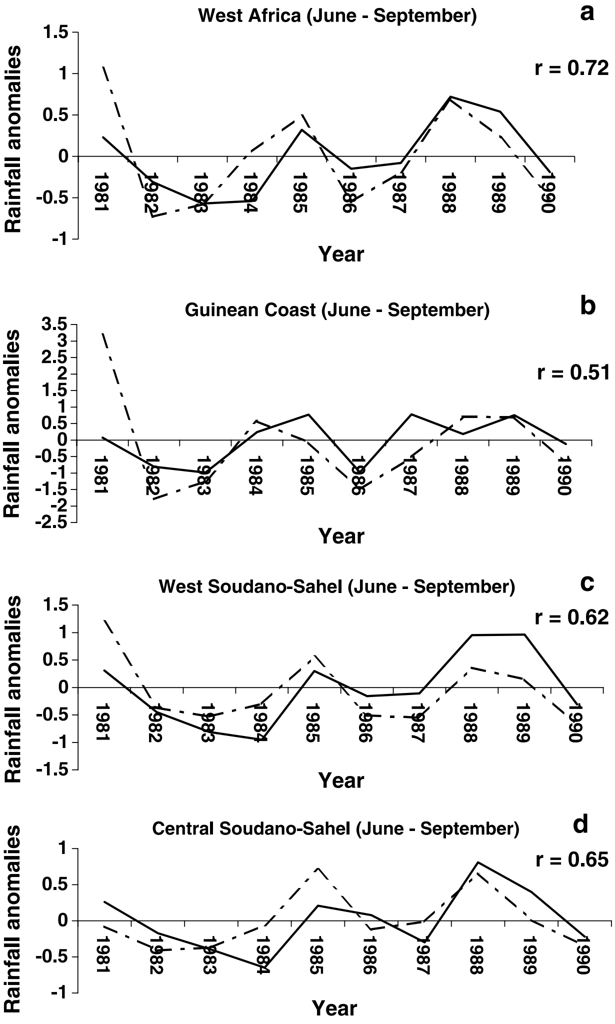

Fig. 8. Interannual rainfall anomalies of model (dashed line) and Observed (solid line) during wet season with respect to their 1981–1990 means

Over the entire West Africa (Fig. 8a), the model simulation and observation show that the years 1981, 1985, 1988 and 1989 are wetter than the 10-year mean (1981–1990) while the years 1982–1984, 1986, 1987 and 1990 are drier. The RegCM3 in all cases, except for the dry conditions in 1984, simulates the sign of the anomaly and generally the magnitude ($r = 0.72$). In particular, note that the well-documented drought of 1983 is accurately simulated by the RegCM3 in the simulation.

However, the model accuracy decreases somewhat when analysing the individual sub-regions (Fig. 8b–d). This decrease in accuracy is demonstrated in the lower regional correlation coefficient (0.51 for GC, 0.62 for WS, 0.65 for CS). In most of the years, the RegCM3 simulates the correct direction of the anomaly; however, the magnitude of the anomaly is not always accurately simulated. Not surprisingly, the Guinean coast, the region with the largest precipitation bias (Fig. 8b), has the lowest correlation coefficient. Nevertheless, the model still demonstrates skill in this region in simulating the interannual variability of precipitation.

Vizy and Cook (2002) have attributed the increase in rainfall along the coast to the change in moisture content of the atmosphere. Higher evaporation rates over the warm SST anomalies of the gulf increase the water vapour content in the lower troposphere. Subsidence over the Gulf of Guinea limits the vertical transport of moisture from the lower troposphere, so the moisture is advected northward by the low-level flow. The strong moisture flux is associated with an increase in moisture convergence and rainfall (condensational heat release) along the Guinean coast.

In the other regions (Fig. 8c, d), there is general decrease in rainfall over Soudano-Sahel. One possible reason for the decrease in rainfall over these zones is dynamical. The low level southwesterly winds from the gulf decreases in response to the weakening of the land–sea temperature gradient between the Gulf of Guinea and the Saharan desert. However, the model result clearly indicates an enhanced low-level convergence over the Guinean coast, which may reduce the monsoon penetration into the Sahara. In general, the model still agrees with the observation time series in the interannual variability.

4.3.2 Temperature

The interest in most previous work has been on rainfall since it directly impinges on agriculture and water resource management. Here, the temperature distribution will be important also to examine the forcing from human emissions of carbon dioxide.

The interannual variability of temperature in West Africa during the monsoon season is generally small (±0.5 °C; Fig. 9). During the 10-year simulation period, the largest anomaly is 0.72 °C which occurs during 1987, a relatively normal year for precipitation (Fig. 8). Despite this relatively small interannual variability, the RegCM3 generally simulates the differences between warmer and colder years over all of West Africa

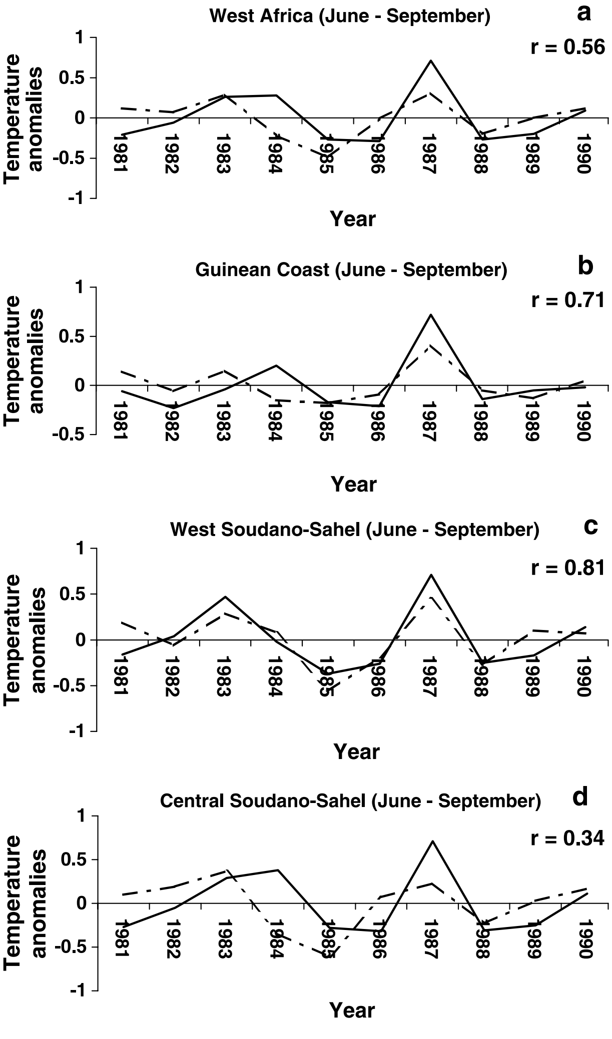

Fig. 9. Interannual temperature anomalies of model (dashed line) and Observed (solid line) during wet season with respect to their 1981–1990 means

(Fig. 9a). One exception is 1984 where the model also was not able to simulate the sign of the anomaly.

Analysis of the interannual variability of monsoon temperatures for the sub-regions displays mixed results in terms of model performance. On one hand, the simulations over GC and WS show a considerable accuracy ($r = 0.71$ and 0.81, respectively). On the other hand, over the CS, the accuracy decreases ($r = 0.34$). The reason for the decrease in performance over the CS is likely due to deficiencies in the land surface model. In addition, the other two regions are closer to the ocean where the SSTs have more pronounced controls on climate.

In another analysis (not shown) over the entire region, there is a consistent agreement in the pattern of the interannual variability in both the model simulation and observation, although the model simulation tends to be colder in summer by about 2 °C. The underestimation in summer is probably due to excessive precipitation in the model. One possible implication is that there may be an error in the prediction of cloudiness and the subsequent effect on the radiative flux field. It is also possible, of course, that some other important physical process has been neglected or treated inadequately.

The model result from the Guinean coast shows the interannual variability although with lower temperatures than observed. There is a cold bias in all seasons, which is linked to a consistent positive bias in rainfall over the same zone. Temperature patterns for the West Soudano-Sahel and Central Soudano-Sahel are similar in many respects. The model tends to have a cool or at most neutral bias in summer and a warm bias in winter. Concurrently, in precipitation for these two regions, the model has a negative bias in summer and is approximately neutral in winter. So for these two regions, warm bias is associated with neutral precipitation bias and cool bias is associated with negative precipitation bias. This is opposite of what is occurring in the Guinean Coast, where cool bias is associated with positive precipitation bias. Nevertheless, even though the observed interannual variability of temperature during the West African monsoon is relatively small, the RegCM3 displays skill in its simulation.

5. Conclusion

This paper is the first of two papers that are designed to examine the physical processes associated with land surface modifications related to deforestation and desertification over West Africa. This particular paper focuses on model validation to set the stage for the companion paper. It is directed at describing the model used in our study and how result of the model reproduces the mean climate and interannual variability of West Africa when compared against observational data.

We use the ICTP RegCM3 to study the West African monsoon and integrated the model from 1979 through 1990. Overall, the results of this study suggest that the model is capable of reproducing the West African climate variability. The precipitation, averaged over the region is well represented by the RegCM3 simulations. In addition, the simulations demonstrate considerable skill in reproducing the interannual climatic variability over the region. The spatial and temporal variations in temperature are well captured by the model, except for a relatively small cold bias over the coastal region. The changes in wind pattern are also in agreement with interseasonal meridional oscillation of the monsoon trough.

The model however shows a tendency to overestimate rainfall amounts generally over the region by about 2 mm/day and this value is slightly higher close to the Guinean coast, particularly around mountainous areas, and to underestimate it by about the same amount over the Soudano-Sahel.

An analysis of West African sub-regions shows that the simulations tend to overestimate rainfall along the Guinea Coast and underestimate rainfall in the Sahel. As a result, the model produces more frequent rains over the coast. Temperatures along the Guinean coast were also comparatively lower in the model by about 1–2 °C.

There are a number of potential reasons for the differences between model results and observations. Firstly, the model horizontal grid spacing (90 km) is too coarse to accurately simulate the mesoscale systems (e.g. squall lines) over West Africa. Secondly, driving fields from the NCEP/NCAR reanalyses are likely to have substantial errors at the boundaries, except in the north, due to the fact that they are placed in data sparse ocean regions (equatorial oceans). Of course, when compared to output from GCM simulations, which tend to have a higher degree of uncertainty, the choice of reanalysis data to drive the model is still preferred. Thirdly, the physics options used in the model integration are also sources of concern and could lead to the differences, particularly the convection scheme. Although, preliminary experiments over West Africa demonstrate that the Grell (1993) mass-flux based cumulus convection scheme with the Fritsch and Chappell (1980) closure assumption give a superior reproduction of the observed distribution and magnitude of meteorological variables, a further examination of other schemes may provide useful results. Similarly, the representation of the land-surface is crucial over West Africa and is likely to be a source of error. Lastly, the vegetational representation especially over the rain forest may not be adequate. For example, the GLCC/BATS land cover classification makes no distinction between degraded and old-growth broadleaf forest. In addition, Savanna in BATS is represented as tall grass. Therefore, there may be significant errors in the vegetation parameters (e.g. leaf area index, roughness height, albedo, etc). All of these are potential sources of errors and may be responsible for the southward shift in monsoon location. However, there is no expectation of an exact match between model and observations, and the usefulness of these results are more for examining the interannual variability of climate in West Africa. We conclude therefore that this simulation has produced encouraging results and it suggests that there is a good potential for using this regional climate model for the study of climate variability and physical processes over West Africa.

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References

Adedoyin JA (1989) Initiation of West African squall lines. Meteorol Atmos Phys 41: 99–103

Adedoyin JA (1997) Instability of squall-inducing waves, global sea surface temperature anomalies and climate change in tropical North Africa. Meteorol Atmos Phys 62: 79–89

Adedoyin JA (2000) Atlantic hurricanes and tropospheric dynamics over tropical Africa: influence of global sea surface temperature anomalies. Proceedings of the Workshop on the West African Monsoon Variability and Predictability. WMO/TD No. 1003, 153–156

Adefolalu DO (1974) On scale interactions and the lower tropospheric summer easterly perturbations in tropical West Africa. Ph.D Thesis, FSU, Tallah. Fla, 276 pp

Adegoke JO, Lamptey BL (2000) Intraseasonal variability of summertime precipitation in the Guinea coastal region of West Africa. Proceedings of the Workshop on the West African Monsoon Variability and Predictability. WMO/TD No. 1003, pp 115–118

Bailey RG (1998) Ecoregions: The ecosystem geography of the oceans and continents. Springer, 176 pp

Charney JG (1975) Dynamics of deserts and drought in the Sahel. Quart J Roy Meteor Soc 101: 193–202

Christensen JH, Machenhauer B, Jones RG, Schar C, Ruti PM, Castro M, Visconti G (1997) Validation of present-day regional climate simulation over Europe: LAM simulations with observed boundary conditions. Climate Dyn 13: 489–506

Dhonneur G (1971) General circulation and types of weather over Western and Central Africa. Annex-IV, GARP-GATE 23 Design, p 22

Folland C, Owen J, Ward MN, Colman A (1991) Prediction of seasonal rainfall in the Sahel region using empirical and dynamical methods. J Forecasting 10: 21–56

Fritsch JM, Chappell CF (1980) Numerical prediction of convectively driven mesoscale pressure systems. Part 1: Convective parameterisation. J Atmos Sci 37: 1722–1733

Fulakeza M, Druyan LM (2000) A regional climate model adapted to West Africa. Proc. of the workshop on the West African Monsoon Variability and Predictability (WAMAP), WMO/TD No. 1003

Giannini A, Saravanan R, Chang P (2003) Oceanic forcing of Sahel rainfall on interannual to decadal time scales. Science 302: 1027–1030

Giorgi F (1989) Two-dimensional simulations of possible mesoscale effects of nuclear war fires. I: Model description. J Geophys Res 94: 1127–1144

Giorgi F, Bates GT (1989) The climatological skill of a regional model over complex terrain. Mon Wea Rev 117: 2325–2347

Giorgi F, Marinucci MR, Bates GT (1993a) Development of a second generation regional climate model (REGCM2). Part I: Boundary layer and radiative transfer processes. Mon Wea Rev 121: 2794–2813

Grell GA (1993) Prognostic evaluation of assumptions used by cumulus parameterizations. Mon Wea Rev 121(3): 764–787

Grell GA, Dudhia J, Stauffer DR (1994) A description of the fifth-generation Penn State/NCAR mesoscale model version 5 (MM5), Tech. Note TN-398 + IA, Technical Report, National Center for Atmospheric Research

Grist JP, Nicholson SE (2001) A study of the dynamic factors influencing the rainfall variability in the West African Sahel. J Climate 14: 1337–1359

Hastenrath SL (1984) Interannual variability and annual cycle: mechanisms of circulation and climate in the tropical Atlantic sector. Mon Wea Rev 112: 1097–1107

Holtslag AAM, De Bruijn EIF, Pan H-L (1990) A high resolution air mass transformation model for short-range weather forecasting. Mon Wea Rev 118(8): 1561–1575

Janicot S, Moron V, Fontaine B (1996) Sahel droughts and ENSO dynamics. Geophys Res Lett 23: 515–518

Janicot S, Trzaska S, Poccard I (2001) Summer Sahel-ENSO teleconnection and decadal time scale SST variations. Clim Dyn 18: 303–320

Jenkins G (1997) The 1988 and 1990 summer season simulations for West Africa using a regional climate model. J Climate 10: 1255–1272

Jenkins GS, Kamga A, Garba A, Diedhiou A, Morris V, Joseph E (2002) Investigating the West African climate system using Global/Regional climate models. Bull Amer Meteor Soc 83: 583–595

Kalnay E et al. (1996) The NCEP/NCAR 40-year reanalysis project. Bull Amer Soc 77: 437–471

Kidson JW (1977) African rainfall and its relation to the upper circulation. Quart J Roy Meteor Soc 103: 441–456

Kiehl JT, Hack JJ, Bonan GB, Boville BA, Breigleb BP, Williamson DL, Rasch PJ (1996) Description of the NCAR community climate model (CCM3). NCAR Tech. Note, NCAR/TN-420 + STR, 152 pp, Natl. Cent. for Atmos. Res; Boulder, Colorado

Lamb PJ (1978) Large-scale tropical Atlantic surface circulation patterns associated with sub-Saharan weather anomalies. Tellus 30A: 240–251

Lamb PJ, Peppler RA (1992) Further case studies of tropical Atlantic surface atmospheric and oceanic patterns associated with sub-Saharan drought. J Climate 5: 476–488

Liang X-Z, Kunkel KE, Samel AN (2001) Development of a regional climate model for U.S. Midwest applications. Part I: Sensitivity to buffer zone treatment. J Climate 14: 4363–4378

Lough JM (1986) Tropical Atlantic sea surface temperature and rainfall variations in sub-Saharan Africa. Mon Wea Rev 114: 561–570

Loveland TR, Reed BC, Brown JF, Ohlen DO, Zhu J, Yang L, Merchant JW (2000) Development of a global land cover characteristics database and IGBP DISCover from 1-km AVHRR Data. Int J Remote Sensing 21(6/7): 1303–1330

Mitchell TD, Carter TR, Jones PD, Hulme M, New M, (2003) A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100). J Climate (submitted)

Mohr K (2004) Interannual, monthly and regional variability in the wet season diurnal cycle of precipitation in sub-Saharan Africa. J Climate 17: 2441–2453

Newell RE, Kidson JW (1984) African mean wind changes between Sahelian wet and dry periods. J Climatol 4: 27–33

Nicholson SE (1981) Rainfall and atmospheric circulation during drought periods and wetter years in West Africa. Mon Wea Rev 109: 2191–2208

Nicholson SE (1993) An overview of African rainfall fluctuations of the last decade. J Climate 6: 1463–1466

Nicholson SE, Some B, Kone B (2000) An analysis of recent rainfall conditions in West Africa, including the rainy seasons of the 1997 El Niño and the 1998 La Niña years. J Climate 13: 2628–2640

Nicholson SE (2000) Land surface processes and the Sahel climate. Rev Geophys 38: 117–139

Nicholson SE (2003) Comments on "The south Indian convergence zone and interannual rainfall variability over south Africa" and the question of ENSO's influence on Southern Africa. J Climate 6: 1463–1466

Pal JS, Small EE, Eltahir EAB (2000) Simulation of regional-scale water and energy budgets: representation of subgrid cloud and precipitation processes within RegCM. J Geophys Res 105: 29579–29594

Pal JS, Giorgi F, Bi X, Elguindi N, Solmon F, Gao X, Ashfaq M, Francisco R, Bell J, Diffenbaugh N, Karmacharya J, Sloan LC, Steiner A, Winter JM, Zakey A (2005) The ICTP RegCM3 and RegCNET: regional climate modeling for the developing world. BAMS (submitted)

Palmer TN (1986) The influence of the Atlantic, Pacific and Indian Oceans on Sahel rainfall. Nature 322: 251–253

Pan Z, Christensen JH, Arritt RW, Gutowski WJ Jr, Takle ES, Otieno F (2001b) Evaluation of uncertainties in regional climate change simulations. J Geophys Res 106: 17735–17752

Reynolds RW, Rayner NA, Smith TM, Stokes DC, Wang W (2002) An improved in situ and satellite SST analysis for climate. J Climate 15: 1609–1625

Rowell D, Folland CK, Maskell K, Ward MN (1995) Variability of summer rainfall over tropical North Africa (1906–92): observations and modeling. Quart J Roy Meteor Soc 121: 669–704

Rowell DP (2001) Teleconnections between the Tropical Pacific and the Sahel. Quart J Roy Meteor Soc 127: 1683–1706

Rowell DP (2003) The impact of Mediterranean SSTs on the Sahelian rainfall season. J Climate 16: 849–862

Shinoda M, Kawamura R (1994) Tropical rainbelt, circulation, and sea surface temperatures associated with the Sahelian rainfall trend. J Meteor Soc Japan 72: 341–357

Shinoda M (1995) West African rainbelt variation: an update to 1990. J Meteor Soc Japan 73: 259–266

Sun L, Semazzi FHM, Giorgi F, Ogallo L (1999b) Application of the NCAR regional climate model to eastern Africa, 2, Simulation of interannual variability of short rains. J Geophys Res 104: 6549–6562

Trenberth KE, Guillemot CJ (1998) Evaluation of the atmospheric moisture and hydrological cycle in the NCEP/NCAR reanalyses. Clim Dyn 14: 213–231

Udo RK (1978) A comprehensive geography of West Africa. London: Heinemann Educational Books, pp 1–50

Vizy EK, Cook KH (2001) Mechanisms by which Gulf of Guinea and eastern North Atlantic sea surface temperature anomalies can influence African rainfall. J Climate 14: 795–821

Vizy EK, Cook KH (2002) Development and application of a mesoscale climate model for the tropics: influence of sea surface temperature anomalies on the West African monsoon. J Geophys Res 107(D3): 4023

Wang G, Eltahir EAB (2000) The role of vegetation dynamics in enhancing the low-frequency variability of the Sahel rainfall. Water Resources Research 36(4): 1013–1021

Xue Y, Shukla J (1993) The influence of land surface properties on Sahel climate. Part 1: Desertification. J Climate 6: 2232–2245

Xue Y, Shukla J (1996) The influence of land surface properties on Sahel climate. Part II: Afforestation. J Climate 9: 3260–3275

Yang Z, Arritt RW (2002) Tests of a perturbed physics ensemble approach for regional climate modelling. J Climate (in press)

Zheng X, Eltahir EAB (1997) The response to deforestation and desertification in a model of West African monsoons. Geophys Res Lett 24(2): 155–158

Zheng X, Eltahir E (1998) The role of vegetation in the dynamics of West Africa monsoons. J Climate 11: 2078–2098

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