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Ecosystem Dynamics and the Sahel Drought

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Abstract. The Sahel region in West Africa has been experiencing a persistent drought throughout the last three decades. Here, we present a new perspective on the underlying physical mechanism behind this phenomenon. We use a coupled biosphere-atmosphere model including explicit representation of ecosystem dynamics to demonstrate that, regardless of the nature of the initial forcing, the natural response of the local grass ecosystem to the dry conditions of the late 1960s played a critical role in maintaining the drought through the following decades. The onset of the drought has been marked by a forced shift from a self-sustaining wet climate equilibrium to a similarly self-sustaining but dry climate equilibrium.

Introduction The Sahel region (10°N-17.5°N, 15°W-15°E) has experienced a severe and persistent drought since the late 1960s. There are two general theories on the physical mechanism behind this drought. The first theory suggests that intense human activities have resulted in a sustained change in land cover at the regional scale and caused the drought conditions. Several modeling studies (e.g., Charney *et al.*, 1977; Sud and Molod, 1988; Xue and Shukla, 1993; Zheng and Eltahir, 1997) have demonstrated that the rainfall distribution over Sahel is sensitive to changes in land use and land cover. The second theory suggests that the observed shifts in the regional and global patterns of sea surface temperature (SST) distributions have modified the atmospheric circulations over West Africa and favored the development of the drought conditions. This theory has been supported by many empirical and modeling studies (e.g., Lough, 1986; Rowell *et al.*, 1995; Ward, 1998; Zheng *et al.*, 1999). However, both groups of studies focused exclusively on the response of the atmospheric processes to changes in the lower boundary conditions. Thus, both theories neglect most of the two-way biosphere-atmosphere-ocean interactions that are vital for the working of the climate system.

Here, we present a different approach to the study of the Sahel drought by emphasizing the role of the two-way biosphere-atmosphere interactions using a zonally symmetric, synchronously coupled biosphere-atmosphere model (ZonalBAM) (Wang and Eltahir, 1999a). With explicit representation of ecosystem dynamics, the model considers the full cycle of the biosphere-atmosphere feedback: atmospheric conditions regulate the vegetation growth and competition, and the resulting state of the biosphere dictates the lower boundary conditions for the atmosphere. Several studies (e.g., Kutzbach *et al.*, 1996; Claussen *et al.*, 1999) on the paleoclimate of West Africa have concluded that ecosystem dynamics played a critical role in the dynamics of the major climatic shifts in the past. This report argues for a similar important role for ecosystem dynamics in the modern climate of this region.

Model Description and Application ZonalBAM combines a zonally symmetric atmospheric model and a fully dynamic biospheric model. The atmospheric model includes representation of atmospheric dynamics, a radiation scheme, a moist convection scheme, a boundary layer scheme, and a cloud parameterization scheme. The biospheric model uses IBIS (Foley *et al.*, 1996), which integrates a wide range of terrestrial phenomena, including the biophysical, physiological, and ecosystem dynamical processes, into a single, physically consistent simulator. The full model has been carefully validated using observations and has been used in several previous studies (Wang and Eltahir, 1999a,b,c,d).

The land-ocean boundary in the model is set at 6°N, with land in the north and ocean in the south. Over the ocean, SST is prescribed, but varies with time as observed (Parker and Horton, 1999). Here we use the SST average between 10°W and 10°E. Over land, terrestrial processes are simulated by the biospheric model IBIS. Different from previous studies, here we divide each grid cell into two parts: vegetation is static over the area of fraction f and is dynamic over the area of fraction $(1-f)$. The fraction with static vegetation represents the managed landscape where vegetation is prescribed according to land use conditions; the fraction with dynamic vegetation represents the natural landscape where vegetation is updated yearly based on the simulated carbon budget and allocation. Here the division of the grid cell is limited to the surface, and we assume that the two areas are subjected to the same meteorological forcing. Fluxes from the land surface to the atmosphere use the area-weighted averages of the two parts. The fraction of managed landscape f may increase with time to simulate the progressive impact of human activities. Vegetation over the managed fraction of each grid cell is specified according to the type

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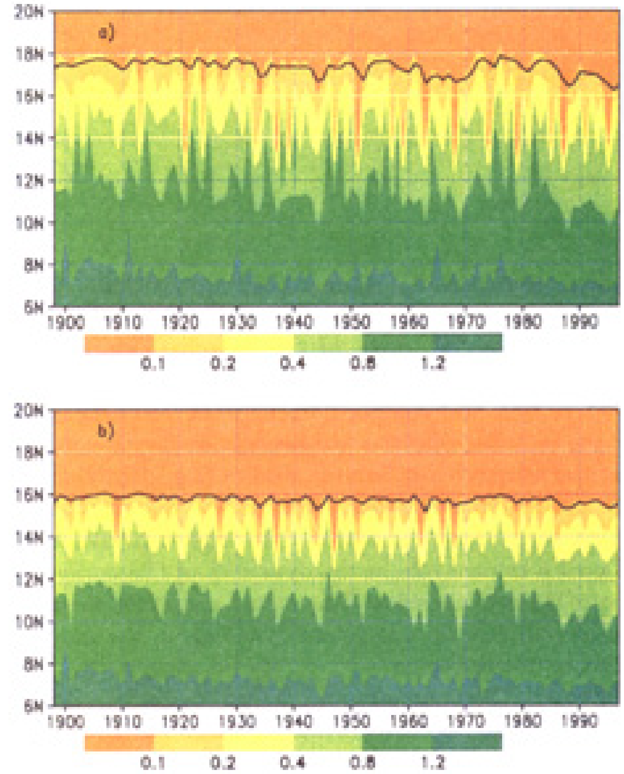

Figure 1. Net primary productivity (NPP, in $kgC/m^2/year$) during the period 1898-1997 for the two equilibria of the simulated natural climate system over West Africa: (A) the wet equilibrium; (B) the dry equilibrium. The isohyets of the 200-mm annual rainfall (red lines) are used to approximately mark the desert border. The only difference between the two simulations is that the density of the initial vegetation over the Sahel region in simulation B is 80% less than in simulation A. No human activity is considered.

of human activities. For example, when desertification is considered, the managed fraction features bare soil; when deforestation is considered, it features grassland.

Using ZonalBAM, Wang and Eltahir (1999b,d) documented that the natural biosphere-atmosphere system in West Africa is intransitive (Lorenz, 1976, 1990). Depending on the initial conditions, two distinct and stable statistical equilibria are viable in the twentieth century (Wand and Eltahir, 1999d), as shown in Fig. 1. The wet climate equilibrium features a desert border at around 17.5°N compared to 16°N for the dry equilibrium. The Sahel region is significantly wetter at the wet equilibrium than the dry equilibrium. Comparison with rainfall observations (Hulme, 1995) suggests that conditions in the Sahel before the onset of the drought were in general similar to those of the wet equilibrium, while current conditions are somewhat similar to those of the dry equilibrium. It appears that the current drought is associated with a climate transition from the wet equilibrium to the dry equilibrium. In the following we explore the potential mechanisms for causing such a transition around the time of the drought onset.

Drought Initiation by Human Activities Here we consider the scenario that human activities provided a triggering mechanism that is significant enough to cause a climate transition and hence to account for the drought. This hypothesis is explored by performing a set of numerical experiments on man-made desertification using ZonalBAM: Control ($f = 0$); Desertification ($f > 0$) experiments; Control without ecosystem dynamics; Desertification experiments without ecosystem dynamics. In the desertification experiments, we assume that the fraction f of the bare soil exposure over the Sahel grassland region linearly increases from 0 in 1950 to f_{max} in 1970 and stays constant afterwards, where f_{max} varies for different sensitivity experiments. No man-induced desert expansion after 1970 is considered because there was no systematic increase of grazing population (Warren, 1996). Our experiments suggest that, when ecosystem dynamics is included, an f_{max} of 20%, i.e., a slow man-made desertification at a rate of about 1% per year during the two decades preceding the drought onset, is sufficient to induce a transition of the regional climate system from the wet equilibrium to the dry equilibrium (Fig. 2 a,c,d). Here 20% is the threshold value for inducing the wet-to-dry climate transition (according to experiments not shown). Such a transition takes place in the form of a severe persistent drought, which causes the expansion of the Sahara desert: the grassland near the desert border before the drought onset is transformed to desert afterwards (Fig. 2c,d). It is important to note that, without ecosystem dynamics, the imposed change in land cover only results in a minor reduction of rainfall without causing any climate transition (Fig. 2b). Thus, we conclude that the simulated drought conditions are primarily caused by the feedback involving the response of the natural ecosystem to the imposed change in land cover. When the initial damage of the ecosystem due to land use change reaches a certain threshold, the atmospheric climate starts to change significantly leading to deterioration of the other healthy sections of the natural grass ecosystem. This response adds to the natural response of the system to the observed oceanic forcing during the late 1960s and early 1970s to cause a significant drought in the following decades.

Drought Initiation by SST Forcings The potential role of SST variability as a triggering mechanism for the drought is explored in a separate set of numerical experiments: Control; SST perturbation experiments; Control without ecosystem dynamics; SST perturbation experiments without ecosystem dynamics. The control simulations are the same as those in the previous section. Due to its zonal symmetry, the model cannot represent the global-scale oceanic forcings which have significant impact on the Sahel rainfall. Here in the SST perturbation experiments, we impose a uniform SST warming sustained for 4 years (1968-1971) over the Atlantic ocean as a surrogate for the observed warming in the southern hemisphere oceans in association with a

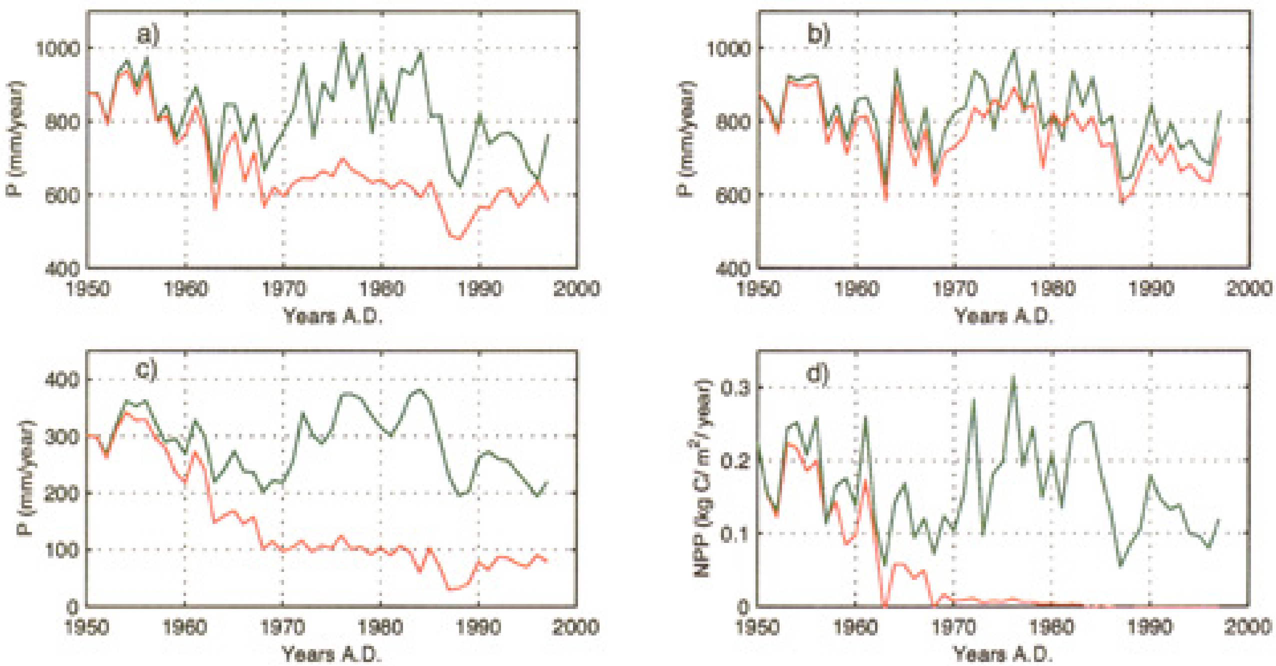

Figure 2. Drought initiation by desertification. (A) Rainfall average over the Sahel region, in the control (green) and desertification (red) experiments; (B) Similar to (A), but without ecosystem dynamics; (C) Rainfall at a grid point near 16°N, in the control (green) and desertification (red) experiments presented in (A); (D) Similar to (C), but for net primary productivity (NPP). All the experiments are carried out by driving the coupled model with the observed SST variations during the period 1950-1997. The desertification experiment assumes a desertification rate of 1% per year from 1950 to 1970. After 1970, the fraction of bare soil is constant (20%).

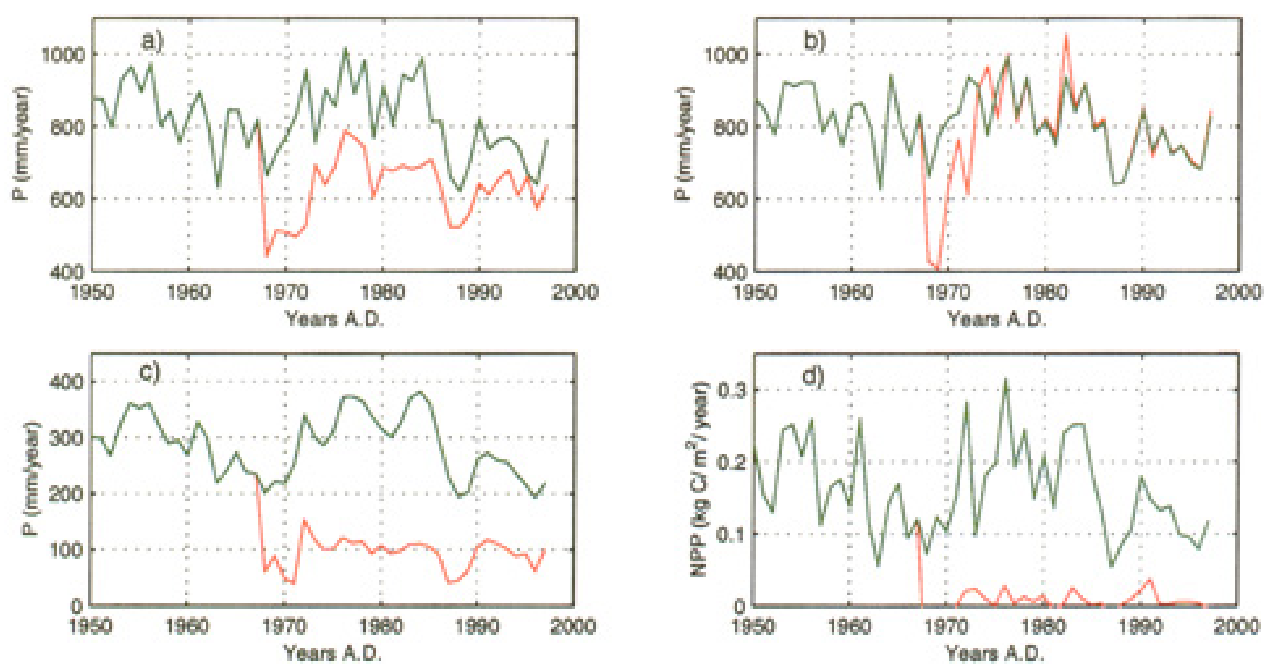

Figure 3. Drought initiation by SST warming. (A) Rainfall average over the Sahel region, in the control (green) and SST perturbation (red) experiments; (B) Similar to (A), but without ecosystem dynamics; (C) Rainfall at a grid point near 16°N, in the control (green) and SST perturbation (red) experiments presented in (A); (D) Similar to (C), but for net primary productivity (NPP). The control experiment uses observed SST variations during 1950-1997. In the SST perturbation experiment, an extra warming of 2.5° is uniformly imposed for the period 1968-1971.

documented shift of the inter-hemispheric distributions of SST and surface pressure. Previous studies (Rowell *et al*, 1995; Ward, 1998) have emphasized the potential impact of this shift on the Sahel rainfall, since it took place around the time of the drought onset. According to our experiments, a uniform warming of 2.5°C during 1968-1971 is indeed sufficient to trigger a transition of the regional climate system from the wet climate equilibrium to the dry climate equilibrium, thus resulting in a significant drought over the Sahel (Fig. 3a,c,d). This magnitude of the SST perturbation stated above represents a threshold for causing such a climate transition (according to experiments not shown). Similar to the case of the changes in land cover, when the SST forcing reaches a certain threshold, the response of the atmospheric climate becomes significant enough to cause a change in the natural ecosystem, which then works in the same direction as the initial forcing in changing the regional climate. The dynamic response of the biosphere is indeed critical for achieving the simulated transition from the wet equilibrium to the dry equilibrium, and for simulating a severe and persistent drought in the following decades. Without ecosystem dynamics, the regional climate system can quickly recover after the termination of the SST anomaly, as shown in Fig.3b.

Conclusions The most likely scenario for the triggering mechanism of the Sahel drought would involve a combination of several processes including regional changes in land cover as well as changes in the patterns of global and regional SST distributions. Here we identify the response of the natural ecosystem to the initial external forcing as the critical process for explaining the severity and persistence of the observed drought. Regardless of the triggering mechanism, the natural response of the grass ecosystem near the desert border to the dry conditions of the late 1960s seems to have played a significant role in the dynamics of the drought. The intransitiveness of the regional climate system over West Africa provides the theoretical basis for the special role of the biosphere in the modern and past climates of this region (Claussen *et al.*, 1999; Betts, 1999; Wang and Eltahir, 1999b,d).

The findings of this study suggest that climate prediction, at least in West Africa, should be treated as an initial value problem (Pielke, 1998), thus challenging the general traditional view of climate as a boundary value problem. In the context of this modeling study, initial conditions, during the early 1900s (Fig. 1) or the late 1960s (Fig. 2 and 3), clearly play a significant role in dictating future climate equilibrium.

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