Late 20th century attribution of drying trends in the Sahel from the Regional Climate Model (RegCM3)

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[1] The RegCM3 has been integrated for the period of 1960–2002 using initial and lateral boundary conditions from the NCEP re-analyses at 6-hour intervals. Greenhouse gas concentrations remain fixed and the land-use/soil properties are not altered. The RegCM3 accurately portrays a trend from wetter conditions in the 1960s to very dry conditions in the 1980s. The dry 1980s temperatures in the Sahel are approximately 3°K warmer than the wet 1960s, caused by a reduction in precipitation and clouds leading to an increase in the net absorbed solar radiation at the surface. This anomalous warming maintains the steepest meridional temperature gradient and therefore the African Easterly Jet in lower latitudes. The initiation of dry conditions starts in June and persists through July and August in the model simulations. The initiation of dry conditions appears to be related to a weaker Tropical Easterly Jet which may be linked to warmer Indian Ocean temperatures over the past several decades.
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1. Introduction

[2] Over the past three decades, there has been a concerted effort to understand the causes for a downward trend in wet season rainfall in West Africa. Observations show that the trend towards reduced seasonal rain began in the late 1960's and continued through the 1990s [*Nicholson et al.*, 2000; *Dia et al.*, 2004]. The semi-arid region known as the Sahel (10–18°N, 17.5°W–20°E) has been impacted the most causing a significant disruption to post-independence economic development.

[3] In the last few years, global climate modeling (GCM) studies using observed SSTs as boundary conditions have shed new insights on the causes of the Sahelian drying trend. In particular, GCM simulations suggest that Indian Ocean warming [*Giannini et al.*, 2003; *Bader and Latif*, 2003; *Hoerling et al.*, 2005] and Atlantic SST anomalies [*Hoerling et al.*, 2005] are responsible for the decadal trends in Sahelian rain rates. *Hoerling et al.* [2005], through an ensemble of coupled and uncoupled GCM simulations show that while the Indian Ocean warming is responsible for drying over the Guinea and Southern Sahelian region, it also produces wetter conditions over the Central and Eastern Sahelian regions. SST anomalies in the southern/northern tropical Atlantic Ocean, however, are responsible for drier conditions over the Central and Eastern Sahelian regions and wetter conditions over the Guinea/Southern Sahelian region.

[4] In this paper, we use observed SSTs and meteorological fields (1960–2002) to drive a regional climate model to determine if lateral boundary forcing is responsible for the downward trends in Sahelian rain. The objectives of this study are: (1) to compare simulated summer season (JJA) Sahelian precipitation anomalies to observed values over the last 4 decades, (2) to examine potential feedbacks on a regional scale especially during dry years and, (3) to determine the linkages between the African Easterly Jet (AEJ), Tropical Easterly Jet (TEJ) and precipitation anomalies.

2. Model Description and Experiment

[5] The Regional Climate Model version 3 (RegCM3) is used to simulate the regional climate of West Africa using meteorological boundary conditions from the National Center for Environmental Prediction (NCEP) Reanalysis for the period of 1960–2002. The RegCM3 [*Giorgi et al.*, 1993] is a sigma-coordinate limited area model that has been used over the last decade for a number of climate related studies.

[6] In this simulation a horizontal grid spacing of 60 km is assumed, with 14 vertical levels, and the center of the grid is located at (14°N, 2°E) with 52 north-south points and 88 east-west points. This creates a domain from approximately 0.5–27°N, 25°W–22°E and the top of the model is at 100 hPa. The NCEP boundary conditions are updated 4 times a day through the 43-year period, while observed monthly SSTs were obtained from the UK Meteorological Office for the same period. The model simulation is initiated on January 1st, 1960 and ends on December 31st 2002. Observed monthly precipitation and temperatures at $0.5° \times 0.5°$ [*New et al.*, 2000] are compared to the RegCM3 simulations.

3. Results

[7] Figures 1a–1c show observed June, July, and August Sahelian precipitation anomalies based on 1961–1990 means. The observations show wetter conditions during the 1960s during each month with a shift to drier conditions after the 1970. The largest negative precipitation anomalies are found during August (Figure 1c) in agreement with *Dennett et al.* [1985] and *Nicholson et al.* [2000]. Observed positive precipitation anomalies return after 1988, however, dry conditions still exist during the 1990s. The RegCM3

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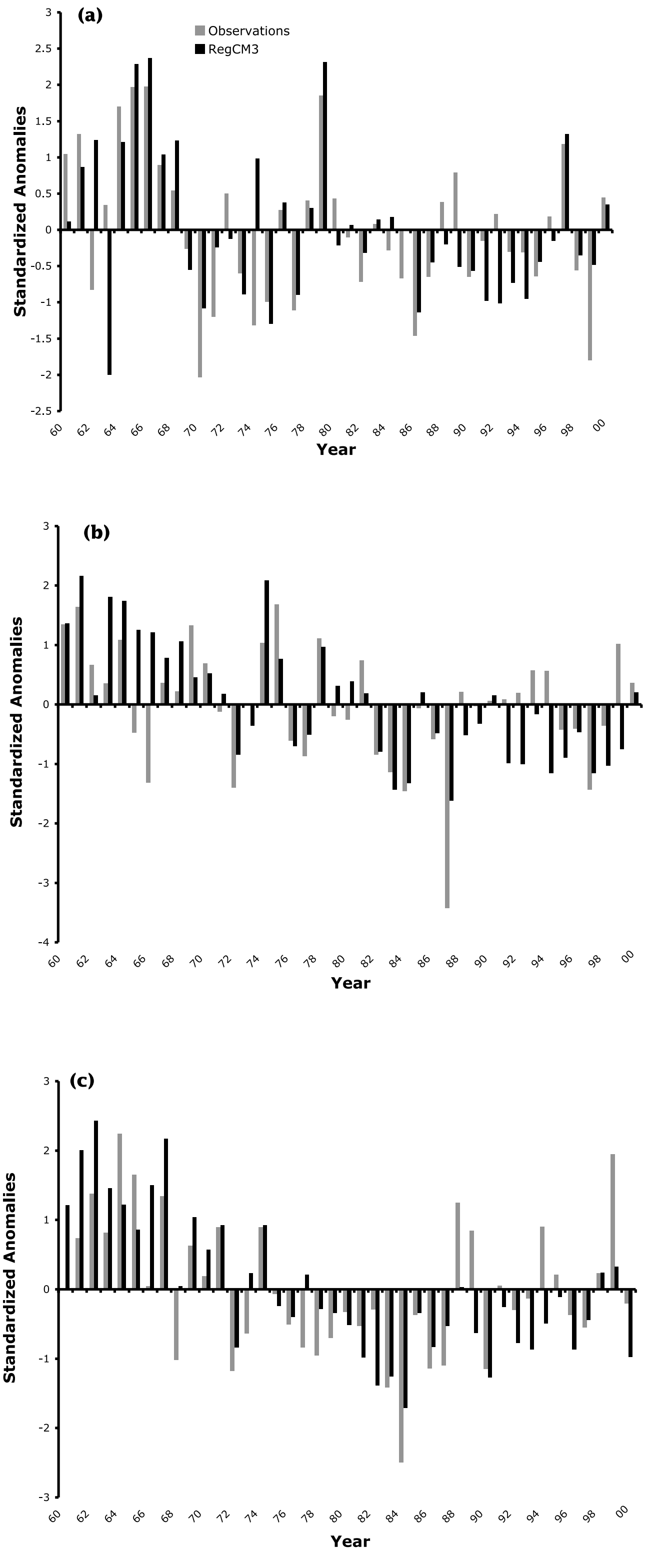

Figure 1. 1960–2000 (a) June, (b) July and (c) August precipitation anomalies from observations (gray) and the RegCM3 (black) for the Sahel (10–18°N–17°W–10°E).

also shows a shift to drier conditions beginning in 1970 with approximately 20 years of negative precipitation anomalies beginning in 1980 (Figures 1a–1c). The correlation between the observed and RegCM3 Sahelian JJA precipitation anomalies is 0.69 for 1960–1990.

[8] During anomalously dry seasons in West Africa, observational studies show that that the TEJ is weakened and that the AEJ is located in lower latitudes [*Kidson*, 1977; *Newell and Kidson*, 1984; *Grist and Nicholson*, 2001]. Figure 2a–2c shows a weakening trend in the magnitude of the simulated TEJ (located between 6–8°N) over the period of 1960–2002 during June, July and August. During the 1960s TEJ winds are stronger during each month but a transition to a weaker TEJ occurs after the 1970s and is consistent with observations over the Bay of Bengal [*Rao et al.*, 2004]. Even though the TEJ strength is stronger in the 1990s through 2002, these winds are considerably weaker when compared to the 1960s when there were wetter conditions in the Sahel. Figures 2d–2f also show a trend for the simulated AEJ to be located in lower latitudes during June, July and August lower latitudes after the 1970s. The poleward migration of the AEJ to higher latitudes between the months of June and July is very small, especially during the period of 1980–1987. Although the AEJ position is at higher latitudes during 1990s, the position is still found at lower latitudes (3–4°) when compared to the 1960s. Hence, the RegCM3 results for a weaker TEJ and more equatorward AEJ are in concert with observational studies. Because the AEJ is found above the steepest meridional temperature gradient [*Cook*, 1999], it suggests that

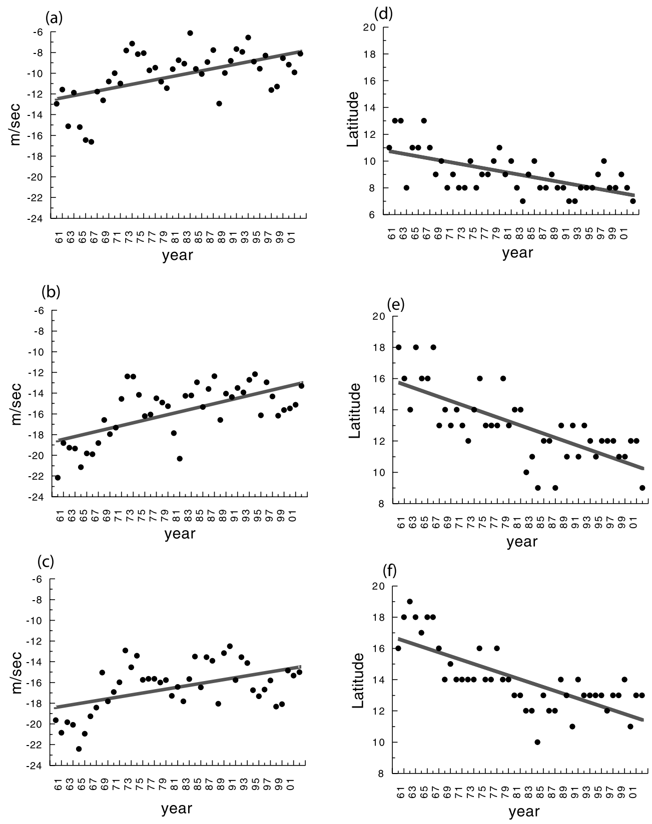

Figure 2. 1960–2002 (a) June, (b) July and, (c) RegCM3 August Tropical Easterly Jet wind speeds (m-s^{-1}) between latitudes of 6–8°N. 1960–2002 (d) June, (e) July and, (f) August RegCM3 African Easterly Jet position (latitude).

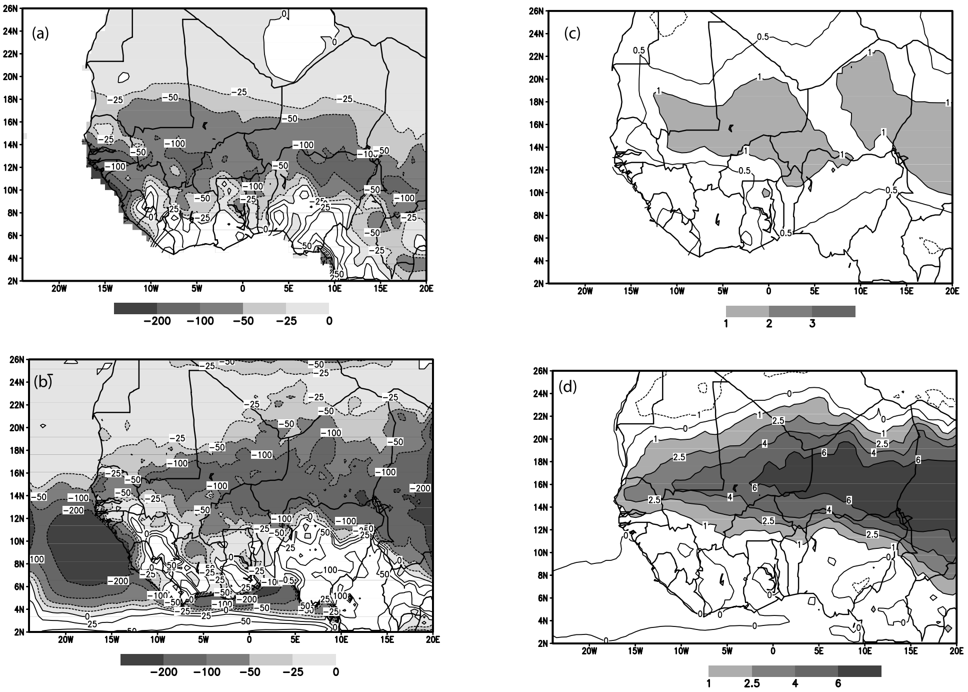

Figure 3. RegCM3 August 1980–87 minus 1960–67 (a) precipitation amount (obs), (b) precipitation amount (RegCM3), (c) temperature difference (obs), (d) temperature difference (RegCM3).

this gradient was found in the lower latitudes after the 1960s.

[9] Next we compare the simulated wet 1960s to the dry 1980s by examining August 1960–67 and 1980–87. During August, the Sahel receives the highest rain rates and is the month with the largest observed negative precipitation anomalies. Figures 3a and 3b show that the observed and simulated precipitation differences have a similar pattern with dry conditions in the Sahel and wetter conditions in the Guinea region. The intensity of drier/wetter august conditions is larger in the RegCM3 relative to the observations. The drier conditions during the 1980s are associated with an observed warming in the Sahel of 1–2°C during August (Figure 3c). The observed warming is most likely associated with a decrease in precipitation and cloud cover leading to an increase in incident solar radiation at the surface. The simulated RegCM3 temperature change is much larger than the observed values, especially in the Sahel region, where up to 6°C temperature increases are found (Figure 3d).

[10] Table 1 shows that reduction in precipitation and the subsequent warming (3°K) in the Sahel during the 1980s is associated with a significant increase (55 W-m^{-2}) in absorbed solar radiation at the surface. There is also a large increase in sensible heat and a reduction in latent heat during the 1980s when compared to 1960s. The simulated AEJ located near 12° in August during 1980–87 but 17.5° during 1960–67 and the TEJ is weaker by 4–5 m-s^{-1} when comparing the two periods.

4. Discussion and Conclusion

[11] In this paper, the RegCM3 has been forced at the lateral boundaries by NCEP reanalysis at 6-hour intervals for the period of 1960–2002. The results show a trend toward drier conditions over the Sahel beginning in the late 1960s. The results also show the trend towards a weaker TEJ and AEJ that is located in lower latitudes beginning in the late 1960s. Although there is an indication of smaller precipitation anomalies in the 1990s, the magnitude of the TEJ and the location of the AEJ have not returned to the pre-1970 strength and location. The results are in line with studies by *Giannini et al.* [2003], *Bader and Latif* [2003] and *Hoerling et al.* [2005] and imply that forcing outside of West Africa is responsible for the trend towards lower rain rates.

[12] Because the regional model is forced by meteorological data, the forcing that is responsible for drying in West Africa is most likely in the wind field. This makes upstream conditions the likely source that is responsible for the trend towards lower rain rates. In particular, warmer ocean conditions over the tropical Indian Oceans may be directly or indirectly responsible for a weaker TEJ. In West Africa a weaker TEJ translates to more westerly shear and potentially more (less) tropospheric convergence (divergence) as suggested by *Janicot et al.* [1996] and *Janicot* [1997] during ENSO years. Such conditions provide a more

Table 1. Comparison of Simulated Wet Period (1960–67) to Dry Period (1980–87) and Model Climatology (1961–1990)

Variable	1960–67	1980–87	1961–1990
Rain rates, mm-d^{-1}	6.5	3.9	5.0
Absorbed solar, W/m^{-2}	173.1	228.3	209.4
TS2, degree K	297.0	300.1	298.8
Sensible heat, W/m^{-2}	40.5	79.1	63.7
Latent heat, W/m^{-2}	104.2	87.0	96.6
Position of AEJ, latitude	17.5	12.1	14.4
TEJ magnitude, m-s^{-1}	−20.2	−15.6	−16.2

hostile environment for long-lived westward propagating mesoscale convective systems (MCSs – Squall lines, mesoscale convective complexes and non-squall tropical clusters) as they cross West Africa. The RegCM3 simulation suggests such a relationship may exists as the correlations between the TEJ and Sahelian precipitation anomalies for June, July and August are (−0.65), (−0.68) and (−0.70). Hence a weaker TEJ is associated with negative precipitation anomalies and a stronger TEJ is associated with positive precipitation anomalies.

[13] An even stronger relationship exists between the location of the AEJ and Sahelian precipitation anomalies in June, July and August. In this case the June, July and August correlations are (0.77), (0.86) and (0.90) between the location of the AEJ and Sahelian precipitation anomalies. This is plausible, given that most of the precipitation in West Africa is associated with MCSs [*D'Amato and Lebel*, 1998], which are organized along the AEJ [*Mathon and Laurent*, 2001]. Thus, an AEJ in lower latitudes would increase MCSs in lower latitudes and the Sahelian region would be drier than normal.

[14] While the simulated decadal trends toward lower Sahelian rain rates have been found, the RegCM3 can also provide a framework for the initiation of dry conditions in West Africa. We propose, based on the RegCM3 simulation, that a weakened TEJ during June and July would lead to reduction in precipitation amounts due to westerly shear or enhanced upper tropospheric convergence. The reduction in precipitation would reduce clouds and increase incident solar radiation thereby warming surface temperatures. Anomalously, warmer surface temperatures would confine the steepest meridional temperature gradient and therefore the AEJ to lower latitudes. These conditions would set the stage for very dry August conditions in the Sahel.

[15] While some GCM simulations suggest that the 21st century may be wetter over the Sahelian region [*Kamga et al.*, 2005; *Hoerling et al.*, 2005], uncertainty exists because: (a) the relationship between Indian Ocean warming and TEJ strength is unclear, (b) GCM biases exist over West Africa that may influence future scenarios [*Jenkins et al.*, 2002; *Jenkins and Mikovitz*, 2003; *Cook and Vizy*, 2005], (c) land-use change and degradation can and will likely influence the surface meridional temperature gradient in West Africa and therefore the position/strength of the AEJ and, (4) nonlinear feedbacks may exists within the West African climate system.

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