Impact of CO$_2$ concentration changes on the biosphere-atmosphere system of West Africa

G U I L I N G W A N G* and E L F A T I H A . B . E L T A H I R†

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Abstract

Vegetation dynamics plays a critical role in causing the decadal variability of precipitation over the Sahel region of West Africa. However, the potential impact of changes in CO$_2$ concentration on vegetation dynamics and precipitation variability of this region has not been addressed by previous studies. In this paper, we explore the role of CO$_2$ concentration in the regional climate system of West Africa using a zonally symmetric, synchronously coupled biosphere-atmosphere model. We first document the response of precipitation and vegetation to incremental changes of CO$_2$ concentration; the impact of CO$_2$ concentration on the variability of the regional biosphere-atmosphere system is then addressed using the second half of the twentieth century as an example. An increase of CO$_2$ concentration causes the regional biosphere-atmosphere system to become wetter and greener, with the radiative effect of CO$_2$ and improved plant-water relation dominant in the Sahelian grassland region and the direct enhancement of leaf carbon assimilation dominant in the tree-covered region to the south. Driven by the observed sea surface temperature (SST) of the tropical Atlantic Ocean during the period 1950–97 and with CO$_2$ concentration prescribed at a pre-industrial level 300ppmv, the model simulates a persistent Sahel drought during the period of 1960s$-$1990s. The simulated drought takes place in the form of a transition of the coupled biosphere-atmosphere system from a wet/ green regime in the 1950s to a dry/barren regime after the 1960s. This climate transition is triggered by SST forcing and materialized through vegetation-climate interactions. The same SST forcing does not produce such a persistent drought when a constant modern CO$_2$ concentration of 350ppmv is specified, indicating that the biosphere-atmosphere system at higher CO$_2$ level is more resilient to drought-inducing external forcings. This finding suggests that the regional climate in Sahel, which tends to alternate between dry and wet spells, may experience longer (or more frequent) wet episodes and shorter (or less frequent) dry episodes in the future than in the past. Our study has significant implications regarding the impact of climate change on regional socio-economic development.

Keywords: CO2-induced climate changes, drought, plant-water relation, vegetation dynamics, water-use efficiency, West Africa, biosphere-atmosphere interactions

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Introduction

Historical records and proxy data demonstrate that precipitation over the Sahel region of West Africa features significant variability at the decadal time scale (Maley, 1973; Nicholson, 1981; Farmer & Wigley, 1985). Climate in this region tends to persist in alternating dry and wet episodes that typically last for more than a decade. The

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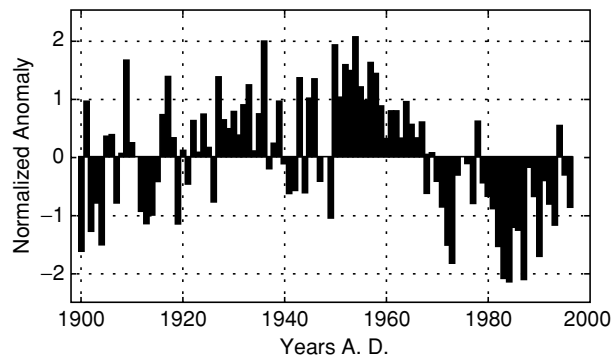
Fig. 1 Annual rainfall index (i.e. the normalized anomaly of annual precipitation) averaged over the Sahel region (15 W-15 E, 10 N-20 N).

latest example of such climate persistence is a major drought that commenced in the late 1960s and has lasted for more than three decades (Fig. 1, reproduced from Wang & Eltahir, 2000c).

The Sahel drought of the late twentieth century has been the topic of numerous studies that collectively documented the impact of man-made land cover changes (Charney et al., 1977; Sud & Molod, 1988; Xue & Shukla, 1993, 1996; Xue, 1997; Zheng & Eltahir, 1997, 1998, Clark et al., 2001) as well as regional and global sea surface temperature (SST) distributions (Lamb, 1978; Folland et al., 1991; Rowell et al., 1995; Ward, 1998) on precipitation over Sahel. For example, numerical experiments by Zheng & Eltahir (1997) showed that while local man-made desertification can significantly reduce the Sahelian precipitation, deforestation in the Guinea Coast region south of Sahel is also a major factor causing precipitation in the Sahel region to decrease; statistical analysis by Ward (1998) suggested that the drying trend in Sahel is correlated with the trend of inter-hemispheric SST gradient. A new group of studies emphasized the role of biosphere-atmosphere interactions, and treated vegetation as a dynamical component of the integrated land-atmosphere-ocean system. Claussen (1998) and Brovkin et al. (1998), using an iteratively coupled biosphere-atmosphere model that features a series of atmospheric simulations with periodic updates of equilibrium vegetation cover, found two different equilibrium states for the West African climate resulting from dramatically different initial vegetation conditions; Zeng et al. (1999) and Wang & Eltahir (2000c, d), considering both the impact of SST forcing and biosphere-atmosphere interactions, demonstrated that the slow response of vegetation enhances the low-frequency variability of the Sahel precipitation thus contributing to the development of the persistent Sahel drought.

Using a synchronously coupled biosphere-atmosphere model that includes the transient change of vegetation

cover, Wang & Eltahir (2000b–d) systematically documented the important role of vegetation dynamics in the climate of West Africa. Wang & Eltahir (2000b) showed that the regional climate system in West Africa has multiple regimes. Under the influence of small disturbances, vegetation dynamics induces a negative feedback, which maintains the climate system within one regime; in response to large enough disturbances, the feedback due to vegetation dynamics becomes positive, thus triggering a transition of the climate towards a different regime. While vegetation dynamics generally enhances low-frequency variability of precipitation by carrying information about water stress from one year to the next, a special form of precipitation fluctuation at the multi-decadal time scale can result from the persistence of the regional climate system at each individual regime and its transition between different regimes (Wang & Eltahir, 2000c). Within this framework, a persistent drought similar to what has been observed in Sahel can take place as a transition of the coupled system from a wet regime to a dry regime. Such a transition can be triggered by external forcings such as SST variability or anthropogenic land cover changes, and sustained through vegetation dynamics (Wang & Eltahir, 2000d).

Despite the well-documented importance of vegetation dynamics and land cover changes in the climate of West Africa, the role of CO_2 concentration, which is closely coupled with vegetation, has not been adequately considered. For example, in the Wang & Eltahir (2000c,d) studies, atmospheric CO_2 concentration was fixed at a modern level 340 ppmv. However, in reality, atmospheric CO_2 concentration has risen from less than 300 ppmv in the early 1900s to the current level of more than 370 ppmv, and accumulation of CO_2 in the atmosphere is still continuing. As CO_2 concentration in the atmosphere increases, it will have a significant impact on the Earth's biosphere-atmosphere system through both its radiative effect and its biological effect.

As reported by numerous climate modelling studies (e.g. Stouffer et al., 1989; Murphy & Mitchell, 1995; Meehl et al., 2000; Stott et al., 2000), the radiative effect of elevated CO_2 causes warming in the troposphere, thus increasing the atmospheric water content and intensifying the global hydrological cycle. Such climate changes would create a favourable environment for vegetation in regions where plant growth is limited by water availability or low temperature. However, the more direct impact of CO_2 concentration changes on global vegetation is through the physiological effect. An increase in atmospheric CO_2 concentration enhances leaf photosynthesis rate, but reduces stomatal conductance for water vapour, therefore, plant transpiration rate. This significantly improves the plant-water use efficiency as defined by the amount of carbon gain per unit water loss, and favours

greater vegetation growth. It has been observed, not only in well-controlled green house trials but also in field experiments using open-top growth chambers as well as free air CO$_2$ enrichment facilities, that plants at elevated CO$_2$ have higher carbon assimilation rate and/or larger biomass than those at ambient CO$_2$ (e.g., Owensby *et al.*, 1993, 1997, 1999; Ghannoum *et al.*, 1997, 2000; Warwick *et al.*, 1998; Wand *et al.*, 1999; Hamerlynck *et al.*, 2000; Smith *et al.*, 2000; Seneweera *et al.*, 2001). This positive growth response is not only observed in C3 plants, but also, though to a lesser degree, in C4 plants whose photosynthesis is traditionally viewed as not responsive to CO$_2$ enrichment because of its saturation at the present CO$_2$ level. However, only a few modelling studies (Betts *et al.*, 1997, 2000; Levis *et al.*, 1999, 2000) have included the full impact of CO$_2$ enhancement. Special attention should be paid to integrated research that considers the impact of CO$_2$-induced vegetation changes on climate and the impact of CO$_2$-induced climate changes on vegetation in a consistent way.

In their study on long-term climate changes due to atmospheric CO$_2$ doubling, Sellers *et al.* (1996) and Bounoua *et al.* (1999) included in their model both the radiative and physiological effects of elevated CO$_2$, but prescribed vegetation type and leaf area index based on observations. They found that the CO$_2$-induced decrease of stomatal conductance enhances the greenhouse warming in the tropics and offsets part of the precipitation increase caused by the radiative effect of CO$_2$. This study documented an increase of net primary productivity over the globe caused by CO$_2$ enrichment, although the subsequent changes in vegetation structure are not simulated. Betts *et al.* (1997, 2000), using an equilibrium vegetation model iteratively coupled with a global climate model (GCM), and Levis *et al.* (1999, 2000), using a transient dynamic vegetation model synchronously coupled with a GCM, both considered the role of vegetation feedback in CO$_2$-induced climate changes. It was found that allowing vegetation structural changes overrides the direct physiological effects of CO$_2$ on climate in many regions, and this feedback may operate differently in different regions depending on climate characteristics and vegetation. Recently, using a coupled atmospheric-biogeochemical model which includes both land use and vegetation growth, Eastman *et al.* (2001) showed that during the growing season in central United States, land use change and the 'fertilization' effect of CO$_2$ doubling have more immediate influence on the regional weather than the radiative effect of CO$_2$. The biosphere feedback at elevated CO$_2$ stands as an important factor not only for long-term regional to global climate but also for short-term weather (Pielke, 2001).

Given the high sensitivity of West African climate to vegetation changes and the extreme importance of vegetation dynamics in shaping the long-term variability of the Sahel precipitation, atmospheric CO$_2$ concentration changes may have a major impact on this regional climate. In this paper, considering not only the radiative and physiological effects but also the vegetation dynamical effects of CO$_2$ changes, we investigate the full impact of atmospheric CO$_2$ concentration changes on the climate system over West Africa using a synchronously coupled, dynamic biosphere-atmosphere model.

Model description, methodology, and experiment design

In this study we use the zonally symmetric, synchronously coupled biosphere-atmosphere model ZonalBAM (Wang & Eltahir, 2000a). ZonalBAM was designed to simulate the regional climate system of West Africa. It includes a zonally symmetric atmospheric model, an integrated terrestrial biosphere model, and a simple oceanic surface flux scheme. The atmospheric model simulates the atmospheric processes from pole to pole and from the surface layer to the top of the atmosphere, including atmospheric dynamics, radiation, convection, and boundary layer processes. Meridional resolution used in this study is close to 2.5 degree in the tropics and becomes coarser towards the poles. The land-ocean boundary is set at about 6 N (the approximate location of the Atlantic coast), with West African continent in the north and the tropical and southern Atlantic Ocean in the south. For the continental part, the terrestrial biosphere model IBIS (Foley *et al.*, 1996) is used to simulate the land surface processes, plant physiological and phenological processes, as well as ecosystem dynamical processes; for the oceanic part, sea surface temperature is prescribed based on observations, and the oceanic surface flux scheme computes the energy, water vapour and momentum fluxes from the ocean surface to the atmosphere. Due to the zonal symmetry of the model, even though the zonal wind is simulated, variability in the zonal direction is not represented. Further details about ZonalBAM can be found in Wang & Eltahir (2000a). ZonalBAM has been tested against various observations, and has been used to study both the present day climate (Wang & Eltahir, 2000a–e) and palaeoclimate (Irizarry *et al.*, 2002) of West Africa.

Here we carry out two types of experiments using ZonalBAM. The first type of experiments document the model climate for both the biosphere and the atmosphere under different levels of CO$_2$ concentration, using climatological SST in the tropical and southern Atlantic Ocean to force the model. Due to the zonal symmetry of the model, we use the climatological SST averaged between 15 W and 15 E. The purpose of these experiments is to study the mechanisms involved in the response of the

biosphere-atmosphere system to CO_2 changes. Instead of dramatic changes of CO_2 concentration, such as doubling or tripling, we consider four incremental CO_2 levels: 300, 350, 400, and 450 ppmv, and choose 350 ppmv as the control level. It is so designed to avoid the uncertainty that some model physics, though valid for the current climate, may not necessarily apply to future climate under dramatically different (e.g., doubled or tripled) CO_2 concentration. ZonalBAM does not include an interactive ocean model, so the CO_2-induced warming over the ocean cannot be simulated. While the lack of oceanic warming does impact the model results quantitatively, it does not cause qualitative changes in the experiment results, as will be discussed later.

We first run the fully coupled biosphere-atmosphere model at a CO_2 level of 350 ppmv, starting with an initial vegetation distribution close to current conditions, until the model yields a stable biosphere-atmosphere equilibrium, labelled as Control. At this equilibrium, vegetation type and their peak growing season leaf area index are listed in Table 1. To distinguish same vegetation type of different density, the term 'woodland' is used to refer to tree-type vegetation with a lower value of leaf area index than that of 'forest'. Here vegetation type is named after the dominant plant functional type, while the leaf area index presented in Table 1 is the sum of leaf area index for all existing plant functional types. For example, while the dominant plant functional type in rainforest is tropical broadleaf evergreen tree, some drought-deciduous trees can also exist. As shown in Table 1, from the coast northwards, vegetation ranges from dense rainforest to drought-deciduous forest and woodland, then to grassland in Sahel before reaching the Sahara desert. The annual precipitation distribution of this equilibrium is plotted in Fig. 2(a). Our previous studies (Wang & Eltahir, 2000a, b) already showed that the model reproduces West African climate with a reasonable accuracy. In addition, although the model equilibrium captures the main feature of both the vegetation and precipitation distribution in West Africa, it is technically not comparable with observations due to the lack of several disturbance mechanisms in the model (e.g. land use and land

cover changes, fire disturbance). Therefore, without duplicating the effort to compare the model simulation against observations, in this study we focus on the sensitivity of the model climate to CO_2 concentration changes.

Similar to Levis *et al.* (2000), we consider three different forcing mechanisms: the radiative effect ('R') of CO_2 concentration changes, the physiological effect ('P') that represents the response of canopy physiology to CO_2 concentration changes, and the vegetation dynamical effect ('V') that represents the response of vegetation cover to environmental changes (including both the CO_2
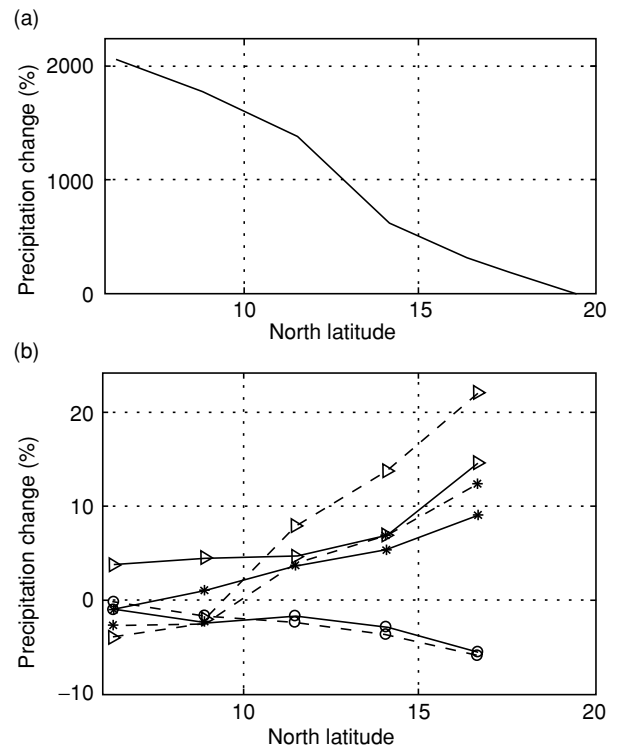
Fig. 2 (a) Annual precipitation in mm/year for the Control climate; (b) CO_2-induced precipitation change in percentage with respect to the Control. Dash lines with 'O', '∗', and '▷' symbols are for experiments R_300, R_400, and R_450, respectively; solid lines with 'O', '∗', and '▷' are for experiments RP_300, RP_400, and RP_450, respectively.

Table 1 Vegetation distribution at the Control climate equilibrium

Latitudes	Vegetation type	Peak LAI (Plant type)
6.0 N−7.2 N	Evergreen Rainforest	~8.4 (trees)
7.2 N−9.7 N	Drought-Deciduous Forest	~6.2 (trees)
9.7 N−12.3 N	Deciduous Woodland	~4.8 (trees)
12.3 N−14.8 N	Grassland	~5.7 (grass)
14.8 N−17.5 N	Grassland	~2.2 (grass)
North of 17.5 N	Desert	< 0.02 (grass)

concentration change itself and the CO$_2$-induced climate changes). With respect to the Control equilibrium climate, three sets of experiments are conducted: set 'R' (including R_300, R_400, R_450) considers only the radiative effect of CO$_2$ changes; set 'RP' (including RP_300, RP_400, RP_450) considers both the radiative and physiological effects CO$_2$ concentration changes; set 'RPV' (including RPV_300, RPV_400, RPV_450) considers the radiative, physiological, and vegetation dynamical effects all together. Here, the experiments are named by the effect(s) considered followed by the level of CO$_2$ concentration in ppmv. This is further elucidated by the experiment conditions listed in Table 2. With vegetation distribution fixed at the Control equilibrium shown in Table 1, experiments R_300, R_400, and R_450 were run for six years to simulate the response of model climate to the radiative effects of CO$_2$, and experiments RP_300, RP_400, and RP_450 were run for six years to simulate the combined impact of the radiative and physiological effects of CO$_2$. Climate conditions averaged over the last five years of the simulation are used for analysis in this study. Due to the long time scale associated with vegetation dynamics, similar to the Control, experiments RPV_300, RPV_400, and RPV_450 are run for several decades until the model evolves into a stable equilibrium. Climate conditions at equilibrium are used for analysis in this study. Note that the Control simulation is in fact a 'RPV' simulation with CO$_2$ concentration at 350 ppmv. Because the seasonal leaf display is predicted by the model, the CO$_2$-induced growing season length changes are included in the model even if vegetation structure is fixed (as in experiments 'Rs' and 'RPs').

A second type of experiments is designed to study the impact of CO$_2$ concentration changes on West African climate in a more realistic scenario. Instead of using the climatological SST forcing, we use the observed SST during the period 1950–97 to drive the model, and keep vegetation dynamic. With dynamic vegetation and the interannual variability of SST in the model, each simulation runs from 1950 to 1997. Experiment Carbon_300 fixes CO$_2$ concentration at 300 ppmv, and experiment Carbon_350 fixes CO$_2$ concentration at 350 ppmv. Here the value 300 is chosen to represent the pre-industrial CO$_2$ level and 350 the modern level. In experiment Carbon_Ob, CO$_2$ concentration varies with time as observed at the Mauna Loa Observatory from 1950 to 1997. These experiments can demonstrate how the biosphere-atmosphere system of West Africa responds to oceanic forcings at different levels of CO$_2$ concentration.

Due to the non-linearity of the coupled biosphere-atmosphere system, the model climate with dynamic vegetation is sensitive to initial vegetation conditions (Wang & Eltahir, 2000b,c). To avoid the uncertainty related to initial conditions, in this study, the Control simulation and all the 'RPV' experiments use the same initial vegetation condition, which is the observed current vegetation distribution. To facilitate an easy comparison with our previous study (which may be of interest to some), all the experiments with observed varying SST (i.e. Carbon_300, Carbon_350, Carbon_Ob) in this study use the same initial vegetation condition as in Wang & Eltahir (2000d). This initial vegetation condition, derived by running the coupled model into equilibrium with CO$_2$ concentration specified at 340 ppmv, is very similar to the vegetation distribution in Table 1, but has slightly lower values of leaf area index.

Results

Sensitivity of the Regional Climate to Increments of CO$_2$ Concentration

Precipitation   Figure 2(b) presents the five-year averages of annual precipitation changes in experiment sets 'R' and 'RP' with respect to the Control climate. Over the forest region in West Africa, precipitation shows little response to CO$_2$ changes; the most significant changes in precipitation take place in the Sahel grassland region; precipitation over the woodland region in between shows moderate response to CO$_2$ changes. Based on Fig. 2(b), results from experiments with different CO$_2$ concentration changes ($-50, +50, +100$ ppmv) are consistent, and systematically demonstrate that precipitation north of 10 N increases with atmospheric CO$_2$ concentration. This statement holds true for both experiment set 'R' that considers the radiative effect alone and experiment set 'RP' that considers the radiative and physiological effects together.

Table 2 Experiment design. 'Prescribed' vegetation indicates that vegetation is prescribed according to that of the Control equilibrium

Experiment name	Vegetation	CO$_2$ for Biosphere	CO$_2$ for Atmosphere
Control	Interactive	350 ppmv	350 ppmv
R_300	Prescribed	350 ppmv	300 ppmv
R_400			400 ppmv
R_450			450 ppmv
RP_300	Prescribed	300 ppmv	300 ppmv
RP_400		400 ppmv	400 ppmv
RP_450		450 ppmv	450 ppmv
RPV_300	Interactive	300 ppmv	300 ppmv
RPV_400		400 ppmv	400 ppmv
RPV_450		450 ppmv	450 ppmv

In experiments R_300, R_400, and R_450, precipitation changes as a result of the radiative effect of CO_2 through several mechanisms: first, as CO_2 concentration increases, radiative warming allows for higher level of atmospheric specific humidity, which causes precipitation to increase; secondly, the CO_2-induced warming and moistening enhance the land-ocean energy gradient, which allows the monsoon circulation to penetrate further inland thus bringing more rainfall to the Sahel. A third mechanism has to do with vegetation feedback at the seasonal time scale. The CO_2-induced increase of precipitation causes an early onset and late offset of the leaf greenness in the water-stressed grassland region, as shown in Table 3 using one grid point from experiment R_450 as an example. This reduces surface albedo and increases evapotranspiration, which feeds back to the atmosphere to further increase precipitation at the beginning and end of the growing season.

Figure 3 plots the seasonal cycle of precipitation distribution over land for the Control climate (Fig. 3a), and differences in precipitation (Fig. 3b) and surface temperature (Fig. 3c) between R_450 and Control. Precipitation over most of West Africa increases at elevated CO_2, except during the middle summer when a northward shift of the rain belt causes a decrease of precipitation near the coast. The CO_2-induced increase of precipitation eases the water limitation on latent heat flux thus cooling the land surface. As a result, despite the general warming effects of CO_2, regional surface cooling occurs at places and during seasons of significant precipitation enhancement.

As shown in (Fig. 2b), with the same amount of CO_2 concentration changes, the magnitude of precipitation changes (defined with respect of the control) in experiments RP_300, RP_400, and RP_450 is significantly smaller than those in experiments R_300, R_400, and R_450, respectively. This difference reflects the physiological effects of CO_2 on water cycle—plant stomata opening decreases as CO_2 concentration becomes higher, reducing stomatal conductance, therefore, transpiration. As a result, the overall evapotranspiration drops, which limits the local water supply to the atmosphere. This works against the increase of atmospheric specific humidity triggered by the CO_2 radiative effect, causing precipitation to decrease from its level in experiments

set R. However, in the context of this model, the CO_2 radiative effect on precipitation overshadows the physiological effect. The net result is precipitation increasing with CO_2 when both effects are considered. This finding is consistent with Sellers *et al.* (1996) and Bounoua *et al.* (1999).

Net Primary Productivity   Changes of CO_2 concentration pose a dramatic impact on the biosphere, which can be illustrated by the net primary productivity (NPP) and plant water-use efficiency at different CO_2 levels. Figures 4a and 5a plots the NPP distribution and the
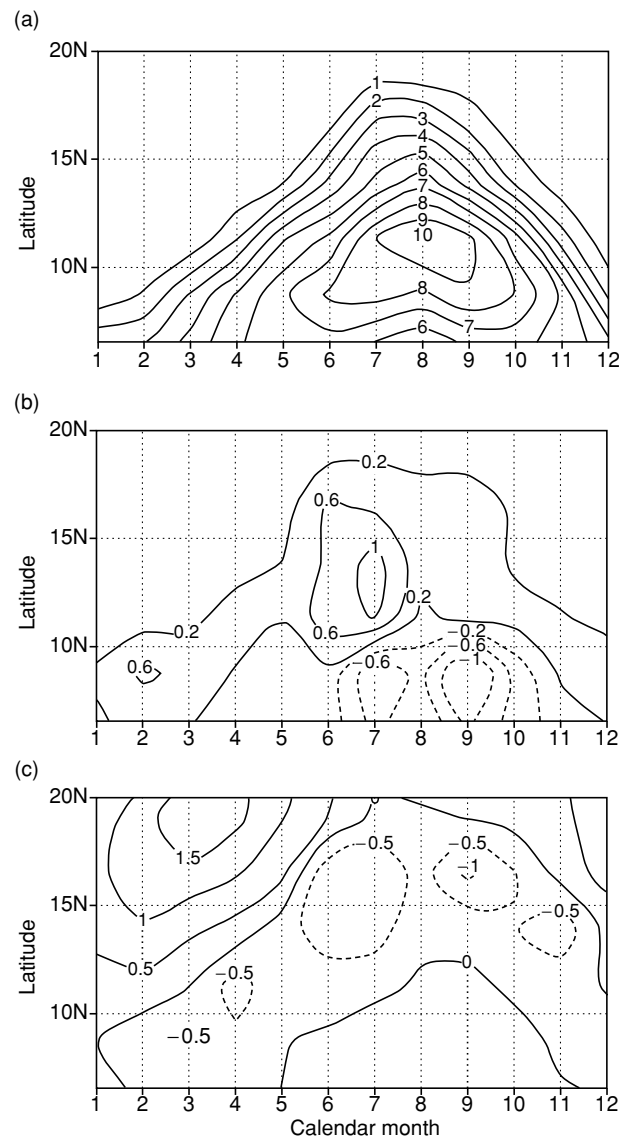

Fig. 3 (a) Seasonal cycle of precipitation over West Africa for the control climate, in mm/day; (b) Precipitation changes (mm/day) and (c) surface temperature changes (K) caused by the radiative effect of CO_2 increasing from the control level 350 ppmv to 450 ppmv: R_450-Control.
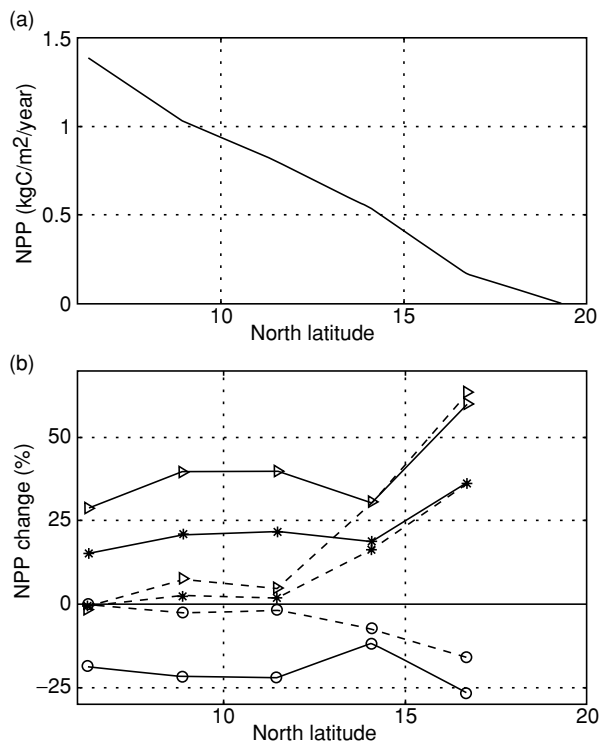
Table 3 Monthly average of green leaf area index at a grassland grid point for Control and experiment R_450

Time	May	June	July	August	September	October	November
Control	0.0	0.04	2.08	2.16	1.78	0.17	0.0
R_450	0.0	0.47	2.16	2.16	2.03	0.37	0.0

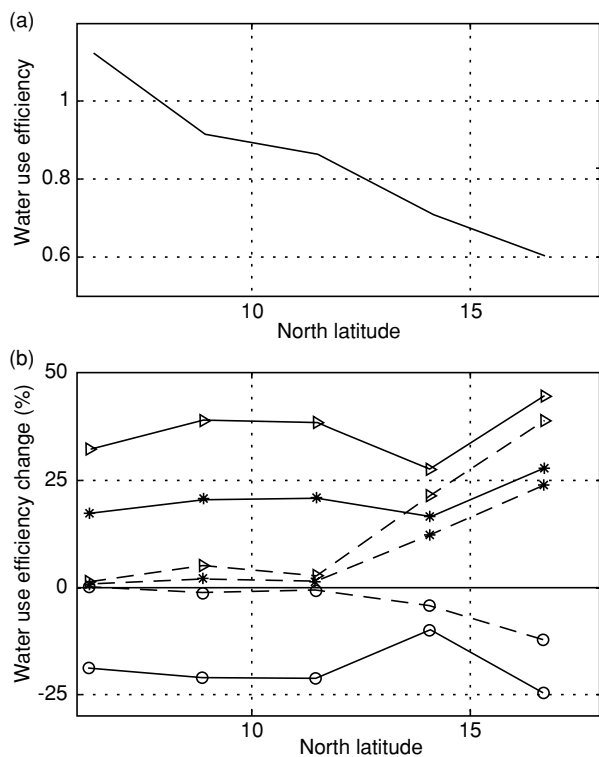**Fig. 4** Same as Fig. 2, but for net primary productivity in kgC/m2/year.

Fig. 5 Same as Fig. 2, but for plant water-use efficiency in kgC/m3.

corresponding plant water-use efficiency for the Control climate. Changes of NPP and water-use efficiency in experiment sets 'R' and 'RP' with respect to the Control are presented in Figs 4b and 5b. In the Control climate, NPP decreases northward as vegetation changes from forest in the south to grassland in the north and climate becomes drier northward. Despite the fact that C4 plants (which include most grass species in the Tropics) tend to be more efficient in water-use than C3 plants (which include most tree species), water-use efficiency decreases northward because of the large water vapour pressure deficit of the atmosphere in arid regions.

The dash lines in Fig. 4(b) document a steady increase of NPP from experiment R_300 to experiment R_450 as CO₂ concentration gradually increases. Since vegetation in experiment set R functions at the control CO₂ level, this increase of NPP is a result of vegetation responding to climate changes (precipitation changes in particular) caused by the radiative effect of CO₂. Vegetation growth over the Sahel grassland region is limited by water availability, which results in a high sensitivity of NPP to CO₂-induced precipitation changes. However, water availability at the land surface is not the only factor causing the NPP changes. Interestingly, as water stress eases, plant water-use efficiency also improves (dashed lines in Fig. 5b), perhaps as a result of reduced water vapour deficit due to the increase of atmospheric humidity. This is another important factor contributing to the response of NPP to CO₂ changes in experiment set 'R'. Over the forest region in the south, little change in NPP takes place in experiment set R both because of the insignificance of precipitation changes and because water is unlikely the limiting factor for vegetation growth there.

The difference between dashed lines and the corresponding solid lines in (Fig. 4b) quantifies the biosphere productivity changes resulting from the physiological effect of CO₂. Over the tree-covered region of West Africa, the model simulates a dramatic positive response of NPP when the physiological effect of CO₂ is included in experiment set 'RP'; in the Sahel grassland region, including the physiological effect in experiment set 'RP' causes little change in the amount of NPP, which indicates an increase of plant water-use efficiency, given the precipitation reduction as shown in Fig. 2b. In fact, plant water-use efficiency all over West Africa is considerably higher due to the physiological effect of CO₂ enhancement (Fig. 5b).

The physiological effect of CO₂ on vegetation productivity occurs mainly through two routes, one direct and one indirect. CO₂ concentration at the site of plant carboxylation increases with that in the atmosphere, thus directly enhancing the leaf carbon assimilation rate for plants whose photosynthesis is not CO₂-saturated. The significant responsiveness of NPP in the southern part of

West Africa shown in Fig. 4b is a reflection of this direct effect. Elevated atmospheric CO_2 concentration reduces the requirement for gas exchange, causing partial closure of leaf stomata, which reduces stomatal conductance and transpirational water loss. As a result, plant water-use efficiency increases (Fig. 5b), leading to a positive impact on productivity, especially where vegetation is water-stressed (e.g. in Sahel). This indirect effect of CO_2 on vegetation productivity through plant-water relation takes place irrespective of photosynthetic pathway, while the direct effect of CO_2 enrichment in our model occurs mostly to plants with C3 photosynthetic pathway (to which belong most tree species with few exceptions). The traditional notion that the photosynthesis of C4 plants (to which belong the dominant grass species in Sahel) shows little favourable response to CO_2 enrichment also applies to our model. Therefore, NPP in the grassland region (north of 12.5 N) responds to CO_2 mainly through plant-water relation. As a result of the stomatal conductance changes at elevated CO_2, plant water-use efficiency increases but precipitation decreases in experiment set 'RP' from their corresponding levels in experiment set 'R'. These two factors offset each other in their impact on photosynthesis, causing little NPP difference between experiment sets 'R' and 'RP' in the Sahel region.

Vegetation Dynamics The large magnitude of CO_2-induced NPP changes will impact the vegetation structure and density if vegetation dynamics is allowed. Changes in vegetation would then further modify the regional climate. In particular, precipitation over the Sahel region is expected to increase as a result of local vegetation enhancement (Xue & Shukla, 1996; Zheng & Eltahir, 1997). Moreover, denser vegetation in the neighbouring region south of Sahel also brings more rainfall to the Sahel (Zheng & Eltahir, 1997). Such feedback between vegetation and regional climate is included in experiment set 'RPV'.

Figure 6 presents the leaf area index and annual accumulated precipitation at the equilibrium climate under different CO_2 levels derived from experiments RPV_300, Control (equivalent to RPV_350), RPV_400, and RPV_450 that consider the full impact of CO_2 concentration changes. Not surprisingly, as CO_2 increases, vegetation grows denser (i.e. leaf area index becomes larger) for both the forest in the south and grassland in the north (Fig. 6a). As discussed earlier, over the Sahel region where C4 grass dominates the biome, vegetation enhancement results from (1) increased precipitation due to the radiative effect of CO_2 and (2) increased water-use efficiency due to the physiological effect of CO_2; over the region to the south colonized by various tree species, denser vegetation is mainly caused by the direct stimulation of carbon assimilation by the physiological effects of
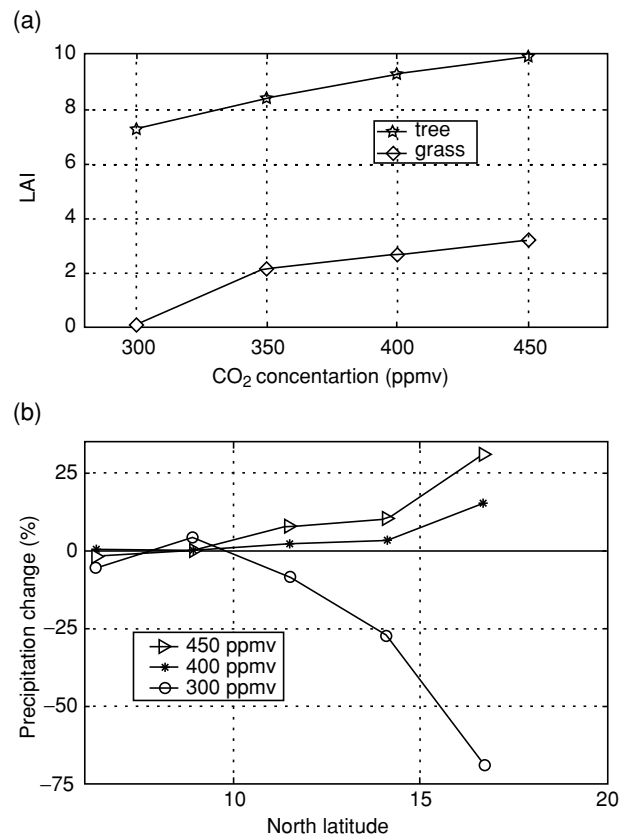

Fig. 6 (a) Increase with CO_2 concentration of the peak growing season leaf area index for rainforest near the coast and grassland near the desert; (b) Precipitation changes (in percentage with respect to Control) caused by the full impact of CO_2 concentration changes in experiments RPV_300 (–O–), RPV_400 (–*–), and RPV_450 (–▷–).

CO_2, known as 'CO_2 fertilization'. Due to the high sensitivity of the Sahelian climate (precipitation in particular) to vegetation changes and the fact that precipitation is the limiting factor for vegetation growth in Sahel, the feedback between vegetation and climate also contributes significantly to the increase of precipitation and grass leaf area index at elevated CO_2. Therefore, the precipitation differences among different 'RPV' experiments (Fig. 6b) are generally larger than those among different 'RP' experiments (Fig. 2b). Overall, in the context of the model, as CO_2 level goes up, vegetation grows denser everywhere over West Africa; precipitation increases in Sahel, but shows little response near the coast in the south. Speaking of the biosphere and the atmosphere as a whole, when the full impact of CO_2 concentration change is considered and within the range of CO_2 changes experimented in this study, the regional climate system becomes wetter and greener at higher CO_2 level.

It is worth emphasizing that the significant response of precipitation in Sahel results from the interplay of several

factors, including the radiative effects of elevated CO_2 causing precipitation to increase, the physiological effects of elevated CO_2 causing precipitation to decrease, and the feedback due to vegetation structure changes (including the increase of leaf area index both locally and in the neighbouring region to the south) causing precipitation to increase. For example, as CO_2 concentration increases from 350 ppmv to 450 ppmv, precipitation averaged between the two grassland grid points increases by 19%, to which the radiative effect contributes $+17\%$, the physiological effect -6%, and vegetation structural feedback $+8\%$. Part of the $+17\%$ attributable to the radiative effect is caused by vegetation feedback at the seasonal time scale, as shown in Table 3. Therefore, the documented 8% due to vegetation structural changes is only part of the total contribution by vegetation feedback. Vegetation dynamics stands out as an important factor contributing to the response of Sahelian precipitation to atmospheric CO_2 concentration changes.

Due to the lack of an interactive ocean model, the above experiments do not include the impact of elevated CO_2 on sea surface temperature. Warmer SST will reduce the energy gradient between land and ocean, thus weakening the monsoon circulation. Therefore, our experiments tend to overestimate the response of precipitation to the radiative effect of CO_2 concentration changes. Specifically, the increase of precipitation due to elevated CO_2 is likely to be less significant if an interactive ocean model is included. To address this uncertainty, we carried out several experiments that include a certain degree of SST changes proportional to the CO_2 concentration changes derived based on the CO_2-induced global warming simulated by the National Center for Atmospheric Research's Community Climate System Model (NCAR CCSM) (Meehl *et al.*, 2000). These experiments (not shown here) indicate that including oceanic warming in our model will not cause qualitative changes in the response of the regional climate in West Africa to the incremental CO_2 concentration changes. It is worth pointing out that the lack of an interactive oceanic model does not impact our experiments on the SST-forced variability of the regional climate as presented in the following, since these experiments are driven by the observed SST forcing.

SST-Forced Variability of the Regional Climate

Based on the understanding developed in the previous section on how changes of CO_2 concentration influence the West African climate under climatological SST forcing, here we address how changes of CO_2 concentration influence the forced variability of this regional climate by the observed SST during the period 1950–97.

Figure 7 plots the annual precipitation and NPP during 1950–97 simulated in experiment Carbon_300 which assumes a CO_2 concentration of 300 ppmv. Both rainfall and the net primary productivity show a clear decreasing trend after the 1950s towards the end of the twentieth century, not only in Sahel but also in the rest of West Africa. Such a desiccation all over West Africa after the 1950s is consistent with observations that the major drought in the past three decades is not limited to the Sahel region alone (Le Barbe *et al.*, 2000). It appears that this drought is most severe near the desert border, considering both the base rainfall in the 1950s and the magnitude of precipitation reduction after the 1960s. For an easier comparison, the red lines in (Fig. 8) show the temporal evolution of precipitation and grass leaf area index in experiment Carbon_300 for a specific grid point at 16 N near the desert border. The gradual loss of productivity in Fig. 7b reflects a drought-induced vegetation degradation (red line in Fig. 8b) that also feeds back to enhance the drought (red line in Fig. 8a). In fact, the vegetation degradation at this specific grid point becomes a complete loss of vegetation cover by the early 1970s and shows no recovery by the end of the
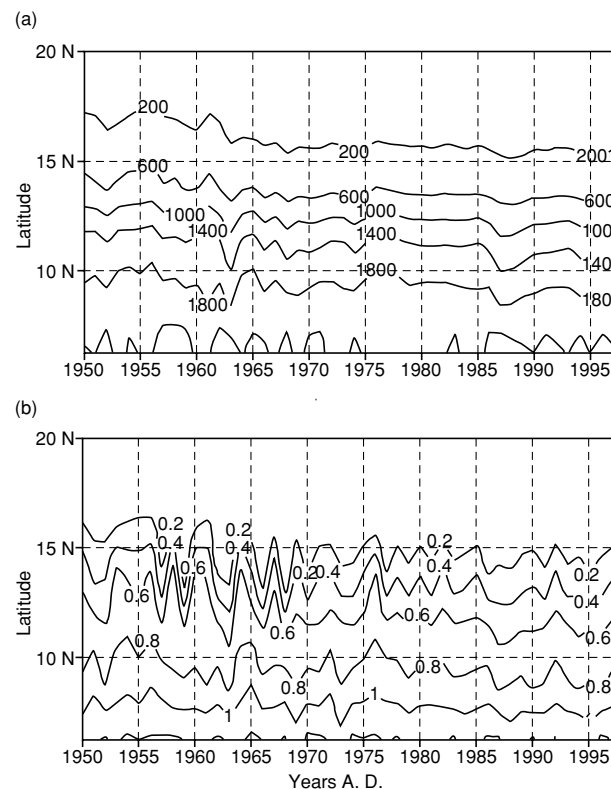

Fig. 7 (a) Annual precipitation (mm/year) and (b) Net primary productivity (kgC/m2/year) over West Africa, simulated by experiment Carbon_300 with CO2 concentration prescribed at 300 ppmv and SST varying as observed from 1950 to 1997.
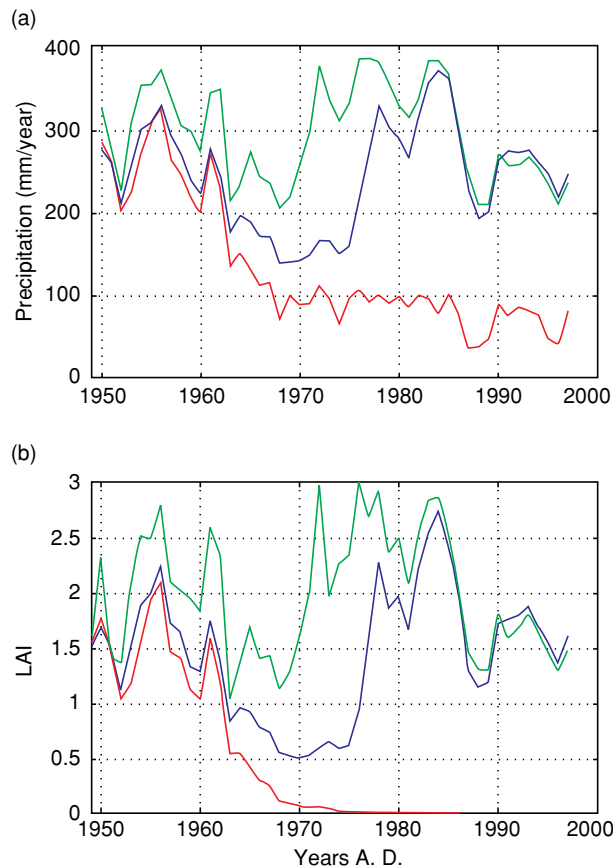
(a)

(b)

Fig. 8 (a) Annual precipitation (mm/year) and (b) the peak growing season leaf area index at the grassland grid point near 16 N (close to the desert border), simulated by experiments Carbon_300 (red lines), Carbon_350 (green lines), and Carbon_Ob (blue lines).

(a)

(b)

Fig. 9 Same as Fig. 8, but for experiments Sens-SST (green lines) and Sens-Veg (red lines). Note that vegetation in Sens-Veg is prescribed.

simulation period in the late 1990s. However, with the same SST forcing but assuming a higher CO_2 concentration of 350 ppmv, experiment Carbon_350 does not produce such a persistent drought and vegetation loss. Instead, Carbon_350 simulates a drought that is interrupted by a long wet episode spanning the 1970s and early 1980s, as shown by the green lines in Figs 8a, b.

Our previous studies (Wang & Eltahir, 2000b–d) using the same model documented that the synchronously coupled biosphere-atmosphere system in West Africa has multiple climate regimes. External forcings (e.g. man-made land cover changes, SST variability) can trigger a positive feedback between the biosphere and the atmosphere, which eventually leads to a transition of the regional climate from one regime to another. A comparison between the Carbon_300 climate in Fig. 8 and the two climate regimes documented by Wang & Eltahir (2000c) suggests that the persistent drought simulated in experiment Carbon_300 is a result of a
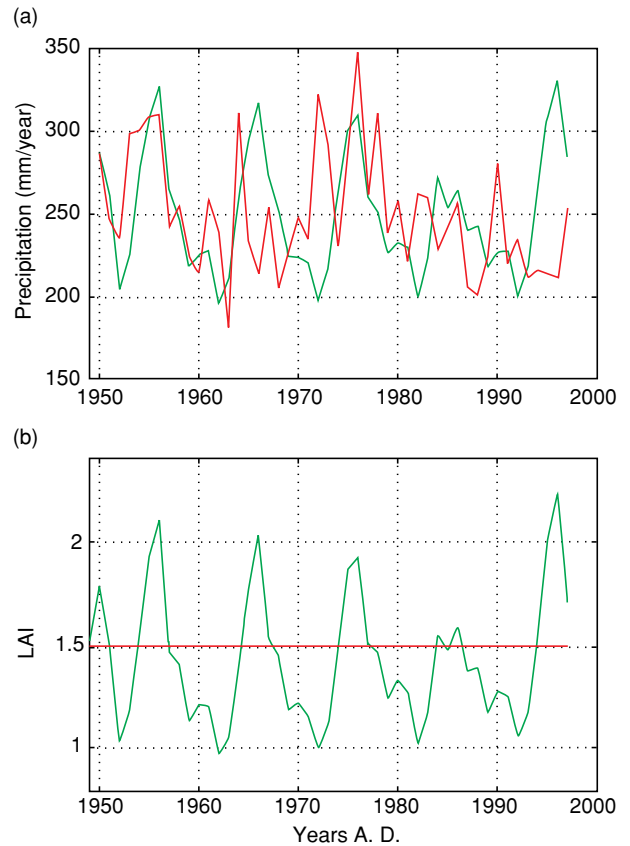
climate transition from its wet/green regime to its dry/barren regime.

To help understand how this climate transition towards the dry regime occurs, two additional sensitivity experiments are carried out here, both assuming a CO_2 concentration of 300 ppmv. In Sens-SST, instead of using the observed SST during 1950–97 as experiment Carbon_300 does, the model forcing repeats the SST observation of the period 1950–59; in Sens-Veg, SST forcing is the same as in Carbon_300, but instead of simulating vegetation dynamics, the model assumes static vegetation throughout the simulation period. The annual precipitation and grass leaf area index at 16 N for these two sensitivity experiments are shown in Figs 9a, b. Results from Sens-SST (green lines in Fig. 9) show that, if SST in the tropical and southern Atlantic Ocean after 1960 had stayed at the same level as in the 1950s, the healthy biosphere-atmosphere system of the 1950s would have survived, wet enough to support a decent grass cover for the following several decades. It is the SST forcing in the 1960s that has triggered the transition of the biosphere-atmosphere system towards its dry regime.

A close examination of the SST anomaly indicates that the 1960s include a number of years of significant warming over the Tropical and Southern Atlantic ocean, which favours a smaller land-ocean contrast and weaker monsoon circulation thus reducing precipitation over the Sahel. The most remarkable warming event occurred in 1963, with a warming of more than 1.8 degrees persisting from April to October throughout the whole rainy season for West Africa. While persistent SST warming occurred several time in the past century, majority of those warming events were either of a smaller magnitude in terms of the absolute temperature change or out of phase with the summer monsoon season, and therefore, did not result in significant precipitation reduction. The warming event of 1963 differs from others in that the persistent warming in 1963 was of a very large magnitude and was right in phase with the summer monsoon season, which caused dramatic rainfall reduction and consequently vegetation degradation in Sahel within the context of the model. Before the regional biosphere-atmosphere system fully recovered from this natural disturbance, subsequent oceanic warming events in 1966, 1968, and 1973–74 further enhanced the dought condition and eventually caused the regional climate system to evolve into its dry regime.

However, such an SST-induced climate transition towards dry conditions as presented in Fig. 8 would not have been possible without the feedback due to vegetation dynamics, as shown by the results from experiment Sens-Veg (red lines in Fig. 9). Clearly, the simulated drought in experiment Carbon_300 results from a wet-to-dry climate transition that is triggered by oceanic forcings, enhanced and sustained through biosphere–atmosphere interactions. The regional climate at higher CO$_2$ level in experiment Carbon_350 (green lines in Fig. 8) recovers easily from a dry spell caused by the same SST forcing, favouring the wet regime over the coexisting dry regime. This suggests that, at the decadal time scale, the response of this regional climate to SST forcing depends critically on the level of CO$_2$ concentration. As CO$_2$ level goes up, the biosphere-atmosphere system in West Africa becomes more resilient to the drought-inducing SST forcing. This higher resilience stems from a faster vegetation growth due to CO$_2$-induced climate and physiological changes.

When the observed CO$_2$ concentration is used in experiment Carbon_Ob, the model climate (blue lines in Fig. 8) falls in between those of Carbon_300 and Carbon_350. This is not surprising since the CO$_2$ concentration during most of the simulation period is between 300 and 350 ppmv, increasing from about 311 ppmv in 1950 to 350 ppmv in 1987–88 and to above 370 in the late 1990s. The Carbon_Ob climate features a severe drought spanning the 1960s and 1970s, a short wet episode in the

1980s, and a relatively dry episode in the 1990s. The drought of the 1960s and 1970s simulated in Carbon_Ob is a result of biosphere–atmosphere interactions enhancing (and persisting) a dry condition initiated by changes of SST forcing in the late 1960s. This is similar to the drought development mechanism in Carbon_300, but different in that with the help of the higher CO$_2$ concentration in Carbon_Ob, SST forcing is able to bring wet conditions back by the early 1980s. Although the wet spell in the 1980s was not observed, several features of the drought simulated by Carbon_Ob are consistent with observations (Fig. 1). These include the timing of the drought onset in the late 1960s, the timing of the worst drought consequence in the early 1970s, and the fact that the drought becomes less severe in the 1990s than in the 60 s and 70 s. While reproducing observations is not the purpose of this study, such agreement with observations is nevertheless encouraging. Discrepancy between model simulation and observations may reflect the existence of other drought-inducing factors in addition to SST and natural vegetation dynamics. Of those, land use and land cover changes come at the top of the list (Wang & Eltahir, 2000d).

Discussion and conclusions

This paper focuses on the response of the regional climate system in West Africa to CO$_2$ concentration changes. Numerical experiments using a coupled biosphere-atmosphere model demonstrate that changes in CO$_2$ concentration impact not only the mean climate of West Africa but also the forced variability of this regional climate by the Atlantic sea surface temperature.

Over the Sahel region, with the same prescribed vegetation distribution, precipitation increases with CO$_2$ concentration, reflecting an intensified regional hydrological cycle. This positive response of precipitation to CO$_2$ results from two competing factors: the radiative effect of CO$_2$ enhancing precipitation; the physiological effect of CO$_2$ reducing transpiration and subsequently reducing precipitation. Overall, in terms of their impact on precipitation, the radiative effect overshadows the physiological effect and brings more rainfall to the Sahel. Over the forest region in the southern part of West Africa, precipitation shows little response to either of these two effects.

Net primary productivity over the whole West Africa increases significantly with CO$_2$ concentration. Over the forest region, enhancement of productivity results from direct CO$_2$ fertilization effect; over the grassland region where C4 plants dominate, direct enhancement of carbon assimilation rate is minimal in the model due to the photosynthesis saturation assumption, but productivity goes up both as a result of CO$_2$-induced precipitation increase and as a result of water-use efficiency

improvement. Plant water-use in the grassland region becomes more efficient both because of the reduced water vapour deficit in the atmosphere and because of the reduced stomatal conductance. Water-use efficiency of the forest improves as a result of direct carbon assimilation enhancement on one hand and reduced stomatal conductance on the other.

As a result of productivity changes, vegetation grows denser at higher CO_2 level when vegetation dynamics is allowed. In the Sahel region, such changes in vegetation feed back to the atmosphere, which increases precipitation and reinforces the response of climate to CO_2 concentration changes. This generally 'healthier' biosphere-atmosphere system at elevated CO_2 level shows greater resilience to disturbances, especially to those that tend to degrade the coupled system. With CO_2 fixed at the preindustrial level, the observed Atlantic SST anomaly during the 1960s can trigger a transition of the biosphere-atmosphere system in West Africa from a wet (and green) regime to a drier (and less productive) one that sustains itself for more than three decades. However, when CO_2 concentration is fixed at the modern level, the same SST forcing can no longer trigger such a dramatic climate transition.

The CO_2-induced increase in the resilience of the biosphere-atmosphere system has significant implications regarding future climate changes. External forcings or disturbances enough to push the regional climate system into a sustained drought episode in the past may no longer be able to do so in the future as CO_2 concentration increases. In the event that a drought episode does take place, the CO_2 enrichment makes it easier for the regional climate system to recover towards its wet and healthy conditions. The overall result would be a future climate that features longer (or more frequent) wet episodes and shorter (or less frequent) dry episodes than in the past. Such expected regional climate changes would suppress the impact of land cover changes such as desertification and favour a more sustainable regional environment. Globally, as concluded by the IPCC (2001b), projected CO_2-induced climate change will have beneficial and adverse effects on both environmental and socio-economic systems. Our finding suggests that the region of West Africa may experience considerable beneficial effect.

In this study we focus on the response of natural biosphere-atmosphere system to CO_2 concentration changes. The impact of anthropogenically induced land cover changes, which is comparable to that of CO_2 concentration changes in some regions of the world (Chase *et al.*, 2001; Eastman *et al.*, 2001), is not considered here. During the late twentieth century in West Africa, human activities have significantly degraded the vegetation cover, leading the regional climate towards a drier condition

(Clark *et al.*, 2001). In addition, degraded vegetation may not respond to the CO_2 fertilization effect as robustly as the healthy vegetation does, which also favours a drier climate than that simulated by experiments Carbon_Ob. The lack of consideration for human disturbance may have contributed to the discrepancy between the observed persistent drought in the past three decades and the simulated rainfall recovery during the drought in our model when driven with the observed SST and CO_2 forcing. The twentieth century Sahel drought may have been triggered by SST forcing or land cover changes or more likely by the combination of both. However, as demonstrated by Wang & Eltahir (2000d), regardless of what the trigger is, feedback due to vegetation dynamics significantly enhances the impact of the triggering forcing and leads to the persistence of the major drought.

While the biosphere model IBIS includes a state-of-the-art representation of the direct effects of CO_2 on vegetation, the physiological effect of increasing CO_2 concentration considered in our study does not include changes in the whole-plant allocation or nutrient cycling, similar to Levis *et al.* (2000). It is also important to recognize that some of the results presented here are presumably dependent on how the biosphere responds to CO_2-induced climate changes, which differs significantly between different dynamic global vegetation models (Cox *et al.*, 2000; Cramer *et al.*, 2001; Friedlingstein *et al.*, 2001; IPCC, 2001a). The response of ecosystem to climate changes has been identified by IPCC (2001b) as a key uncertainty in projecting future changes and in assessing their regional and global impact. Significant effort is needed in order to reduce the range of this uncertainty. Before similar studies using other dynamic global vegetation models are carried out, understanding and interpretation of the current results should be based on the context of the specific model being used.

Another limitation of this study has to do with the lack of zonal variability and zonal disturbance in the model. Only the impact of SST anomaly over the Tropical and Southern Atlantic is considered, while Global SST forcing cannot be represented in our zonally symmetric model. Due to the lack of zonal disturbance, the internal variability of the model is small under fixed SST forcing. Research using a 3-D coupled biosphere-atmosphere model is necessary to address the uncertainty related to the zonal symmetry of the model.

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