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Decadal variability of rainfall in the Sahel: results from the coupled GENESIS-IBIS atmosphere-biosphere model

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Abstract In this study we investigate the impact of large-scale oceanic forcing and local vegetation feedback on the variability of the Sahel rainfall using a global biosphere-atmosphere model, the coupled GENESIS-IBIS model, running at two different resolutions. The observed global sea surface temperature in the twentieth century is used as the primary model forcing. Using this coupled global model, we experiment on treating vegetation as a static boundary condition and as a dynamic component of the Earth climate system. When vegetation is dynamic, the R30-resolution model realistically reproduces the multi-decadal scale fluctuation of rainfall in the Sahel region; keeping vegetation static in the same model results in a rainfall regime characterized by fluctuations at much shorter time scales, indicating that vegetation dynamics act as a mechanism for persistence of the regional climate. Even when vegetation dynamics is included, the R15 model fails to capture the main characteristics of the long-term rainfall variability due to the exaggerated atmospheric internal variability in the coarse resolution model. Regardless how vegetation is treated and what model resolution is used, conditions in the last three decades of the twentieth century are always drier than normal in the Sahel, suggesting that global oceanic forcing during that period favors the occurrence of a drought. Vegetation dynamics is found to enhance the severity of this drought. However, with both the observed global SST forcing and feedback from dynamic vegetation in the model, the simulated drought is still not as persistent as that observed. This indicates that anthropogenic land cover changes, a mechanism missing in the model, may have contributed to the occurrence of the twentieth century drought in the Sahel.

1 Introduction

Over the Sahel region of Africa, both instrumental measurements and proxy data from the past several centuries indicate that regional rainfall patterns are dominated by low frequency variability (e.g., Farmer and Wigley 1985; Nicholson and Entekhabi 1986). Dry and wet spells, each lasting for multiple decades, tend to alternate over this region. The most recent example is the occurrence of the major drought in the last three decades of the twentieth century, which caused extreme hardship for people in the region.

A significant amount of research effort has been devoted to investigate possible causes of the twentieth century Sahel drought, including the impact of regional and global sea surface temperature (SST) anomalies (e.g., Folland et al. 1991; Rowell et al. 1995; Ward 1998; Giannini et al. 2003) and that of anthropogenic land use/land cover changes (e.g., Charney 1975; Charney et al. 1977; Xue 1997; Zheng and Eltahir 1997; Clark et al. 2001; Taylor et al. 2002). Less studied, however, are the mechanism(s) that *sustain* a dry or wet episode for several decades when such an event does initially occur. Such mechanism(s) do seem to exist since all the plausible causes of the twentieth century drought are not as

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persistent or long-lasting as the drought itself was, as reviewed by Foley et al. (2003). In order to understand the long-term variability and possible future changes of the regional climate of the Sahel region, the mechanism(s) responsible for the strong persistence of wet and dry periods have to be understood first.

In a pioneering study, Charney (1975) proposed that the positive bio-geophysical feedback induced by desertification may provide a mechanism for the persistence of drought conditions in the Sahel. This hypothesis was corroborated by Claussen's (1997, 1998) studies using a global atmosphere-biome model that demonstrated two solutions of the atmosphere-biome system, each representing a persistent climate regime. Differences between these two solutions in the atmospheric state and biome distribution over Sahel support Charney's (1975) notion of bio-geophysical feedback through albedo enhancement as a mechanism of climate persistence. However, the biome model used in Claussen's (1997, 98) studies is static and does not account for the transient vegetation dynamics. Recently, a set of reduced-form climate models, simpler than comprehensive general circulation models (GCMs), has been used to investigate the mechanism of climate persistence in the Sahel region (Zeng et al. 1999; Wang and Eltahir 2000a). Compared with GCMs, these models simplify the representation of all or some components of the Earth's climate system, but consider the impact of two-way feedback between different components, between the atmosphere and the dynamically evolving vegetation in particular. Representation of vegetation dynamics is therefore included in these reduced-form climate models.

Zeng et al. (1999), using a quasi-equilibrium tropical circulation model (QTCM) that includes a simple land surface parametrization, found that changes in SST patterns could have initiated the recent Sahel drought, but feedbacks between atmosphere and vegetation cover are largely responsible for the severity and persistence of the drought. Wang and Eltahir (2000a), using a zonally symmetric coupled biosphere-atmosphere model (ZonalBAM) that includes a fully dynamic ecosystem model, examined the rainfall variability during the entire twentieth century in the Sahel. They concluded similarly that vegetation dynamics enhance the low-frequency variability of the Sahelian rainfall while suppressing the high-frequency variability. Only when vegetation feedback is included can ZonalBAM reproduce the full spectrum of observed rainfall variance in the Sahel. In a further study, considering the suggested existence of two distinct climate regimes in the Sahel region (Claussen 1998; Brovkin et al. 1998; Wang and Eltahir 2000d), Wang and Eltahir (2000b) demonstrated that vegetation feedback can enhance a SST or desertification-triggered dry event into a persistent climate anomaly, causing the regional climate to evolve into its alternative regime. These studies all pointed to the important role of vegetation dynamics as a mechanism that provides the multi-decadal persistence of regional climate.

Simple models such as QTCM and ZonalBAM provide excellent tools for exploring the feedbacks between vegetation and the rest of the climate system, but are often criticized as being less accurate representations of the climate system than comprehensive general circulation models. For example, QTCM exploits the constraints placed on the atmospheric flow by convective parametrization with quasi-equilibrium thermodynamic closure, an approximation aimed at the tropical convective zones. In extending the model domain beyond the tropics, a sponge boundary is applied outside 45° latitudes in QTCM, which leaves the interaction of tropical processes with mid-latitudes suspect; and the parametrization for the temporal variation of vegetation cover in the model is kept very simple (Neelin and Zeng 2000; Zeng et al. 2000). Although ZonalBAM uses a sophisticated dynamic vegetation model the Integrated Biosphere Simulator (IBIS) (Foley et al. 1996; Kucharik et al. 2000), its atmosphere model suffers even more limitations than QTCM, and is not able to account for the impact of easterly waves and mid-latitude eddies due to the zonal symmetry assumption (Wang and Eltahir 2000c). Studies using these simplified models have left unanswered the critical question of whether atmosphere-vegetation feedback can still sustain the decadal persistence of rainfall anomalies when the regional climate is subject to the impact of zonal disturbances and of realistic interactions with mid-latitudes.

In this study, we address the question identified above using a comprehensive atmospheric general circulation model (AGCM) coupled with the dynamic global vegetation model. Section 2 briefly describes the model and methodology applied; Sect. 3 presents the key results of this study; conclusions and discussion are in Sect. 4.

2 Model and methodology

The research tool used here is the coupled GENESIS-IBIS atmosphere-biosphere model (Foley et al. 1998), which consists of version 2 of the GENESIS (Global ENvironmental and Ecological Simulation of Interactive Systems) AGCM and version 1 of the IBIS dynamic global vegetation model. GENESIS simulates the physics and dynamics of the atmosphere, while IBIS predicts transient changes in vegetation structure based on carbon balance and competition among plants within terrestrial ecosystems. The two models are synchronously coupled through a common treatment of land surface and eco-physiological processes, which governs the energy, mass (including water and carbon), and momentum flux exchanges between land system (including vegetation and soil) and the overlying atmosphere.

The GENESIS AGCM is a spectral model. It was developed at the National Center for Atmospheric Research (NCAR) for use in greenhouse gas and palaeoclimatic studies. An earlier version of the model (version 1.02) has been described in Thompson and Pollard (1995a, b) and Pollard and Thompson (1994, 1995). The primary improvements in version 2 and the model's present-day climate are documented in Thompson and Pollard (1997).

IBIS (version 1) is designed around a hierarchical modeling framework (Foley et al. 1996), in which information flows between various subsystems at appropriate frequencies. IBIS simulates land surface and physiological processes operating at a sub-hour time step; phenological behavior of leaf display and plant activity in response to changing climatic conditions at the daily time scale; and transient changes in carbon balance and vegetation structure at the annual time scale that result from changes in primary productivity, competition, carbon allocation, carbon turnover, and mortality. If needed, the transient vegetation structure changes can be turned off so that IBIS functions as a sophisticated land surface model with a static vegetation state.

Vegetation in IBIS is represented by a combination of different plant functional types, which are defined based on physiognomy (trees or grass), leaf form (broadleaf or needle-leaf), leaf longevity (evergreen or deciduous), and photosynthetic pathway (C_3 or C_4). Vegetation canopy is divided into two layers, woody plants in the upper layer and herbaceous plants in the lower layer, and the rooting depth differs between plants in different canopy layers. There are six soil layers in the root zone, which total up to 4 m. IBIS explicitly solves the exchange of water vapor, energy, carbon dioxide, and momentum between the ground and vegetation, between the two vegetation layers, and between vegetation and the atmosphere, as well as the water and energy exchanges between different soil layers. Further details about IBIS can be found in Foley et al. (1996) and Kucharik et al. (2000).

In this study, we operate the coupled model at both the R15 (approximately 4.5° in latitudinal direction and 7.5° in zonal direction) and R30 (2.25° in latitudinal direction and 3.75° in zonal direction) spectral resolutions, with the GENESIS AGCM and IBIS running on the same grid cells. The time step is 30 min in the R15 model and 20 min in the R30 model. While GENESIS has been previously coupled to a variety of ocean models, in this study we prescribe sea surface temperatures based on observations and using the UK Meteorological Office monthly SST data (Parker et al. 1995; Rayner et al. 1996).

The performance of the coupled GENESIS-IBIS model at the R15 resolution was documented by Foley et al. (1998). When the global sea surface temperature is prescribed based on climatology, the model at R15 resolution reproduces with reasonable accuracy the main features of global precipitation, temperature, and vegetation distribution, although some regional biases do exist. Specifically, comparing the coupled model with observations identifies a warm bias in the high northern latitudes, a cold bias over the Himalayas, central South America, and north-central Africa, underestimation of precipitation over South America, equatorial Africa and Indonesia, and overestimation of precipitation in northern Africa and China. Despite these local differences, the reasonable resemblance of the model climate to observed climate at the global scale indicates that the GENESIS-IBIS model is an appropriate tool for studies of the present-day climate at the least. In fact, the model has been used to study the climates of the Last Glacial Maximum (Levis et al. 1999a), the middle-Holocene (Doherty et al. 2000), the present (Levis et al. 1999b), and the future (Levis et al. 2000).

In this study we use the coupled model to investigate the role of biosphere-atmosphere feedback as a mechanism for the decadal variability of rainfall over the African Sahel region. With global SST prescribed to its 1950–1979 climatology, a 90-year integration of the coupled GENESIS-IBIS model is carried out first (labeled as "Spinup"), in order for the atmospheric climate and vegetation to reach an equilibrium state. Conditions at this equilibrium state will then be used for the initialization of a set of experiments that are designed to separate the impact on the Sahelian rainfall variability of global SST forcing and vegetation-atmosphere interactions. Subsequent model experiments are based on century-long simulations with SST varying as observed from January 1898 to December 1997. This period was chosen as a result of data availability at the time when these experiments were first planned.

In the main type of experiments (labeled as "Veg_Dynamic"), the coupled GENESIS-IBIS model is used in its full form, with vegetation being treated as a fully dynamic component of the climate system and vegetation-atmosphere interactions being active at all time scales; in the secondary type of experiments (labeled as "Veg_Static"), vegetation is treated as a static boundary condition, with seasonal variation but without year-to-year vegetation cover changes. Vegetation state in the Veg_Static experiments is prescribed according to the equilibrium state obtained from the Spinup simulation. Climate variability simulated in Veg_Static quantifies the response of the atmosphere alone to the inter-annual variation of global SST distribution; that simulated in Veg_Dynamic results from the response of the coupled vegetation-atmosphere system to SST variations. As such, differences between the two are attributed to the impact of vegetation cover dynamics.

Due to the long time scale of vegetation dynamics, numerical experiments tackling the issue of dynamic biosphere-atmosphere interactions are computationally expensive. It is therefore often appealing to opt for the coarse resolution approach. However, the question one has to address is how quality of the simulations is degraded by the use of coarse resolutions. In this study, all experiments are carried out at two different resolutions, the coarse R15 resolution and the medium R30 resolution, in order to illustrate the impact of model resolution on our study.

3 Results

After the first 60 years of integration in the Spinup simulations, further spin up reveals no identifiable trend in the model climate. Therefore, the last 30 years of the 90-year Spinup simulation is used to define the equilibrium state of the coupled biosphere-atmosphere system. Figure 1a–d presents the precipitation characteristics, including the mean and standard deviation of annual precipitation, based on the last 30 years of the 90-year Spinup integration using models at two different resolutions. For comparison with observations, the mean and standard deviation of annual precipitation over land based on the CRU climate data for the period of 1901–1995 (New et al. 2000) are presented in Fig. 1e, f. It is important to note however that, due to limited data availability in our study domain the Sahel region, precipitation statistics based on the CRU data should be viewed with caution.

When the coupled GENESIS-IBIS model is run at the medium resolution (R30), its mean climate is generally similar to that of the coarse resolution model (R15) (Fig. 1a versus. 1c). Most of the model biases

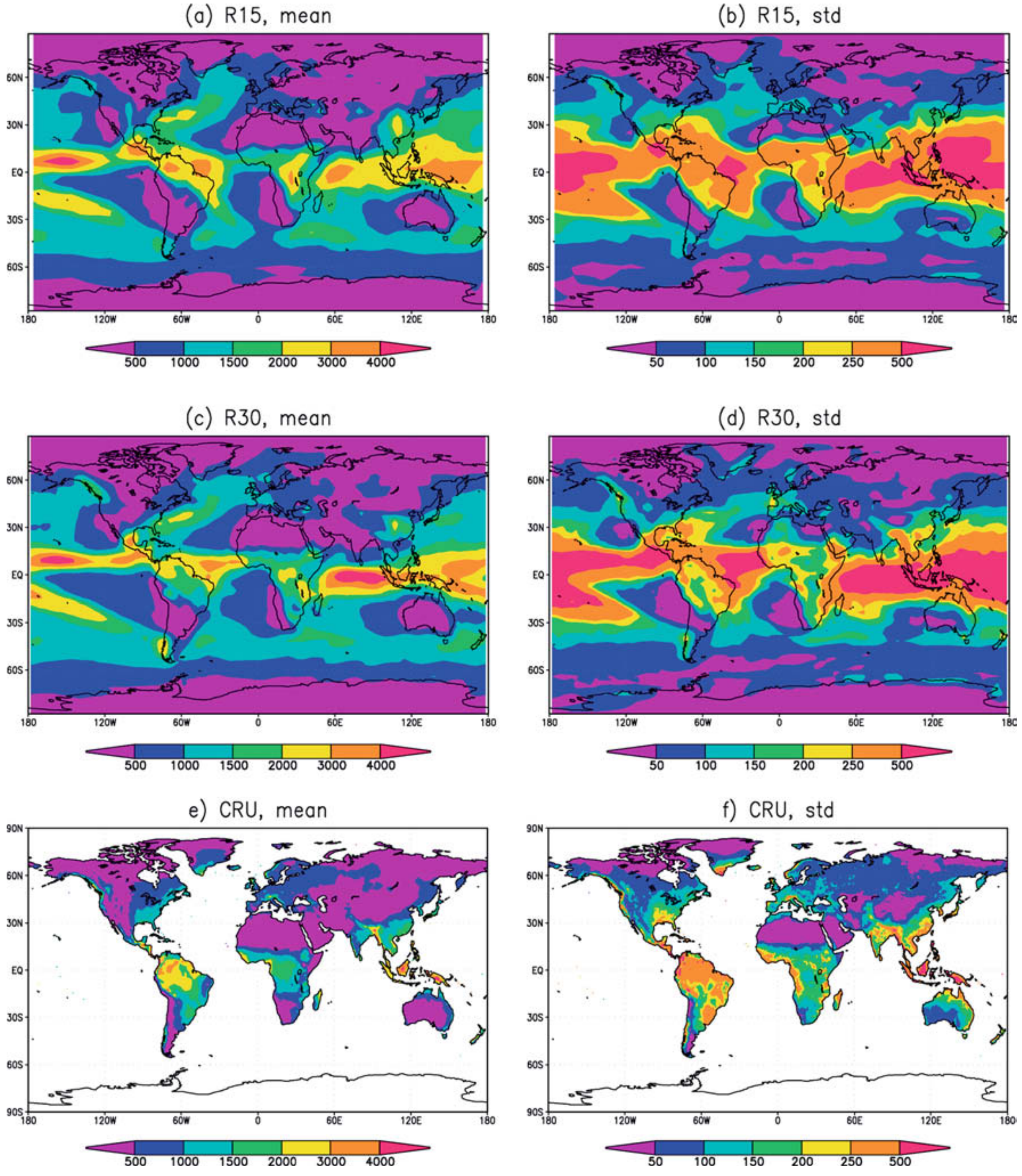


Fig. 1 Statistics of annual precipitation based on model simulations of different spatial resolution and observations: **a** mean and **b** standard deviation from the R15 model; **c** mean and **d** standard deviation from the R30 model; **e** mean and **f** standard deviation of precipitation over land, based on the CRU data (1901–1995)

identified by Foley et al. (1998) for the R15 model still remain, with the underestimation of precipitation getting worse over South America and somewhat alleviated over Indonesia in the R30 model. Over the Sahelian region of northern Africa, the R30 model performs slightly better than the R15 model in capturing the east-west contrast of precipitation distribution according to the CRU data (Fig. 1e). Both the R15 and R30 models overestimate the northward penetration of monsoon rainfall in northern Africa, resulting in a rather wet condition over the southern part of the Sahara desert. Consistently, the model simulates a grassland cover (not shown here) that extends northward well beyond 18°N latitude, the approximate location of the desert border. However, as will be shown later (Fig. 2), rainfall temporal variability over majority of northern Africa (except for the Guinea Coast) is characterized by a high degree of spatial homogeneity. The wet bias over the Sahara is therefore not expected to have an adverse impact on the simulated temporal variability of rainfall in the Sahel.

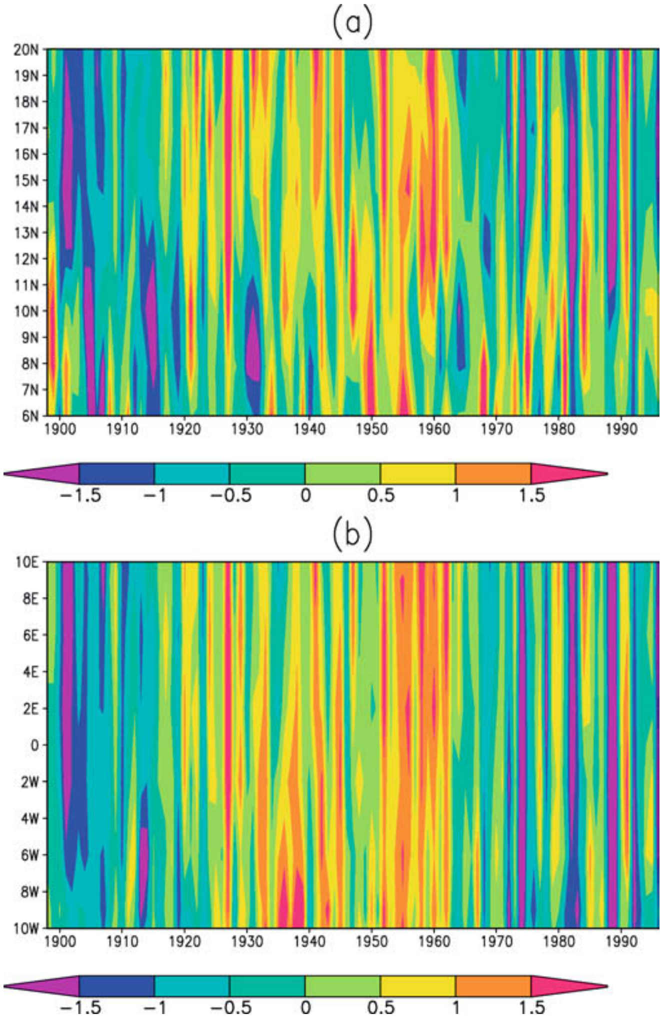


Fig. 2 **a** Normalized anomalies of annual rainfall varying with latitude and time at 0° longitude; **b** normalized anomalies of annual rainfall varying with longitude and time at 15°N latitude

Differences in the standard deviation of precipitation between the R15 and R30 models are more pronounced than those in the mean. Specifically, the R15 model produces a much larger standard deviation than the R30 model almost everywhere and over the African Sahel region in particular (Fig. 1b versus. 1d). Compared with the statistics based on the CRU data (Fig. 1f), over Africa, the R30 model performs much better than the R15 model in simulating the standard deviation of rainfall. The R30 model captures not only the right magnitude of the standard deviation but also its east-west contrast in the Sahel. Since the global SST in the model is prescribed based on climatology and model climate indicates no trend in the three decades on which Fig. 1a–d is based, the standard deviation of model precipitation in Fig. 1b, d reflects the magnitude of atmospheric internal variability. Consequently, the difference between Figures 1b and 1d suggests that atmospheric internal variability in the coarse resolution (R15) model is much larger than that in the medium resolution (R30) model. Unavoidably, such differences will impact the temporal variability of precipitation, which may further influence the skill of the model in simulating vegetation-precipitation feedback as a mechanism of decadal climate persistence.

In the following we first focus on rainfall variability simulated by experiments at the R30 resolution; comparison with results from the R15 resolution experiments is then made to demonstrate the sensitivity to model resolution.

3.1 Long-term variability of the Sahelian biosphere-atmosphere system

Long-term variability of the coupled biosphere-atmosphere system can be simulated by the GENESIS-IBIS model in its full form, i.e., with the vegetation cover treated as a dynamic component of the Earth's climate system. Here we analyze the variability of the Sahelian biosphere-atmosphere climate using results from experiment Veg-Dynamic where the coupled model is driven with the 100-year observed SST forcing.

Within a major part of North Africa, the temporal variability of precipitation is characterized by a high degree of spatial coherency. Figure 2a takes the 0° longitude in the model as an example and shows the normalized anomalies of annual rainfall varying with latitude and time; Fig. 2b takes the 15°N latitude in the model as an example and shows the normalized anomalies of annual rainfall varying with longitude and time. Here "normalized anomaly" is defined as the difference from long-term mean normalized by the standard deviation, and climate normal (mean and standard deviation) is defined based on the period 1900–1996. Precipitation variability at other longitudes and latitudes in North Africa follow patterns similar to Fig. 2. It is clear that the pattern of temporal rainfall variability does not change along the longitudinal direction in this region (Fig. 1b); nor does it change along the latitudinal direction north of approximately 12.5°N (Fig. 2a). It appears that, from about 12.5°N southward to the coast, rainfall variability follows a different pattern than that in the north. Such a south-north contrast was also found in previous studies (e.g., Wang and Eltahir 2000a). Within the Sahel (defined as the region between 12.5°N and the Sahara desert) however, spatial variation can be neglected. We can therefore focus on the spatial average in the following to analyze the temporal variability of the Sahelian precipitation.

Figure 3a presents the 100-year time series of the normalized annual precipitation anomaly averaged over the region 10°W–10°E, 12.5°N–20°N of the Sahel, based on experiment Veg_Dynamic at R30 resolution. Each bar in Fig. 3 stands for one individual year, and the solid line plots the five-year moving average. Comparison with the normalized anomaly based on the Hulme rainfall data (Hulme et al. 1998) in Figure 3b indicates that the medium-resolution model captures the main features of the long-term rainfall variability in the twentieth century. For the first two decades when observed conditions were generally drier than normal, the model simulates a continuous drought, although with a greater severity than observation; from the 1920s to the early 1960s, wetter-than-normal conditions prevailed in both the model and the data, with the 1950s being the wettest; for the last three decades of the century, the conditions were predominantly dry, although the simulated drought was not as persistent as in observations.

Although the model simulation is not comparable with observations on a year-to-year basis, multi-year to multi-decadal scale variations simulated by the model are remarkably similar to that observed, as shown by the 5-year moving average (solid lines in Fig. 3a and b). The difference in model performance at different time scales may be attributed to the interplay between atmospheric chaos, oceanic impact, and feedbacks from land. While the land-atmosphere interactions work to maintain a persistent anomaly (labeled as δ_1) of the regional climate, atmospheric chaos and/or SST inter-annual variability causes significant climate variations at the inter-annual time scale (labeled as δ_2) that adds on top of the persistent anomaly. The actual climate anomaly can be considered as the sum of the two (i.e., $\delta = \delta_1 + \delta_2$). Unless the chaos- and/or SST-induced inter-annual variability is much larger in magnitude than the persistent decadal climate anomaly, the sign of the actual climate anomaly follows that of the decadal climate anomaly. Although atmospheric chaos or internal variability diminishes the model skill in simulating the inter-annual climate variability, the model may still do well at decadal or longer time scales.

As shown in Fig. 3, the simulated Sahel drought in the last three decades of the twentieth century is not as persistent as the observed, which may have to do with

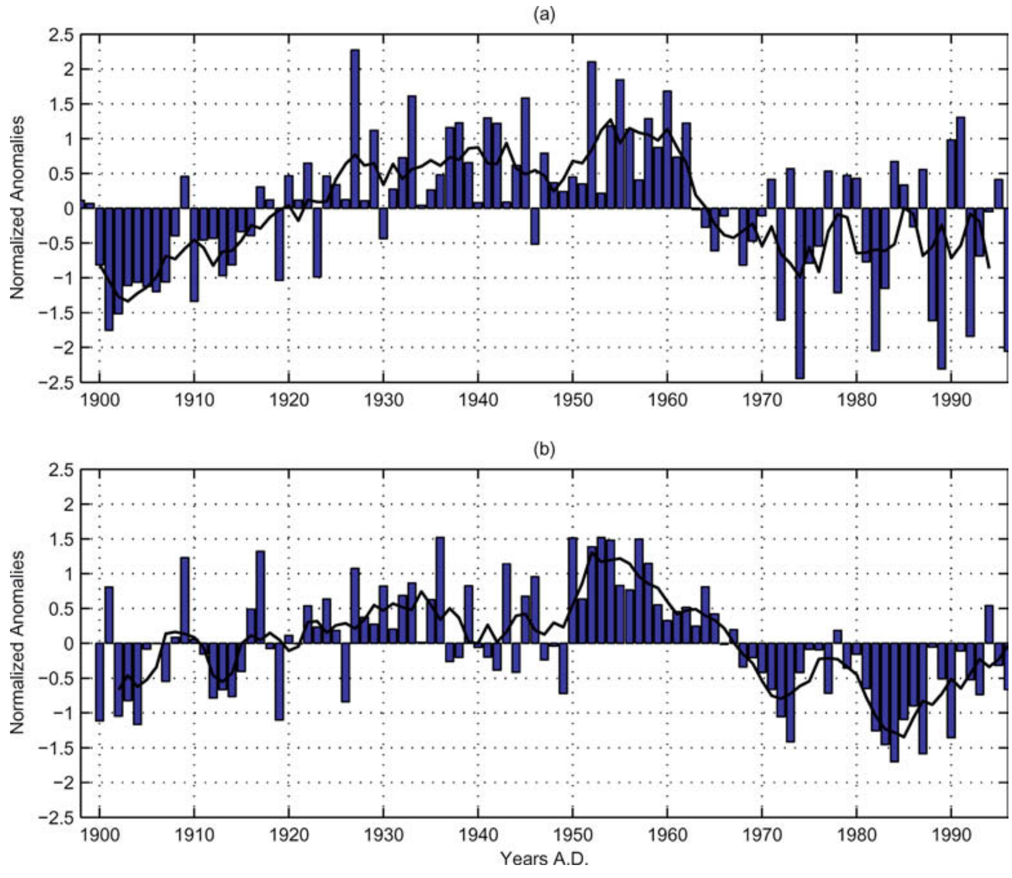


Fig. 3 Time series of the normalized annual rainfall anomalies averaged over the Sahel region (10°W–10°E, 12.5°N–20°N), based on **a** Experiment Veg_Dynamic at R30 resolution and **b** Observations (Hulme et al. 1998). *Solid lines* represent the five-year moving averages of the two time series

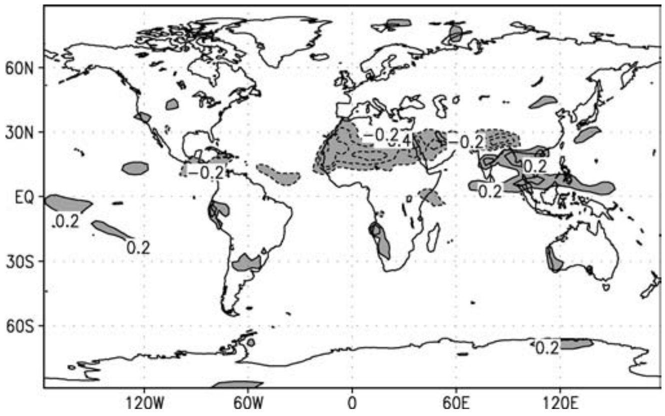
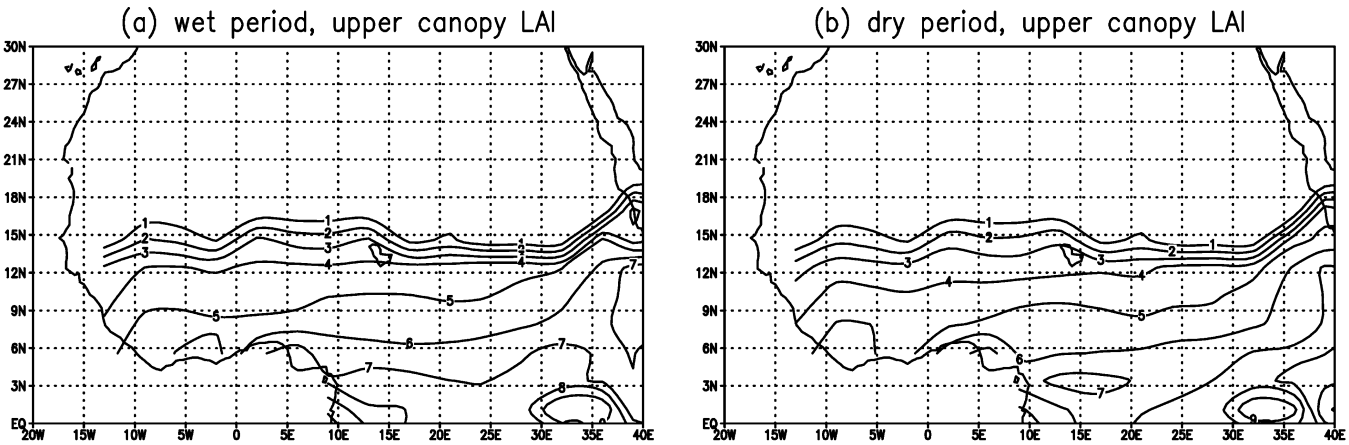


Fig. 4 Fractional decrease of rainfall amount from the wet period in the 1950s to the dry period after 1970, based on experiment Veg_Dynamic at R30 resolution

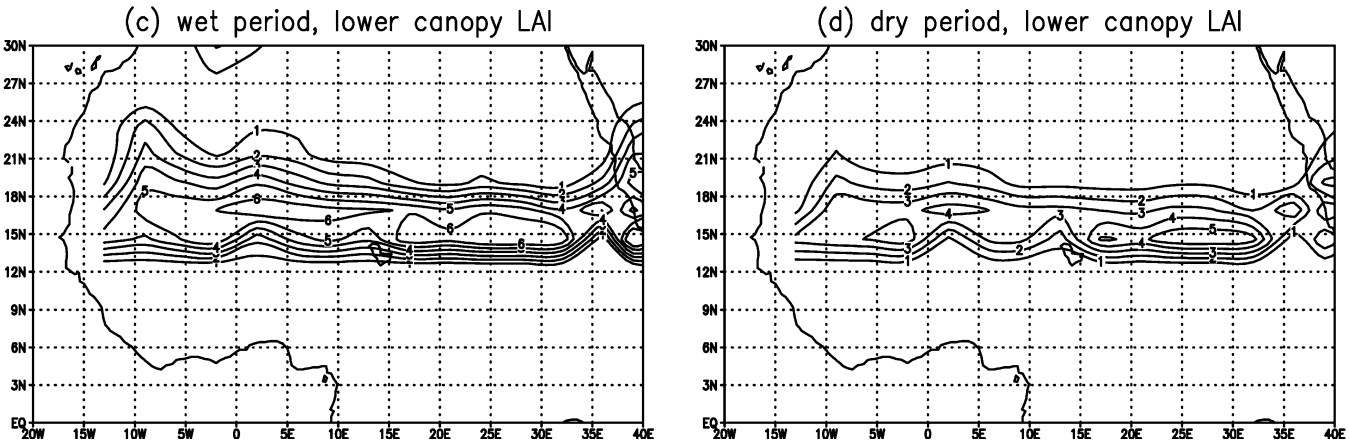
the lack of anthropogenic land cover changes (including desertification and deforestation) in the model. However, the model captures fairly well the timing of the drought onset, i.e., in the 1960s. The severity of this drought can be quantified using the percentage decrease of precipitation amount from the wet 1950s (1950–1959) to the dry period after 1970 (1971–1997), and the same analysis is expanded to cover the whole globe, as shown in Fig. 4. Evidently, North Africa (mainly the Sahel) stands out as the only region in the model that experienced such a severe large-scale drought in the last third of the past century, with a decline corresponding to more than 40% of precipitation over majority of the region. The magnitude of the relative precipitation reduction is comparable to observations based on both the CRU data and the Hulme rainfall data.

Consistent with the major desiccation event, simulated vegetation state before and after the 1960s is substantially different. Figure 5 compares the leaf area index (LAI) of the upper (trees) and lower (shrubs and grasses) canopy averaged in the post-1960s dry period with those averaged in the wet 1950s. While the spatial coverage of vegetation in the upper canopy (i.e., trees) stays the same, a noticeable reduction of vegetation density in the form of LAI decrease is simulated (Fig. 5b versus 5a). For example, tree LAI near 12°N is over 4 in the wet 1950s and is about 3.5 in the dry period. Significant changes are simulated for vegetation in the more vulnerable lower canopy (typically shrubs and grass) in both its spatial coverage and density (Fig. 5d versus 5c). From the wet period to the dry period, the northern boundary of grassland (defined by the contour line of unit LAI) retreated southward by approximately 2°–3° latitude, and the spatial maximum

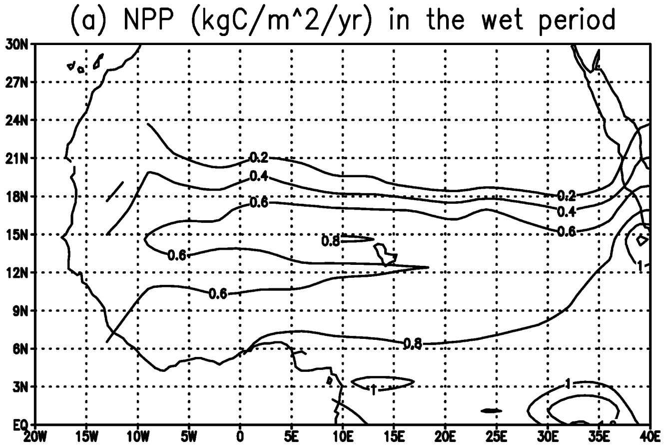
Fig. 5a–d Leaf area indices for the upper and lower layer canopy averaged in the wet 1950s and in the dry period after 1970, simulated in experiment Veg_Dynamic at R30 resolution


(a) wet period, upper canopy LAI

(b) dry period, upper canopy LAI


(c) wet period, lower canopy LAI

(d) dry period, lower canopy LAI



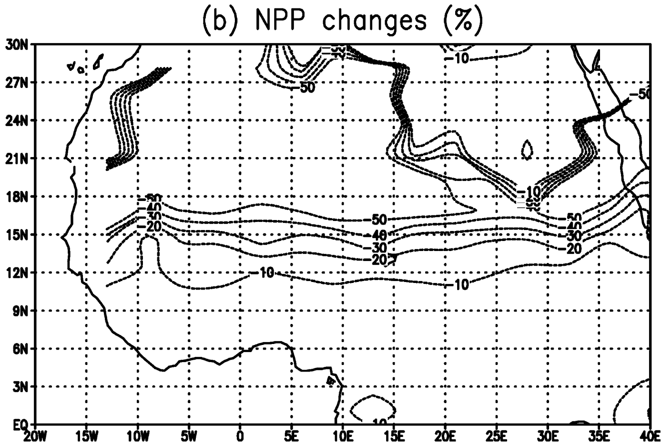


Fig. 6 a Net primary productivity (in kgC/m^2 /year) averaged during the wet 1950s, simulated by the experiment Veg_Dynamic at R30 resolution; **b** decrease of net primary productivity from the 1950s to the dry period after 1970

of LAI decreased by about 2. Long-term water stress and the resulting degradation of vegetation both contribute to the loss of land productivity. Compared to that in the wet period (Fig. 6a), the net primary productivity (NPP) in the dry period is lower by 20%–80% (Fig. 6b), with the largest NPP reduction near the desert border.

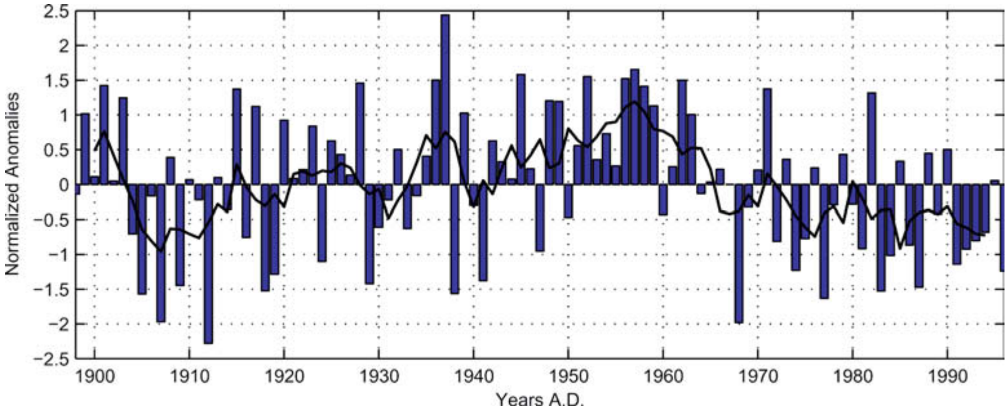
In addition to the severe drought, the significant fluctuation of precipitation at multi-decadal time scale also seems to be unique to the region of the African Sahel. Time series analysis similar to Fig. 3a has also been carried out for several other regions, including the Amazon in South America, Mississippi River Basin in North America, Central Africa, and the Asian Monsoon region. In the context of the model we use, the African Sahel is the only region where rainfall regime is characterized by strong powers of variance at low frequencies.

3.2 Impact of vegetation dynamics on decadal rainfall variability

As shown already, the coupled GENESIS-IBIS model captures the primary features of the multi-decadal variability of the Sahel rainfall. Based on this model, a twentieth century Sahel drought can result from the response of the coupled vegetation-atmosphere system to global SST forcing, though in observations it may have been enhanced by human activities (deforestation and desertification).

To distinguish the contribution to rainfall variability from SST forcing and that from dynamic vegetation feedback, we analyze the normalized rainfall anomaly averaged over the Sahel region derived from experiment Veg_Static where vegetation is treated as a static boundary condition of the climate system (Fig. 7). This rainfall time series, compared with that simulated by experiment Veg_Dynamic (Fig. 3a), includes more frequent oscillations between positive and negative anomalies. For example, in the first half of the twentieth century, rainfall anomalies of the same sign in experiment Veg_Static rarely exceed four years in duration; in contrast, conditions in experiment Veg_Dynamic are predominantly dry in the first two decades and predominantly wet afterwards. The difference in the degree of climate persistence is also made clear by the five-year moving averages of the two time series. Without accounting for the feedback due to dynamic vegetation, the model produces a climate with a significantly lower degree of persistence. As a quantitative measure of this

Fig. 7 Time series of the normalized annual rainfall anomalies averaged over the same region as in Fig. 2, but based on simulations by experiment Veg_Static



difference, Fig. 8 presents the power spectrum of the simulated precipitation averaged in the Sahel from the Veg_Static and Veg_Dynamic experiments. Comparison of the power spectra between the two experiments indicates that vegetation dynamics enhances the power of climate variance at low frequency and reduces the power at high frequency. This confirms previous findings using simplified models (e.g., Wang and Eltahir 2000a; Zeng et al. 1999), and enhances our confidence in the previously used simple models such as ZonalBAM (Wang and Eltahir 2000c) and QTEM (Neelin and Zeng 2000; Zeng et al. 2000).

The enhancement of low-frequency rainfall variability by vegetation dynamics derives from the slowness of vegetation response to environmental changes. In the global dynamic vegetation model IBIS, vegetation varies at a wide range of time scales. Specifically, leaf area index is updated daily according to plant phenology, leading to the seasonal variation of vegetation; vegetation structure and carbon stores are updated yearly based on the annual carbon budget, which eventually determines the growth and mortality of plants. When vegetation is kept static as in the Veg_Static experiment, the carbon stores stay the same from year to year, so the peak growing-season leaf area index does not change from one year to the next. However, plant phenology is still simulated, resulting in a seasonal cycle of leaf area index that varies from year to year depending on the hydro-meteorological conditions during the course of each year. Apparently it is the biological processes at the yearly time scale that are responsible for the spectrum differences between the Veg_Dynamic and Veg_Static experiments shown in Fig. 8. However, since the yearly variation of vegetation derives from the accumulation of products from processes at much shorter time scales, it is not possible to completely separate the contribution of slow processes from that of the fast ones.

Comparing Figs. 7 to 3a, one cannot help noticing the similarity between the two time series in the last three decades of the past century, with a long-lasting drought in both. Note that rainfall variability simulated by the Veg_Static experiment results from the response to global SST forcing of the *atmosphere* alone, as opposed to the response of the coupled *vegetation-atmosphere system* in the "Veg_Dynamic" experiment. The presence of the drought condition in Fig. 7 implies that global SST in the last three decades of the twentieth century was favorable for a drier-than-normal condition over the Sahel region.

However, the drought condition simulated by the Veg_Dynamic experiment is slightly more persistent, and substantially more intense (Fig. 9). Differences between annual rainfall averaged during the dry period after 1970 and that averaged during the wet 1950s, derived from the Veg_Static experiment, are presented in Fig. 9a; those derived from the Veg_Dynamic experiment are in Fig. 9b. It is evident that, in addition to enhancing the climate persistence (Fig. 8), feedbacks from dynamic vegetation amplify the impact of global SST forcing on the Sahelian precipitation and intensify the drought, thus increasing the drought severity. Therefore, although the global SST forcing alone can trigger a drier-than-normal condition in the last three decades of the twentieth century, the drought would

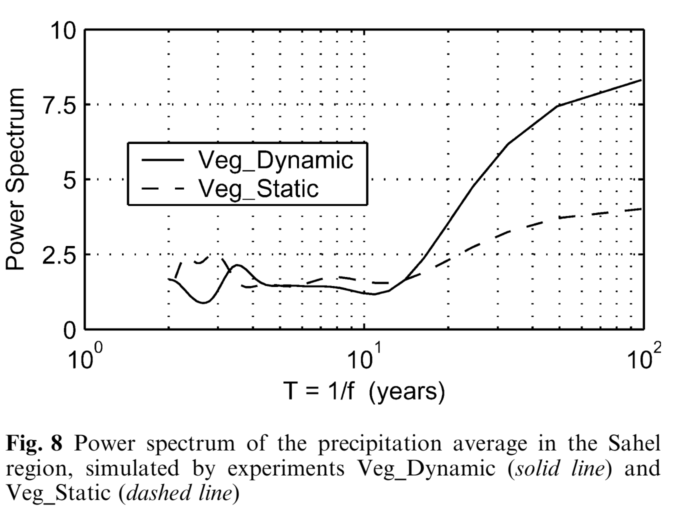


Fig. 8 Power spectrum of the precipitation average in the Sahel region, simulated by experiments Veg_Dynamic (*solid line*) and Veg_Static (*dashed line*)

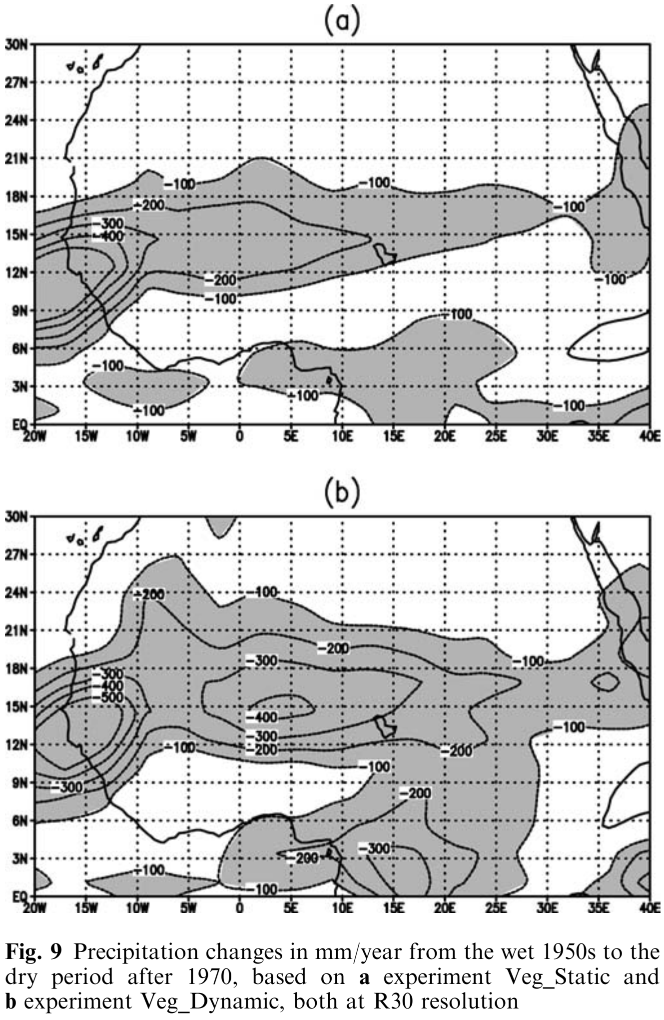


Fig. 9 Precipitation changes in mm/year from the wet 1950s to the dry period after 1970, based on **a** experiment Veg_Static and **b** experiment Veg_Dynamic, both at R30 resolution

have been much less severe if it were not for the amplification of climate anomalies by vegetation dynamics.

Even when both the global SST forcing and feedback from vegetation dynamics are included in the model, the simulated drought in the last three decades of the twentieth century is still not as persistent as the observed drought (Fig. 3). This discrepancy may be due to the lack of representation of human induced land cover changes (e.g., desertification) in the model. In addition, from Fig. 9b, it is noted that the simulated precipitation deficit is mainly concentrated in the Sahel and the region to the north. However, observations indicate that rainfall differences between the wet period and dry period is relatively evenly distributed in West Africa (e.g., Le Barbe et al. 2002), with the drought coverage extending to the Guinea Coast region located south of the Sahel (Nicholson and Palao 1993). Since deforestation can cause a major precipitation reduction in the Guinea Coast region (e.g., Zheng and Eltahir 1997), the difference in the spatial extension of the drought between our model simulation and observations again points to the role of anthropogenic land cover changes.

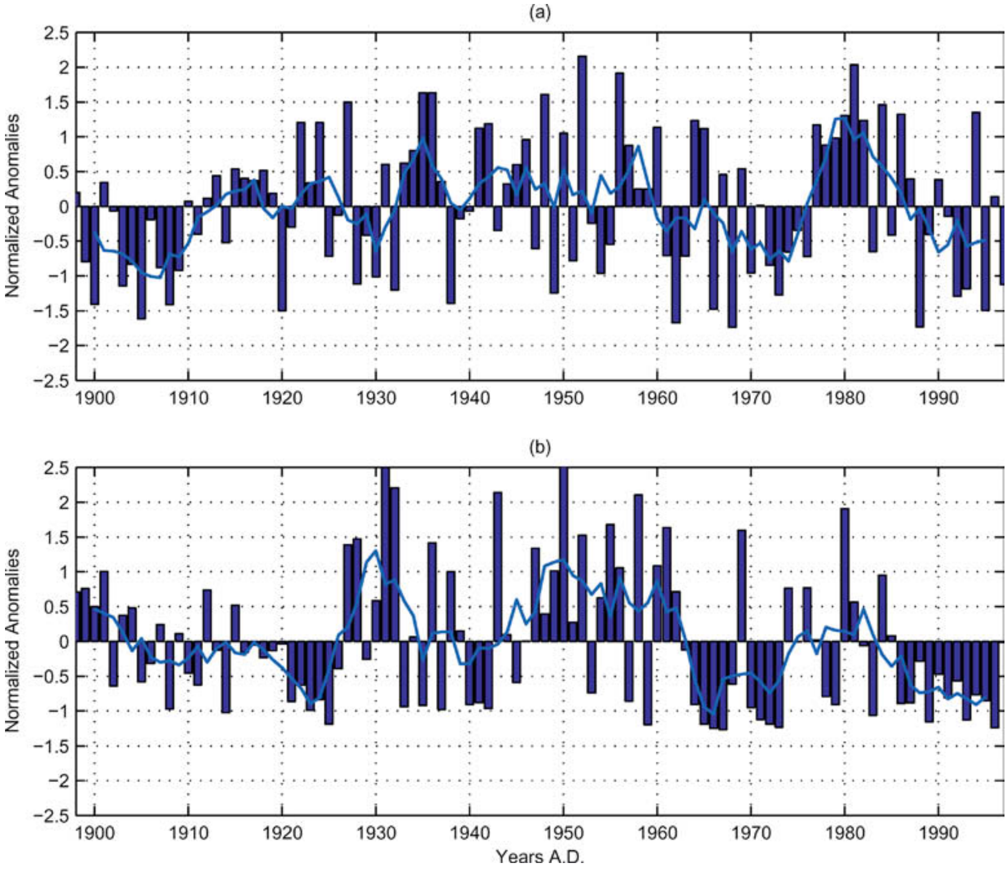
3.3 Sensitivity to model resolution

As illustrated in Fig. 1, for the coupled GENESIS-IBIS model, increasing the model resolution from R15 to R30 leads to significant difference in the standard deviation of the model climate between the two resolutions, despite the similarity in their mean climate. It is therefore expected that the temporal variability of the model climate may show a certain degree of sensitivity to model resolution. Figure 10 plots the time series of the normalized rainfall anomalies averaged over the Sahel region derived from experiments Veg-Dynamic (Fig. 10a) and Veg-Static (10b) using models at the R15 resolution, for comparison with their counterparts at the R30 resolution (Fig. 3a, Fig. 7) and with observations (Fig. 3b) as well.

Based on spectral analysis (not shown here), there is no identifiable difference in the dominant time scale of variability between the two time series in Fig. 10. The role of vegetation dynamics as a mechanism to enhance the persistence of the regional climate in Sahel is not obvious in the coarse-resolution experiments. When vegetation dynamics is active in the model, the long-term rainfall variation simulated by the coarse-resolution model (Fig. 10a) bears no similarity whatsoever to that simulated by the medium-resolution model (Fig. 3a). Nor does it resemble anything from observations (Fig. 3b).

Comparing Fig. 10 with Fig. 3 indicates that the change from coarse resolution to medium resolution leads to a significant improvement of the model performance in simulating the variability of the regional hydrological regime, the low-frequency variability in particular. This improvement has to do with the fact

Fig. 10 Time series of the normalized annual rainfall anomalies averaged over the same region as in Fig. 3 and 7, but based on simulations by experiment Veg_Dynamic **a** and Veg_Static **b**, both at R15 resolution



that the R30 resolution model does better than the R15 model in reproducing the standard deviation of annual rainfall over the Sahel. The latter significantly overestimates the standard deviation. According to Wang (2004), the coupled biosphere-atmosphere system can be considered as a stochastically driven nonlinear system, and overestimation of the stochastic forcing leads to exaggerated power of the climate variance at high frequency. The magnitude of this stochastic forcing can be quantified using the internal variability of the model climate. Therefore, in the coarse-resolution model where the magnitude of internal variability is much larger than that in the medium-resolution model (as shown in Fig. 1), the biosphere-atmosphere system is subject to a much larger stochastic forcing. Consequently, based on Wang (2004), the characteristic time scale of rainfall variability simulated by the coarse resolution model is shorter than that simulated by the medium resolution model. Such sensitivity of model performance to spatial resolutions makes it essential that climate variability studies invest in finer resolution models, and highlights the need for climate models that succeed in reproducing not only the mean climate but also the standard deviation.

Despite the inability of the coarse resolution model to capture the general low-frequency feature of the rainfall variability in the Sahel, it does simulate a long-lasting drought in the second half of the twentieth century in experiment Veg_Static. This characteristic of the coarse resolution model is similar to the medium resolution model (Fig. 10b versus Fig. 7), both indicating that the global SST forcing during the last three decades of the twentieth century favors drier-than-normal conditions in the Sahel. This again underscores the contribution of global SST forcing to the occurrence of the observed Sahel drought.

4 Conclusions and discussion

Using a fully coupled atmosphere-biosphere model (GENESIS-IBIS), which allows feedbacks between atmosphere and vegetation cover to operate in both directions, we carried out a numerical modeling study on the role of ocean forcing and vegetation feedbacks in the long-term variability of the Sahelian rainfall. A set of century-long simulations driven with observed global SST variations allowed us to experiment on different ways of treating vegetation cover (as a dynamic component versus. as a static boundary condition) and on different model resolutions (coarse resolution versus. medium resolution). Our analyses focused on the impact of three different factors, including the SST forcing, feedback due to vegetation dynamics, and model resolution, on the characteristics of the simulated rainfall variability.

When the vegetation cover is treated as a dynamic component of the global climate system (with year-to-year changes of vegetation cover based on the balance of vegetation growth, turnover and mortality), the coupled GENESIS-IBIS model of R30 resolution driven with observed SST forcing reproduces with reasonable accuracy the multi-decadal fluctuation of precipitation over the African Sahel. This includes a relatively dry period in the beginning, a wet episode of more than four decades in the middle followed by a dry episode of more than three decades towards the end of the twentieth century. If vegetation is treated as a static boundary condition (with only seasonal changes in vegetation), however, the model cannot simulate the observed low-frequency rainfall variability. Clearly, it is the feedback due to vegetation dynamics that provides the mechanism for the multi-decadal persistence of this regional climate. This persistence mechanism can be attributed to vegetation's ability to carry multiple-year memory of the regional hydrological conditions. Over wooded areas, this multiple-year memory can be provided by the woody structure that results from multiple years of carbon accumulation; in the portion of the Sahel where vegetation is dominated by perennial grasses, the year-to-year memory can reside in the perennial underground structure that survives the dry season (Wang and Eltahir 2000a).

While the traditional Charney (1975) hypothesis on biogeophysical feedback emphasized the albedo effect, changes in the Bowen Ratio (therefore evapotranspiration) and surface roughness are also important aspects of vegetation feedback. Instead of each being controlled by a single tunable parameter as is in some simple schemes, these land surface properties are represented in IBIS by a suite of different parameters that are more biophysically derived. Different aspects of vegetation feedback in our model cannot be easily separated from each other. It is therefore not a straightforward task to diagnose whether and which one of the three aspects of vegetation feedback (i.e., albedo, evapotranspiration, surface roughness) is dominant. This topic will be addressed in some of our future research.

In addition to the feedback mechanism related to dynamic vegetation, the model skill or the lack of it in reproducing the low-frequency variability of the Sahel rainfall is also sensitive to model resolution. For the two resolutions we tested with active vegetation dynamics, the R30-resolution model is capable of reproducing the multi-decadal rainfall fluctuations while the R15-resolution model is not. Our explanation of such model dependency, derived from the conceptual modeling study of Wang (2004), relates the strong power of the R15 model climate at high frequency to its overestimation of the atmospheric internal variability.

The enhancement of low-frequency climate variability by vegetation dynamics also takes effect outside the Sahel region. Using the Community Climate Model (CCM3) coupled with IBIS driven with the climatological SST forcing, Delire et al. (in press) demonstrated that in several regions at the limit between very different ecosystems (including the Sahel), the power spectrum of model precipitation resembles that of a white noise when vegetation state is fixed, and gains more red-noise characteristics when dynamic vegetation is included. We examined the time series of precipitation simulated by our model in the several regions identified by Delire et al. (in press) and noted that Sahel is the only one where precipitation regime is characterized by strong multi-decadal persistence. Therefore, it is the multi-decadal persistence of the climate that is a unique characteristic of the Sahel region, not the general enhancement of low-frequency variability by vegetation dynamics.

Our results from the GENESIS-IBIS model also demonstrate that oceanic forcing in the last third of the twentieth century is favorable for drier-than-normal conditions in the Sahel. During that period, the response to global SST variations of *the atmosphere alone* (as opposed to *the coupled vegetation-atmosphere system*) can lead to a slight drought in the model. However, vegetation dynamics amplifies this SST-induced drought and enhances the drought severity. As a result of the natural vegetation-atmosphere feedback, a significant degradation of vegetation accompanies the persistent drought, including a shrinkage of vegetation cover and a decrease of vegetation density over the Sahel in the model.

SST changes and their impact on atmospheric circulation patterns have been suggested as a possible cause of the twentieth century Sahel drought by both numerical modeling studies and statistical analyses (e.g., Folland et al. 1991; Rowell et al. 1995; Ward 1998; Giannini et al. 2003). Based on our results, although it seems plausible that SST forcing may have acted as a trigger of the drought, SST is clearly not the full story. The fact that our model simulates a drought after the 1960s without including human activities does not preclude the role of human activities in the drought occurrence. Quite the opposite, the finding that the simulated drought would not have been as severe if vegetation dynamics was not included highlights the significant contribution of vegetation degradation, be it of natural origin or anthropogenically induced. More over, the lack of strong persistence in the simulated drought when both the global SST forcing and vegetation dynamics are included in the model points to the role of human activities, a mechanism that is currently missing from the model.

Human-induced land cover changes have been considered by many as a potential mechanism that contributes to, or even triggers, the occurrence of the twentieth century Sahel drought (e.g., Xue and Shukla 1993; Xue 1997; Zheng and Eltahir 1997; Clark et al. 2001). In fact, it has been indicated that human-induced desertification reinforced by vegetation dynamics is able to trigger a persistent drought in the Sahel similar to that observed (Wang and Eltahir 2000b). As evidence continues to accumulate (e.g., Charney 1975; Xue 1997; Zheng and Eltahir 1997; Zeng et al. 1999; Wang and Eltahir 2000b; Clark et al. 2001; Dumenil-Gates and Lie*ß* 2001; Taylor et al. 2002; Foley et al. 2003; Giannini et al. 2003; Zeng 2003), it becomes clear that the twentieth century drought in West Africa is most likely to have resulted from the interplay of global ocean forcing, human-induced land use/land cover changes, and the regional climatic feedback due to vegetation dynamics.

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