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A NESTED MODEL STUDY OF THE SAHELIAN CLIMATE RESPONSE TO SEA-SURFACE TEMPERATURE ANOMALIES

Fredrick H. M. Semazzi
Department of Marine, Earth and Atmospheric Sciences & Department of Mathematics
North Carolina State University

Neng-Huei Lin & Yuh-Lang Lin
Department of Marine, Earth and Atmospheric Sciences,
North Carolina State University.

Filippo Giorgi*
National Center for Atmospheric Research

Abstract. A nested high resolution atmospheric model is used to investigate the sensitivity of the Sahelian climate to large-scale sea-surface temperature(SST) anomalies. The nested system has realistic vegetation and detailed bottom orography. Two separate sets of northern hemispheric summer (June, July and August) numerical integrations are performed; one corresponding to the SST anomalies in 1950 when the Sahelian region was relatively much wetter than the long-term average conditions and a second integration based on 1984 SST anomalies when one of the driest rain seasons in the last few decades was experienced.

Although the low resolution (R15 $\approx 4.5^0$ *by* 7.5^0 latitude by longitude) stand-alone global climate model reasonably simulates the lower rainfall amounts in 1984 compared to 1950, the nested system yields more realistic regional climate because its forcing includes more detailed effects of topography, land-sea contrasts, and land surface processes. In particular, two distinct rainfall maxima primarily anchored to the regions of highest terrain are simulated by the model. One corresponding to the highlands in Cameroon over the Adamawa Plateau and a second maxima over Guinea and Sierra-Leone. Inspection of model circulation indicates that the weaker moist cross-equatorial monsoon flow in the 1984 is responsible for the lower amounts of the Sahelian rainfall compared to 1950. Our results are in agreement with several diagnostic and modeling studies performed in the recent years which show that deficient sub-Saharan rainy seasons tends to coincide with the southwesterly surface monsoon flow not extending as far north along the West African coast as in the wetter years (Lamb and Peppler,1990, and others).

Introduction

The receding vegetation over the desert-border Sahelian region during the last few decades has been one of the prime suspects for maintaining the prolonged sub-Saharan drought conditions over the years (Charney et al 1977, and Hastenrath, 1991). Although the land surface processes could be playing an important role in enhancing the severity of the adverse Sahelian climatic conditions, a large body of results based on numerical and statistical modeling indicate that SST is perhaps the primary cause of the observed interannual and decadal scale variability in the Sahelian rainfall (Semazzi et al 1988). Folland, et al. 1986 have recently concluded that the ability of UK Meteorological Office GCM SST anomaly simulations to accurately reproduce the observed seasonal Sahel rainfall for different years indicates that changes in the global SST patterns are indeed the primary cause of the Sahelian interannual climate variability. In the present study we explore the feasibility of using a high resolution nested model climate simulation system to investigate the sensitivity of the Sahelian climate on large-scale SST anomalies.

Model

Two of the primary obstacles that have hampered progress in the modeling investigations of the Sahelian droughts are: (i) lack of adequate GCM resolution to simulate the interactions between the meso-scale and global scale climate circulations which sustain the prolonged Sahelian anomalous climate conditions, and (ii) major deficiencies in the treatment of the land surface processes although the associated mechanisms are thought to be partly responsible for the ongoing expansion of the sub-Saharan desert border region, thus helping to turn it into a true desert (Charney et al 1977). In the present study we adopt the nested climate simulation system developed by Giorgi(1990). The basic design of the model comprises of a meso-scale model nested into a global climate model to achieve the resolution required in regional climate modeling. This one-way nested technique uses GCM results from the NCAR Climate Community Model (CCM1) to provide the large-scale circulation via the initial and boundary conditions for the nested model. In this system the regional Pennsylvania State University/NCAR Mesoscale Model Version 4 (MM4) is used to describe the effect of sub-GCM grid-scale forcing over a specific region.

A historical overview of the evolution of CCM1 is given by Williamson et al. (1987). The model is based on a spectral scheme, truncated at rhomboidal wave number 15 (R15 $\approx 4.5^0$ *by* 7.5^0 latitude by longitude, respectively) in the horizontal. It has 9 sigma layers in the vertical dimension.

Anthes et al. (1987) have described the standard MM4 model, while Giorgi(1990) has described a more recent improved version. We adopt grid spacing of 80 km in the horizontal and 9 layers in the vertical dimension. The nested model domain is centered over the Sub-Saharan region of North Africa and its grid domain extends from 5^0 south of the equator to 25^0 north. In the meridional direction the numerical domain extends from approximately 30^0 east to

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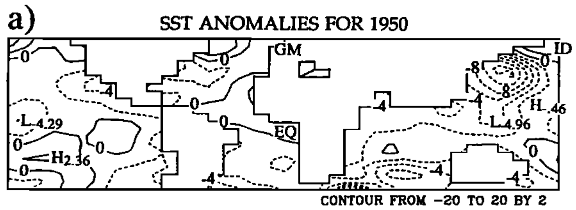
25^0 west. MM4 is coupled to the interactive biosphere atmosphere transfer scheme (BATS) developed at NCAR and described in a series of reports (Dickinson et al 1986).

Each CCM1-MM4 nested simulation comprised of two steps of model integrations involving the CCM1 global model and the MM4 regional model. First, CCM1 was run for 15 months. In each of the CCM1 runs the integration starts from the same initial conditions on October 15. In the second step the CCM1-MM4 nested system is integrated for 3.5 months starting from the last 2 weeks of May through the end of August. The first 2 weeks of the runs are reserved for model spin-up and they are ignored. During the three months of June, July and August the precipitation and circulation fields as well as other model state variables of interest over the Sahel are monitored and saved. Altogether, two separate sets of numerical simulations are performed. The first one is based on the 1950 SST anomalies when the Sahel region was observed to be relatively wet, while the second run employs the 1984 SST boundary conditions when severe droughts prevailed. The monthly average SST dataset used in prescribing the lower boundary conditions for CCM1 and the CCM1-MM4 nested models was obtained from GFDL (Oort, personal communication) and it is a subset of the GFDL analysis based on COADS (Comprehensive Ocean-Atmosphere Data Set) data. Figures 1a and 1b show the average SST anomalies for 1950 and 1984, respectively. We note the dramatic reversal in the sign of the SST anomalies between these two extreme SST anomaly scenarios. The 1950 SST anomalies are generally negative over the entire globe, while 1984 exhibits the opposite sign of anomalies.

Results

CCM1 model simulations: In figure 2a we show the CCM1 total rainfall during the months of June, July and August(northern hemispheric summer) for the 1950 SST anomaly run and the corresponding simulation for 1984 is similar(figure not shown). The difference field, 1984 minus 1950 for the CCM1 rainfall simulations (figure 2b), depicts a broad region of negative rainfall anomalies extending across much of West Africa with the exception of the coastal regions. This feature of the model simulation is consistent with the observed difference between the wetter climatic conditions of 1950 compared to the severe drought of 1984 (Hastenrath, 1991, and references therein). Based on the 1950 and 1984 SST anomaly conditions, Folland et al (1988) also reported similar model response over the Sahelian region.



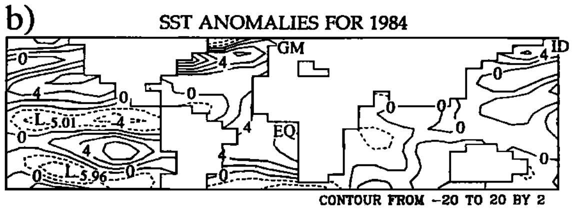
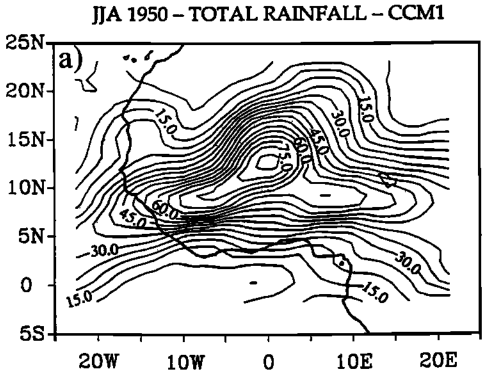


Fig.1. Observed annual mean SST anomalies(X10), (a) wet year: 1950, and (b) dry year: 1984. Contour interval of 2K.



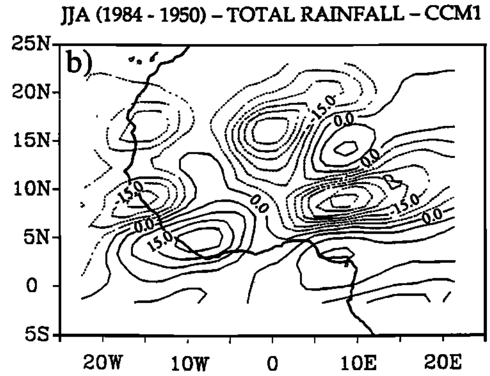
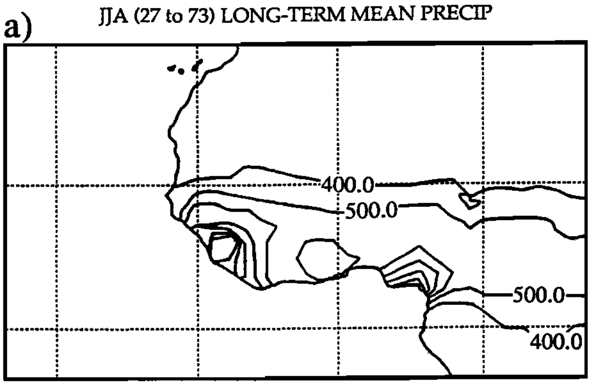


Fig.2. CCM1 June-July-August precipitation for (a) the 1950 run, and (b) the difference (1984-1950). Units in cm/season and contour interval of 5 cm.



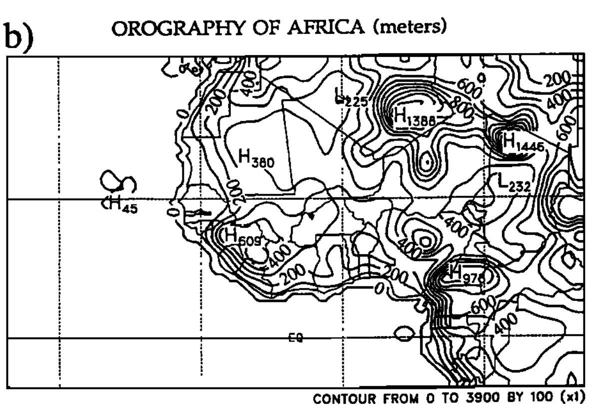
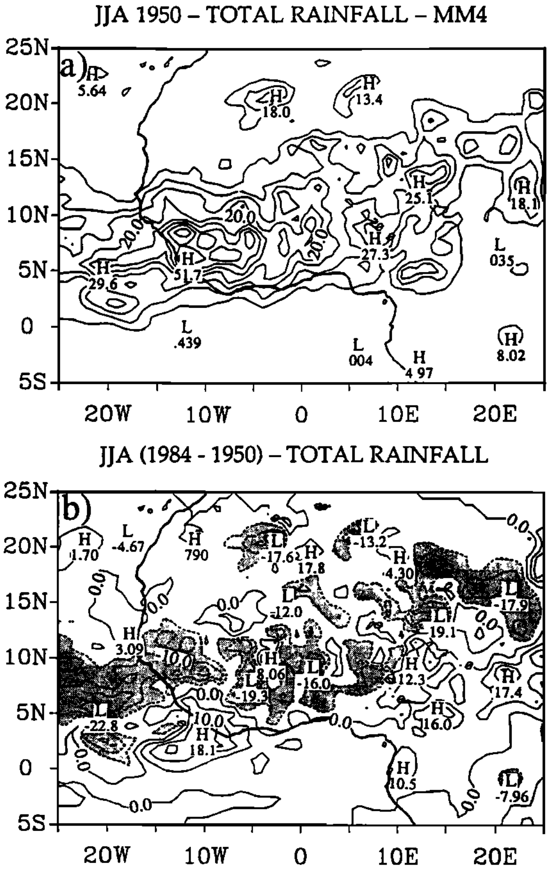


Fig.3. (a) Observed June-July-August precipitation climatology based on the years 1927-1973. Units in mm/season and contour intervals of 100 mm, (b) Orography of North Africa (meters). Contour interval of 100m.

For comparison with the CCM1 model results, we show the observed summer rainfall climatology in figure 3a. The observed historical African rainfall data used to prepare this map was obtained from NCAR and it was originally compiled by Dr. Sharon Nicholson of Florida State University (Nicholson, 1985). Inspection of the observed rainfall shows two distinct rainfall maxima primarily anchored to the regions of highest orography. Figure 3b shows the regional orography for the domain of interest. We note that the maxima adjacent to the Gulf of Guinea(figure 3a), coincide with the highlands in Cameroon. A second and more extensive rainfall maxima is found further to the west and it coincides with the highlands of Guinea and Sierra-Leone. To the north of the primary rain belt, the sharp decrease in precipitation corresponding to the Sahara desert-border region is well portrayed. Overall, it is encouraging to note that the stand-alone global climate model faithfully simulates the primary features of the regional climatology, but obvious deficiencies are also clearly evident. In particular, the rainfall maxima over Sierra-Leone is shifted away from the coastal region compared to the observed rainfall pattern in which the coastline intersects the region of maximum rainfall. We note that the model has difficulty in resolving the high gradients in rainfall distribution associated with the regions of pronounced terrain height variability.

Although the response of the coarse resolution GCM is quite encouraging, closer inspection suggests that use of higher resolution is desirable. In the next section we present the results based on a high-resolution CCM1/MM4 nested system.


JJA 1950 - TOTAL RAINFALL - MM4

JJA (1984 - 1950) - TOTAL RAINFALL

Fig.4. (a) CCM1/MM4 nested model June-July-August precipitation for the 1950 run, and (b) the difference (1984-1950), with areas of negative anomalies shaded. Units in cm/season and contour interval of 5 cm.

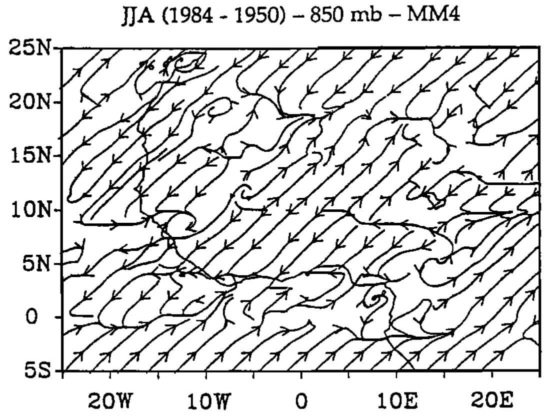

JJA (1984 - 1950) - 850 mb - MM4

Fig.5. CCM1/MM4 nested model June-July-August streamline field for the difference (1984-1950).

<u>CCM1/MM4 nested model simulations</u>: The nested model (CCM1-MM4) accumulative rainfall for June, July and August for 1950 is shown in figure 4a. The corresponding simulation for 1984 is similar and therefore not displayed. We note more detailed structure in the rainfall field compared to the CCM1 simulation in figure 2a. The regional rainfall maxima observed in connection with CCM1 have shift toward the coast thus exhibiting a more realistic distribution. The model reproduces the salient features of the rainfall distribution over Sierra-Leone and near the coast of Guinea. Instead of one rainfall maxima centered near 12^0 North and 1^0 West in the CCM1 simulation, the nested system produces two distinct centers of rainfall maxima. The rain belt extends across the entire sub-continent with the rainfall maximum located near the coast as noted earlier. Other, topographically-induced local maxima are found over the highlands in Cameroon and Nigeria. A band of secondary isolated maxima is located at about 20^0 North. Figure 4b shows the rainfall difference field, 1984 minus 1950. The general reduction in precipitation in 1984 compared to 1950 is clearly apparent over most of the region. It is accompanied by positive anomalies along the coast of West Africa. The MM4 precipitation differences clearly show greater detail and sharper gradients than in CCM1(figure 2b). A major challenge in the future is the need to develop high resolution climate data monitoring platforms required for the evaluation of the high resolution climate models.

Figure 5 portrays the streamline difference field, 1984 minus 1950. We note counter monsoon anomalous low level(850 mb) flow which tends to weaken the cross-equatorial monsoon flow primarily responsible for transporting the Atlantic moisture into the interior of West Africa. Most of the coastline, to the south, experiences confluent motion which is largely responsible for the enhanced rainfall observed in the 1950 simulation. These results are in agreement with the diagnostic results(Lamb and Peppler, 1990) reported in several recent studies showing that deficient sub-Saharan rainy seasons tend to coincide with the southwesterly surface monsoon flow not extending as far north along the West African coast as in the wetter years. Druyan and Hastenrath, (1991 and 1992), and Owen et al (1988) based their GCM investigations of the relationship between Sahelian rainfall and SST on the same years of 1950 and 1984, as we do in the present study. Our results are in agreement with these previous modeling studies and furthermore, the magnitude of the rainfall differences between the two years are consistent with the observations(see Owen et al 1988).

Conclusions

The high resolution nested model successfully simulates the main features of the observed climate changes that occurred between 1950 and 1984 over the Sahelian region. Although CCM1 R15 correctly simulates the general reduction in rainfall amounts for 1984 relative to 1950, the nested system yields more realistic and detailed regional climate because its forcing includes more detailed effects of topography, land-sea contrasts, and land-surface processes. Inspection of the model circulation shows that the reduction in the Sahelian rainfall is due to the weaker moist cross-equatorial monsoon flow in 1984 compared to 1950. Our results are in agreement with the several diagnostic studies performed in the recent years which indicate that deficient sub-Saharan rainy seasons tend to coincide with the southwesterly surface monsoon flow not extending as far north along the West African coast as in the wetter years (Lamb and Peppler,1990).

Because of the exploratory nature of this work, we only performed two sets of simulations, so that statistical significance analysis and investigation of the performance of the nested model under different SST scenarios were not performed. We are now in the process of addressing these important questions. The results from the ongoing investigation will be reported in a separate paper.

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F.H.M. Semazzi, Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27965-8208.

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