A GCM Study of the Teleconnections between the Continental Climate of Africa and Global Sea Surface Temperature Anomalies

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ABSTRACT

In this case study the role of global SST anomaly forcing in promoting the extreme climatic conditions that prevailed in Africa during the years of 1950 and 1973 is examined. In 1950 abundant rainfall was observed over tropical Africa, particularly over the Sahel and Southern Africa. By contrast, in 1973, this rainfall anomaly pattern was characterized by the opposite phase, with most of the continent experiencing severe droughts.

The primary research vehicle in this investigation is the standard version of the NCAR CCM1 GCM with horizontal resolution of rhomboidal spectral truncation at wavenumber 15 (R15). Two separate 10-yr simulations based on the 1950 and 1973 observed sea surface temperature (SST) have been performed. The empirical orthogonal functions method is employed to isolate the annual cycle harmonics in the data and also to remove statistical noise. The filtered seasonal rainfall fields for the model and the observations are compared to investigate the response of the African continental climate to the 1950 and 1973 SST climatologies.

CCMI successfully simulates the primary features of the seasonal mean climate conditions and anomalies over the Sahel and Southern Africa. The authors attribute this to the ability of the model to simulate the annual harmonic oscillation realistically. Over equatorial Africa, where the semiannual oscillation is observed to be relatively more important than it is at the higher latitudes of the continent, the model simulation is not as successful. This occurs because of the deficient simulation of the semiannual harmonic oscillation by the model. A weaker annual cycle comprising the annual mean (nonoscillating component) and the annual harmonic oscillation in the 1973 run relative to the 1950 experiment provides a viable explanation for the synchronous climatic anomaly conditions that prevailed in northern and southern Africa during these two years. Investigation of the relative role of the GCM’s internal variability and the SST externally forced variability during the rainy season over tropical Africa yields valuable insight into the reasons for the observed anomalous climatic behavior. Over the Sahel and Southern Africa, where the annual harmonic oscillation is relatively large, externally forced SST variability dominates over internal variability in explaining the drier conditions in 1973 relative to 1950.

1. Introduction

The climate of Africa is dominated by several distinct continental-scale modes of variability (Nicholson 1986). For instance, the decade of 1950–1959 was characterized by above-normal precipitation over most of Africa, while rainfall deficiencies prevailed over the near equatorial region. Later, during the period of 1968–1973, this rainfall anomaly pattern dramatically reversed in sign, with rainfall deficits observed for most of Africa, while the equatorial region experienced widespread abundance of rainfall. These two time periods also coincide with a reversal in the sign of the Sahelian rainfall anomalies (Lamb and Peppler 1992). Various studies have also observed this peculiar climate behavior. Janowiak (1988) applied the EOF method on the rainfall of Africa and found similar re-

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sults regarding the opposite tendency in the evolution of the annual precipitation anomalies between the near equatorial region and the rest of Africa. Shinoda (1989) analyzed the variability of the African rainfall using an updated version of the rainfall dataset used by Janowiak (1988) and found that during the wet years of the semi-arid regions of tropical Africa, positive anomalies prevailed throughout the continent, with the exception of East Africa near the equator.

The three studies cited above were all based primarily on the same source of rainfall data, however, other studies based on different sources of data have suggested similar results. Lau and Sheu (1989) analyzed global rainfall station data archived at NCAR, and their results showed the presence of a distinct out of phase relationship between the equatorial and the subtropical regions of Africa. Hastenrath (1990) employed the highly reflective clouds (HRC) data derived from satellite retrievals to investigate the climate variability of tropical convection. His results indicate broad regions of negative correlation between the Sahelian zone and equatorial Africa. Inspection of his results also suggests a phase reversal in the precipitation anomalies between the equatorial and southern regions of Africa.

Clearly, all these studies underscore the need to clarify the reasons for the interhemispheric concurrence of annual rainfall variations, although the rains in each latitude band come at different times of the annual cycle. We contend that a comprehensive explanation of the causes of the Sahelian droughts should also address the question of the observed synchronous continental-scale extent of the rainfall anomalies. Previously, most GCM modeling investigations of the Sahelian droughts have primarily focused on the northern region of Africa, although, as we have noted, some of the droughts appear to be part of the continental-scale climate anomaly regimes. We believe that this phenomenon could be a major source of rainfall variability over the Sahel region. We assert that the relative weakness of the teleconnection signal outside the Sahelian region does not diminish the importance of the need to adopt a continental view in the search for the cause-effect relationships associated with the Sahelian droughts. Confining our efforts only to northern Africa could preclude the possibility of discovering other important evidence that could lead to significant advances in our understanding of the mechanisms that are responsible for maintaining the Sahelian drought conditions.

Although the land-surface processes could be playing an important role in modulating the climate conditions over the desert-border regions of Africa (Charney et al. 1977), a large body of results based on numerical and statistical modeling indicate that SST is most likely the primary cause of the observed decadal variability in the Sahelian rainfall (Semazzi et al. 1988, 1989; Druyan 1988; Lough 1986 and Wang et al. 1996). Recent studies concerning GCM simulations of the Sahelian droughts at the United Kingdom Meteorological Office (Folland et al. 1986, 1991) suggest that changes in the global SST patterns are indeed the primary cause of the Sahelian interannual climate variability. In the present study we extend the earlier studies by investigating the role of the global SST anomalies in maintaining the continental-scale climate anomalies of the African climate. We recognize that considerable variations may exist in the causal mechanisms of the African rainfall climate variability within the wet epoch of the 1950s and the dry epoch of the 1970s (Janicot 1992a,b; Ward 1992; and Rowell et al. 1991). Therefore, we characterize the present study, which is based on two specific years—1950 and 1973, as a case study. However, the results could have important implications toward our understanding of the factors responsible for the observed differences in the climates of the 1950s and 1970s decades.

The primary objectives in the present study are (i) to characterize the differences between the 1950 and 1973 climatic anomaly conditions in terms of the dominant annual cycle harmonic oscillations for both the GCM and the observations and (ii) to investigate the relative importance of internal variability and SST-forced climate fluctuations.

2. Model description

The primary vehicle in this investigation is the standard NCAR CCM1 spectral GCM. The rhomboidal spectral truncation at wavenumber 15 (R15) is adopted. A historical overview of the evolution of CCM1 is given by Chervin (1986) and Williamson et al. (1987). The model is based on an implicit scheme in time and it employs a sigma vertical coordinate scheme. Surface temperatures over land and sea ice are obtained via an instantaneous surface energy budget that is solved iteratively at each grid point. SST is prescribed as a lower boundary condition. An interactive surface hydrology scheme is employed in which soil moisture, snow cover, and sea ice are computed as functions of time and thus interact with the other model components. Soil moisture is determined via a surface hydrologic balance.

Two model simulations are performed to study the sensitivity of the African continent seasonal and annual climate response to global-scale SST anomaly patterns. The SST dataset used in specifying the lower boundary conditions in CCM1 was obtained from GFDL (Oort 1993, personal communication), and it is a subset of the GFDL analysis based on COADS (Comprehensive Ocean–Atmosphere Data Set) data. A description of this dataset has been presented by Pan and Oort (1990). It consists of monthly means and covers almost 11 decades for the period 1870–1988. The $2.5^\circ$ lat $\times 5^\circ$ long data obtained from GFDL was further degraded to the CCM1 gaussian grid by applying simple area-
weighted averaging to the original dataset. In the wet year case we set the global SST distribution in CCM1 for each calendar month to the corresponding 1950 SST conditions.

In Fig. 1a we show the 1950 annual mean SST anomalies. The second simulation is based on the 1973 SST anomalies (Fig. 1b). The years 1950 and 1973 correspond to the wettest and driest conditions over most of Africa during the decades of the 1950s and 1970s. In each run the model is integrated for ten years and the numerical integrations start from the same initial conditions where the orbital parameters required for computing the solar zenith angle and the initial conditions correspond to the middle of October.

3. Model and observational precipitation data

The Sahelian rainfall data used for the comparison with the model simulations was obtained from a historical raingauge station dataset archived at NCAR. These data were compiled by Dr. Sharon Nicholson of Florida State University. Our estimate of the rainfall climatology is based on the period from 1949 to 1973 when the data are abundant and also includes the years of 1950 and 1973, which are the focus of this study. During this period there are at least 600 rainfall reporting stations each year. We adopted a procedure nearly analogous to Janowiak (1988), including the treatment of missing data. Janowiak’s (1988) rainfall data was grouped within 4° lat. × 10° long boxes. Here we grouped the precipitation in 2.5° × 2.5° regular grid boxes. With the exception of the data resolution, seasonal stratification, and the fact that only one station (instead of two) was required to be resident in any grid box to be used for the analysis; the rest of the preprocessing of the raingauge data is similar to Janowiak (1988). All available station data within a grid box are averaged to form the elements of the gridded continental rainfall matrix that provides the input to the EOF analysis described in the following section. The analysis of the model output and observed rainfall data are confined to the African region defined by the following coordinates: 40°S, 40°N, 25°W, 55°E. Of course, in the case of the observations we do not include data over the oceans.

4. Filtering of model and observational rainfall data

The physical climate anomaly signals in both the model and observed rainfall data tend to be significantly contaminated by noise. In order to separate the signal from the noise, we filtered each dataset by retaining only the leading empirical orthogonal functions (EOFs). Eliminating the statistical noise through the EOF filtering process of the GCM data provides an elegant way of increasing our confidence in the model difference fields, 1973 minus 1950, and will feature prominently in subsequent discussion of the model results. The EOF method has been widely applied in climate studies since its inception (Lorenz 1956; Kutzbach 1967). The approach adopted here is similar to Weickmann and Chervin (1988: hereafter referred to as WC88). They characterized the annual mean, the annual oscillation, and semiannual oscillation based on a 20-yr GCM simulation. An attempt is made, in the present study, to characterize the differences between the 1950 and 1973 climatic conditions in terms of the most dominant periodic and quasi-periodic oscillations for both the model output and observations. The analysis also explores the sensitivity of the GCM’s annual oscillation on the specification of SST.

The observed rainfall dataset, which was subjected to the EOF analysis, consists of 205 spatial grid points over Africa (Fig. 2) and 300 monthly departure fields covering the period from 1949 to 1973. The mean conditions are based on the entire 25 years. The rainfall data for each of the two model runs, 1950 and 1973, is stratified into 120 monthly departures from the 10-yr mean and 198 spatial grid points defining the subdomain of Africa and the adjacent ocean regions. The EOF analysis is applied on the rainfall correlation matrices to permit adequate representation of the variability over the semiarid regions where the mean rainfall is low but the corresponding relative deviations from climatology are large. Table 1 shows the variance explained by the leading EOFs in the 1950 and 1973 model runs and the observed data.

To test for nondegeneracy we adopt the thumb rule developed by North et al. (1982) and more specifically follow Folland et al. (1991), and thus examine if \( \lambda_1 - \lambda_0 > \frac{\lambda_0}{2(N)} \) is satisfied, where \( \lambda_0 \) and \( \lambda_1 \) are the eigenvalues of two adjacent EOFs and \( \lambda_0 > \lambda_1 \). We choose \( N = 120 \) and \( N = 280 \), for the observations and model, respectively. It is found that for first four modes in each case (Table 1), the condition above is satisfied by a large margin indicating that EOF1 through EOF4 are nondegenerate. In each of the three analyses, EOF5 and the higher modes marginally or fail to satisfy this robustness test. For this reason, they are excluded from further consideration in the rest of the analysis. Note that the explained variance for the leading EOF for the GCM is considerably lower than that based on observations. This may be associated with the absence of interannual variability in the model’s boundary conditions. Also, the observed rainfall data are confined to land in contrast from the GCM rainfall data that is taken from both land and ocean grid points. Considering the higher thermal inertia of the ocean in comparison to that of the land, we expect the GCM’s rainfall to exhibit less variability than the observed rainfall data. Figures 3 through 7 display the 1950 simulation and observational-based EOF patterns, as well as the principal components for the leading four EOFs. The corresponding results for 1973 are similar and therefore not displayed.
The leading eigenmode (EOF1) corresponds to the annual harmonic oscillation. The largest amplitudes occur when the earth approaches the solstices (Hsu et al. 1976a,b). During this time of the year we observe maximum deviation from the annual mean pattern (Fig. 3a). The central axis of the oscillation is located approximately 15° north and south of the equator. In the Northern Hemisphere this axis closely corresponds to the Sahelian zonal strip. The center of the annual harmonic oscillation pattern (Fig. 3a) in the Southern Hemisphere appears to coincide with the recent drought prone region extending across Zimbabwe and the neighboring countries. EOF2 (Fig. 3b) for the model is mainly confined to Western Africa, with its center over the Gulf of Guinea. It is interesting to note that the corresponding time series (Fig. 4b) also primarily describes the annual harmonic oscillation, although not as distinct as the time series for EOF1 (Fig. 4a). We have superimposed the two time series in Fig. 5, and it is apparent that the two modes are out of phase. This behavior is a manifestation of the meridional seasonal migration of the ITCZ over West Africa. We examined this further by projecting the model rainfall onto EOF1 and EOF2. The projected 10-yr mean monthly rainfall was then averaged over the GCM grid points enclosed by 2°–7°N, 10°W–10°E, which correspond to the Guinea Coast of West Africa. The results (not displayed) indicate two rainfall minima, one around July–August when the ITCZ is situated over the Sahel and one again in winter. EOF3 (Fig. 3c) is an equatorial pattern, centered over East Africa, at the border of Uganda and Zaire. The corresponding time series (Fig. 4c)
4c) represents the semiannual harmonic oscillation. EOF4 (Figs. 3d and 4d) has two main centers, one over South Eastern Africa and a second one located over the southern region of the Red Sea. This pattern is indicative of orographic control associated with the highlands of Yemen in the Northern Hemisphere, which in several places exceeds 3 km. In the Southern Hemisphere, the orography of Madagascar coincides with the observed maxima in the model response. It is not entirely clear if this phenomena occurs in reality, perhaps with reduced amplitude. We hypothesize that the Madagascar maxima may be due overreaction of the GCM to the presence of topography.

For comparison, we present the EOFs based on observations in Figs. 6 and 7. We should emphasize that only qualitative comparison is appropriate since there are important fundamental differences between the model data and the observations. In particular, as noted previously, the SST boundary conditions in the model simulations exhibit no interannual variability unlike the SST conditions corresponding to the observed rainfall. Nevertheless, it is useful to qualitatively compare the model's eigenmodes and those that have been derived from actual observations.

<table>
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<th>EOF2 (%)</th>
<th>EOF3 (%)</th>
<th>EOF4 (%)</th>
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<td>4.3</td>
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<td>56.5</td>
<td>10.6</td>
<td>5.7</td>
<td>4.7</td>
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Table 1. EOF (Africa) percentage variance explained by the leading modes for the 1950 model run (model/50), the 1973 model run (model/73), and the observed data for 1949 through 1973 (observed). Domain of EOF analysis: 40°S, 40°N, 25°W, and 55°E.
The pattern for EOF1 based on raingauge data is displayed in Fig. 6a, and the corresponding time series is shown in Fig. 7a. We show the time evolution only for the first 10 years out of the 25-yr time series. This permits easy comparison with the corresponding model results for which the length of the time series is 10 years. The basic features of the time series for the remaining 15-yr segment are very similar. We note the striking similarity between the model pattern (Fig. 3a) and the structure of EOF1 derived from observations (Fig. 6a). In particular, the centers in both hemispheres are in good agreement. EOF2 (Fig. 6b and Fig. 7b) is the semiannual mode and it is mainly confined to the near equatorial region. The temporal phase characteristics of this mode are consistent with the semiannual mode based on the model (EOF3; Fig. 4c). EOF2 (Fig. 6b) is a near-equatorial mode thus consistent with the GCM’s EOF3 (Fig. 3c). However, the pattern for the model is shifted too far to the west compared to the observed pattern. We found that this deficiency of the model in simulating the semiannual harmonic oscillation is primarily responsible for its failure to reproduce the spring and fall climatology realistically. In their global analysis WC88 also found that CCM1 is much
more successful in simulating the observed annual harmonic oscillation than the semianual oscillation. EOF3 (Fig. 6c) is localized over the southern tip of Africa. The corresponding time series (Fig. 7c) is characterized by episodic occurrence of large amplitude peaks approximately every 24 months. This mode does not have a corresponding signal in the model results perhaps because the forcing mechanisms responsible for its existence are not represented in the model. EOF4 in the observations is a dipole, with centers over the Gulf of Guinea and Eastern Africa (Figs. 6d and 7d).

Based on the eigenmodes obtained above, we have reconstructed the seasonal data by retaining only the leading modes necessary to describe the annual march of the rainfall belt and the climate anomalies. This was accomplished by systematic inclusion of a subset of eigenmodes at a time and inspection of the resulting fields. We found that it is sufficient to retain only the first four leading EOFs, which also satisfy the nondegeneracy test of North et al. (1982). The filtered data captures the salient features in the original data. Our data-reconstruction procedure is similar to the approach adopted in WC88. Since the EOF analysis is based on the correlation matrix, we must first denormalize the data by multiplying it by the standard deviation at each grid point and then adding the resulting anomalies to the annual mean. Therefore, the reconstruction may be represented by the following expression,
rainfall resides over western Africa, close to the coastline. However, the model’s region of maximum rainfall is shifted too far to the east and inland relative to the observations. We believe this deficiency arises in part from the coarse model resolution of rhomboidal 15, in addition to the model’s inability to simulate the semiannual harmonic oscillation realistically. The well-known Ethiopian highlands maximum rainfall region is almost undetectable in the observations (Fig. 8b). This may due to the inadequate rainfall observational network in this region. The difference fields, 1973 minus 1950, in Fig. 9 are more informative. They depict negative anomalies over northern and southern Africa. In the model, the rainfall deficits in southern Africa are weaker than in the observations (Fig. 9a). Further inspection of the actual digital data also reveals opposite polarity in the sign of the rainfall anomalies between eastern Africa and the rest of Africa.

b. Seasonal-averaged patterns

As a consequence of its vast size and proximity relative to the equator, Africa experiences a wide variety of climate regimes ranging from deserts to tropical rain forests (Nicholson et al. 1988; and Krishnamurti et al. 1989). The poleward extremes of the continent experience winter rainfall associated with the passage of the midlatitude synoptic disturbances. Across the Kalahari and Sahara desert regions, precipitation is inhibited by sinking motion virtually throughout the year. In contrast, the equatorial and tropical regions are characterized by heavy precipitation concentrated along the intertropical convergence zone (ITCZ). Since the movement of the ITCZ follows the position of maximum surface heating associated with the north–south displacement of the overhead position of the sun, the near equatorial regions have two rainy seasons while most of the other regions of the continent get only one distinct rainy period during the year. The climate of Africa is further modified by the presence of orography. The influence of the synoptic-scale mountain barriers is well known and it is essentially characterized by relatively drier conditions to the leeward side, while wetter climate prevails on the windward slopes of the mountains. On the contrary, the influence of continental-scale orography is not well understood, although there is evidence suggesting that large-scale orography could be playing an important role in modulating the continental climate (Semazzi 1980a,b).

In the previous sections, the eigenmode analysis of the model data indicated that the semiannual oscillation, which is primarily responsible for the seasonal advance of the rain belt in the equatorial region, is not well simulated by the model compared to the annual harmonic oscillation. Therefore, we shall confine subsequent discussion of the seasonal analysis results mainly to the winter season (DJF) and summer season.
(JJA), when the annual harmonic oscillation is dominant. Figure 10a displays the winter rainfall results for the 1950 run. In general, the corresponding features for 1973 (not shown) are similar. The model captures the basic characteristics of the observed rainfall pattern (Fig. 10b). A region of broad maxima extends across the countries of Malawi, Zaire, Zambia, and Zimbabwe in both the model and observations. The Kalahari Desert and the semiarid region surrounding it is also realistically depicted both in location and the amount. The model rainfall anomaly field, 1973 minus 1950, is presented in Fig. 11a and the corresponding difference field based on observed data in Fig. 11b. The center of the rainfall deficit in the model is located approximately 15°S and 30°W, over the Katanga plateau near the triple border region between Zaire, Angola, and Zimbabwe. Positive anomalies are centered off the coast of Africa across Madagascar. The observed rainfall deficits (Fig. 11b) are consistent with the model simulation results. However, the model may be underestimating the east–west extent of the negative rainfall anomalies.

In summer (JJA), we note three rainfall maxima situated over West Africa, Central Africa, and the "Horn" of Africa (Fig. 12a), thus consistent with the
observations (Fig. 12b). However, significant distortion is noted in the relative rainfall magnitudes. Part of this deficiency may be related to the representation of orography that is too smooth in the model. As a result, the large gradients observed in the rainfall distribution over the highlands in Cameroon cannot be resolved adequately. In this region, the terrain rises very steeply, culminating in the Adawala Plateau, which is well over 1 km in many places and in some cases exceeding 2 km. In addition to the coarse resolution, this may also be due to the simple nature of the parameterization of the physics adopted in the version of CCM1 used in this study. Furthermore, the treatment of the surface hydrology, which is essentially based on the bucket model formulation, and the use of a simple moist convective adjustment approach for incorporating the atmospheric moist convective processes are all possible factors that may account for the differences between model and observations. The observations fail to show the rainfall maxima over the Ethiopian highlands because of sparse observational network at these high altitudes. The observed Cameroon rainfall maxima, approximately 5°E and 5°N, is also very weak in the model. North of 20°N, permanent desert conditions prevail and this part of Africa is almost devoid of any measurable amount of precipitation in the observations,
which is also confirmed by the model. The model rainfall maxima over West Africa is slightly displaced to the east and the amounts over Central Africa are relatively low. Nevertheless, the model faithfully represents many of the important climate features, including the Sahara desert and the adjacent desert border climate conditions.

The simulated rainfall anomaly pattern in JJA is characterized by significant rainfall deficits over the Sahelian rainfall belt (Fig. 13a). Inspection of the digital model rainfall data shows that the region between central Sahel and the Red Sea is also covered by negative anomalies. The corresponding observed rainfall difference field, 1973 minus 1950, is shown in Fig. 13b, and we note the general presence of the negative rainfall anomalies extending across the Sahel, thus confirming the model results. The opposite phase anomalies in the Gulf of Guinea are not reproduced by the GCM. We believe that the coarse resolution of CCM1 is partly responsible for the failure to resolve the very steep gradients associated with the observed coastal rainfall anomalies.

Next we have isolated the annual cycle comprising of the combined contributions of the annual harmonic
Fig. 10. Winter (DJF) seasonal mean rainfall projected onto EOF1 through EOF4 for (a) model and (b) observations. Contour interval is 100 mm. Less than 300 mm is suppressed.

Fig. 11. Winter (DJF) seasonal mean rainfall difference, 1973 minus 1950, projected onto EOF1 through EOF4 for (a) model and (b) observations. Contour interval is 20 mm, with less than 60 mm suppressed.

oscillation and the annual mean (nonoscillating component) to determine their role in shaping the model climatic differences between 1950 and 1973. This was accomplished by suppressing all the contributing terms in the eigenmode coefficient Eq. (1) except the annual harmonic oscillation (EOF1) and the nonoscillating component corresponding to the constant term. Further, the 10-yr monthly means were obtained for the filtered data and then averaged over three special regions corresponding to the Sahel (10°–20°N, 15°W–37°E), equatorial Africa (10°S–10°N, 10°–35°E), and southern Africa (30°–15°S, 15°–35°E). The time series corresponding to the 1950, 1973, and the difference 1973 minus 1950 for each of the three special regions is displayed in Fig. 14. These results support the notion that the rainfall deficits that occurred in 1973 relative to 1950 over the Sahelian region were part of a continental-scale climate anomaly pattern that also was responsible for the negative anomalies in southern Africa.
To evaluate the statistical significance of the monthly mean differences displayed in Fig. 14 we employed the Student $t$-test. More specifically, we sought to identify the months for which the probability that the difference occurred just by chance is less than 5%. We found that the differences are highly significant during the peak months of the rainy season for the Sahelian region (Fig. 14a; June through September) and the southern sector (Fig. 14c; December through April). The differences are not significant (at the 5% level) for the equatorial

This interhemispheric synchronous concurrence of the summer rainfall deficits over the Sahel and southern Africa is consistent with reduced amplitude of the annual harmonic oscillation. These results also underscore the need for a continental view in addressing the regional seasonal climate prediction problem over Africa. It is apparent that the upstream conditions concerning the advancing seasonal rainfall anomalies, phase locked with the overhead position of the sun, could provide valuable information for seasonal climate prediction over the Sahel and southern Africa.
region and the dry seasons corresponding to the Sahel and the Southern Hemispheric region, although the phase of the corresponding anomaly signals are highly persistent with time.

Further interpretation of the combined role of the annual harmonic oscillation and the annual climatological mean components of the annual cycle was sought by examining the corresponding spatial patterns for the 1950 and 1973 GCM runs. The analysis is confined to the Northern Hemispheric summer season (JJA) when the Sahel gets most of its rainfall and the winter season (DJF) when the seasonal rains primarily reside over southern Africa. Additional analyses were also conducted for the two transitional seasons of spring and fall but the results are not presented here because of the unsatisfactory performance of CCM1 during these seasons, as noted above in section 4. Figure 15 shows the 1950, 1973, and the difference 1973 minus 1950 for the summer months of JJA. The pattern captures the salient features of the mean climate. We observe realistic representation of the desert-border regions of the Sahel and meridional rainfall gradient. The difference 1973 minus 1950 (Fig. 15c) shows a zonal strip of pronounced negative anomalies over the Sahelian region. Figures 16a–c display the corresponding filtered GCM rainfall data for the winter months of DJF. As we note in the case of the Sahel, the combined role of the annual harmonic oscillation and the annual climatological mean of the annual cycle realistically reproduce the salient features of the rainfall distribution over southern Africa.

To clarify the relative role of internal versus externally SST-forced variability, we adopted the approach recently developed by Rowell et al. (1995). The variance associated with internal variability was estimated from the following formula:

$$\sigma_{\text{INT}}^2 = \frac{1}{N(n - 1)} \sum_{i=1}^{n} \sum_{j=1}^{N} (x_{ij} - \bar{x}_i)^2, \quad (2)$$

where $i = 1$ or 2 and corresponds to the 1950-SST and 1973-SST 10-yr runs, respectively, with $N = 2$; $j = 1, \ldots, (n = 10)$ corresponds to the $j$th-year for each of the two simulations. Each 10-yr average is given by

$$\bar{x}_i = \frac{1}{n} \sum_{j=1}^{n} x_{ij}. \quad (3)$$

The variance due to the SST forcing is estimated from

$$\sigma_{\text{SST}}^2 = \frac{1}{N - 1} \sum_{i=1}^{N} (\bar{x}_i - \bar{x})^2 - \frac{1}{N(n - 1)} \sum_{i=1}^{N} \sum_{j=1}^{n} (x_{ij} - \bar{x}_i)^2. \quad (4)$$

To help in interpreting the results in context of seasonal mean rainfall we calculated the following quantities for each season of the year,
Fig. 15. GCM rainfall annual harmonic oscillation plus annual mean for the three summer months of JJA, (a) 1950 SST-forced GCM run, (b) 1973 SST-forced GCM run, and (c) difference 1973 minus 1950 GCM runs. Contour interval is 50 mm in (a) and (b). Contour interval is 20 mm in (c).

Fig. 16. GCM rainfall annual harmonic oscillation plus annual mean for the three winter months of DJF, (a) 1950 SST-forced GCM run, (b) 1973 SST-forced GCM run, and (c) difference 1973 minus 1950 GCM runs. Contour interval is 50 mm in (a) and (b). Contour interval is 20 mm in (c).
RSST \(=\sqrt{\sigma^2_{SST}}\) and RINT \(=\sqrt{\sigma^2_{INT}}\). (5)

Figures 17 and 18 show that SST-forced variability is primarily responsible for the modeled summer rainfall anomalies, 1973 minus 1950, over the Sahel and southern Africa.

6. Conclusions

We have examined the role of global SST anomaly forcing in maintaining the extreme climate conditions of Africa in 1950 and 1973. Abundant rainfall was observed in 1950 over the Sahelian zonal strip and Southern Africa. These conditions were accompanied by negative anomalies over the equatorial region of the continent. In contrast, this rainfall anomaly pattern dramatically reversed sign in 1973 and was part of prolonged severe drought conditions over the Sahel witnessed over the last three decades.

The primary research vehicle in this investigation is the standard version of the NCAR CCM1 GCM with
horizontal resolution of rhomboidal spectral truncation at wavenumber 15 (R15). Two separate 10-yr simulations based on the 1950 and 1973 SST anomalies have been performed. These two years are among the wettest and driest years of the 1950s and 1970s, respectively. The 10-yr seasonal and annual model output average fields have been compared with observations to assess the sensitivity of the African continental climate on different SST forcing. The SST dataset used in specifying the lower-boundary conditions in CCM1 is the GFDL analysis. The Sahelian rainfall data used for the comparison with the model simulations is a subset of the historical precipitation dataset archived at NCAR. The analysis of the model output and observed rainfall data were confined to the African region. EOF filtering of the model output and observed data has been used to suppress unwanted noise, and an attempt was made to characterize the differences between the 1950 and 1973 climatic conditions in terms of the most dominant annual harmonic oscillation oscillations for both the model output and observations.

CCM1 successfully simulates the primary features of the Sahelian and Southern Africa seasonal rains. We attribute this to the ability of the model to simulate the annual harmonic oscillation realistically. Over equatorial Africa, where the semiannual oscillation is observed to be relatively more important compared to the higher latitudes of the continent, the model simulation is not as successful. This arises from the deficient simulation of the semiannual harmonic oscillation by the model. Analysis of the GCM results suggest that a change in the shape of the annual cycle accounts for the synchronous anomalous climatic conditions that occurred in northern and southern Africa in 1950 and 1973.

During the summer season when the Sahelian region receives most of its rainfall, forcing due to global SST anomalies results in realistic response compared to the observations. Similar agreement between the model simulation and the observed rainfall is noted during the Northern Hemispheric winter season when the rainfall belt is centered over southern Africa. Considerable rainfall anomalies are also observed in the model results during spring and fall but exhibit less agreement with observed data due to the deficient simulation of the semiannual harmonic oscillation. Investigation of the relative role of internal variability and SST-forced variability indicates that the former dominates for both the Sahel and the southern Africa during the rain seasons of JJA and DJF, respectively.

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