JP1.26 CLIMATE VARIABILITY IN A SIMPLE MODEL OF LAND-ATMOSPHERE INTERACTION

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1. INTRODUCTION

Land-atmosphere interaction includes complex feedbacks among soil, vegetation, and atmosphere. Heterogeneity of land surface properties and the chaotic nature of the atmosphere hinder our understanding of land-atmosphere interaction. All kinds of efforts (e.g., remote sensing, field experiments) have been made to study these processes. Currently, modeling is still a primary approach due to limited observations, especially for long-timescale processes. Land cover change can change not only the mean climate but also the climate variability. In many cases, climate variability change comes with land use change (Voldoire and Royer, 2004), and the extreme climate (e.g., drought and flood) may be more important for us than the mean climate.

Vegetation is a primary site for the exchange of water, energy, and momentum between land and atmosphere. As a slow component in the climate system, vegetation is important for regulating climate variability from seasonal (Xue et al., 2004; Levis and Bonan, 2004) to decadal timescales (Zeng et al., 1999; Wang and Eltahir, 2000). With the development of dynamic global vegetation models (DGVM) and their coupling with GCMs, the community began to study two-way biosphere-atmosphere interactions, but the coupled GCM-DGVM runs are still not very common because they require long-term integration and large computational resources.

This study develops a simple model that can be used to study qualitatively the role of the land surface processes on long-term climate variability and computationally efficient. It includes land surface processes important for long-term climate variation, and an empirical relation between precipitation and other variables. Due to its simplicity, it is easy to change any part of the model and study the role of different components for climate variation.

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2. MODEL DESCRIPTION

A simple model is developed to simulate the major biophysical processes in the long-term land-atmosphere interaction. It includes bulk soil hydrology, dynamic vegetation, and land-atmosphere interaction processes. Energy balance is not calculated, but we prescribe an idealized seasonal cycle for some variables to describe the variations related to heat and temperature. The model simulates the land surface fluxes at large spatial and long temporal scales by statistically taking into account smaller and faster scale variations, so it is suitable for interannual to interdecadal study. It is not intended to give a precise description of the land surface processes and their interaction with the atmosphere, but to describe the processes important for long-term climate variation and hence study the role of land surface processes in climate variability. Detailed description of the model and its implementation is in Wei et al. (2005). Here we only give some description of the dynamics vegetation and precipitation, which is important for the understanding of the experiment results.

The simple dynamic vegetation model is based on the simple LAI model of Zeng et al. (1999), but adds a seasonal time-dependence to model the seasonal variation of vegetation (leaf phenology). This model considers the dependence of photosynthesis on light, soil moisture, and temperature by retaining the major biophysical aspects of some complex dynamic vegetation models (e.g., Foley et al., 1996), but sidesteps the carbon cycle completely. It predicts LAI L once a day as

$$\frac{\partial L}{\partial t} = a\beta_1(1-e^{-k_p L}) - \frac{L}{\tau}, \qquad (1)$$

and predicts potential maximum LAI L_w annually as

$$\frac{\partial L_w}{\partial t} = b\beta_2(1-e^{-k_p L_w}) - \frac{L_w}{\tau_w}. \quad (2)$$

L, L_w > 0. The first terms on the rhs of equations (1) and (2) represent photosynthesis while the second terms represent vegetation losses. k_p is the extinction coefficient of photosynthetically active radiation. τ is the leaf growth (phenology) timescale, which is vegetation-dependent. τ_w is the timescale of vegetation type transition (succession) and depends on climate, vegetation and soil properties. L_w is the maximum leaf area that currently can be supported, so it is associated with vegetation types. For instance, trees have larger L_w than grasses because they can support more leaves. For a certain area, L can never exceed L_w. L_w is not related to current LAI and only related to climate condition and vegetation types. The soil moisture and temperature stress for leaf growth β_1 ($0 \le \beta_1 \le 1$) is calculated as

$$\beta_1 = [\eta'(S_v)]^q \xi(t), \quad (3)$$

where ξ is radiation and temperature stress, which has seasonal cycle:

$$\xi(t) = \overline{\xi} + \sigma_\xi \sin(2\pi t / T), \quad (4)$$

and $0 \le \xi \le 1$. For vegetation succession, we only consider water stress because temperature stress is less important in tropical and subtropical areas that more interest in (Nemani et al., 2003):

$$\beta_2 = [\eta'(S_v)]^q. \quad (5)$$

The coefficients a, b are chosen such that under optimal climate conditions (β_1=1, β_2=1) vegetation would grow to its maximum LAI (L= L_w, L_w = L_x), so

$$a = \frac{L_w}{\tau(1-e^{-k_p L_w})}, \quad (6)$$

$$b = \frac{L_x}{\tau_w(1-e^{-k_p L_x})}. \quad (7)$$

L_x is the maximum LAI given as 6.

Although the vegetation model only describes the natural growth of vegetation, the influence of human activities can be added by prescribing some variables. For example, a sudden deforestation can be included by taking L= L_w =0.01 (this is the prescribed minimum LAI to make vegetation be able to start again in the model), and L_w and L can be given values to represent planting. The initial value of L_w depends on what vegetation type you plant, and sapling should has larger L_w than seed.

Precipitation has much uncertainty due to its large temporal and spatial variability. A random time series is added to describe the temporal variability:

$$P = ET \cdot PE / \rho + \sigma \cdot R(t), \quad (8)$$

where *ET* is evapotranspiration (ET), *PE* is precipitation efficiency (PE), which is associated with both local and large scale factors (Eltahir and Bras 1996). ρ is the recycling ratio defined as the ratio of moisture from local ET versus the total of local ET and horizontal transport (Trenberth, 1999), and it has a seasonal cycle (Brubaker et al., 1993). The last term of (8) is a random time series to describe the uncertainty of precipitation due to the external variability, such as from ENSO, and the internal variability from atmospheric dynamics. *R* is noise, and σ is its forcing strength.

3. MODEL RESULTS

The model is used to examine two questions in the study of climate variability with a series of sensitivity experiments: 1) influence of initial vegetation on long-term climate variability; 2) climate variability of cropland.

3.1 Initial Land Cover and Climate Variability

Several 50-year runs are performed with different initial L_w values of 2, 3, 4, and 5 to represent different initial vegetation types. All initial LAIs are given as 1 because we found that the initial LAI is not important for long-term variability. Without outside forcing, small initial L_ws tend to lead to a dry equilibrium while large initial L_ws lead to a wet equilibrium (Figure 1a). It has been demonstrated in many studies that the water-constrained biosphere-atmosphere system tend to go to a stable dry equilibrium or a stable wet equilibrium without outside forcing (Wang, 2004; Zeng and Neelin, 2000; Zeng et al., 2004), and theoretical analysis of our model also shows such a feature. When we add a weak red noise forcing to the rainfall (forcing strength σ =0.2), the different runs still stay at their dry or wet regime but with some variability (Figure 1b). When a stronger noise is added (σ =0.8), the different runs converge to a state between the dry and wet equilibriums, which means that the influence of initial values has disappeared at the forcing of the noise (Figure 1c). The stronger the forcing, the faster they converge.

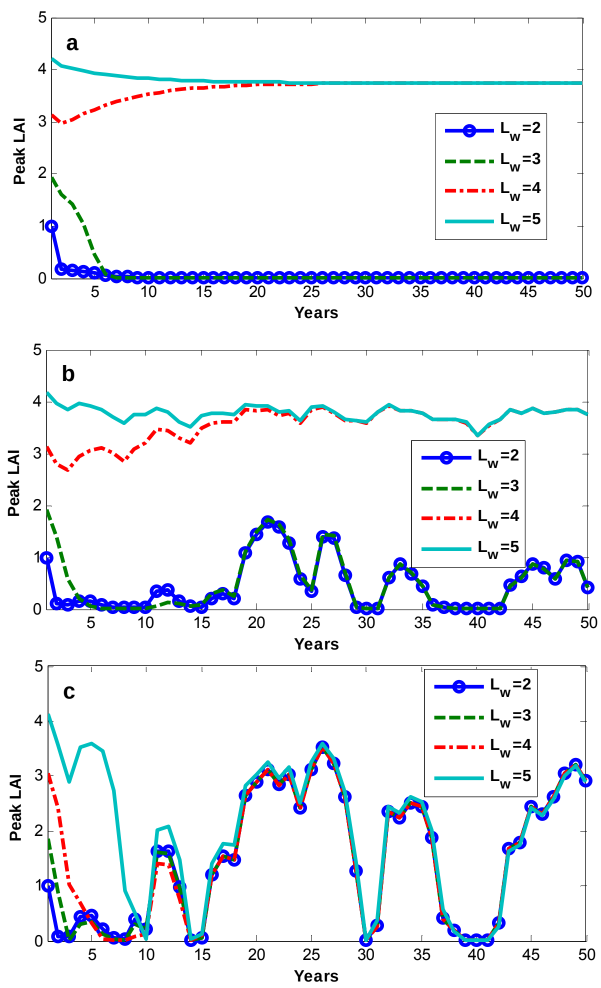

Figure 1. Peak LAI from four 50-year model runs with different initial L_w values (a) without outside forcing, (b) forced by a red noise with forcing strength σ =0.2, and (c) forced by the same noise with forcing strength σ =0.8. Vegetation cover f =80%.

This is the mechanism of African Savanna formation talked about in Zeng and Neelin (2000). At the forcing of interannual variability, the desert climate in the north and forest climate in the south converge to an intermediate Savanna climate. Moreover, it tells us the strength of land-atmosphere interaction is influenced by outside variability, as demonstrated in the analysis of Hu and Feng (2004). These studies have some implications for the regional climate change like in Amazon, Sahel, and Congo basin. How the local climate will change depends not only on the local land use change, but also on the frequency and strength of external forcing (e.g., SST and ENSO) and atmospheric internal variability. Enough outside forcing can shift the climate regime between wet and dry. Our experiments show that strong low frequency forcing has the most significant effects.

The basis of these results is that the vegetated area is little disturbed by human activities and can develop naturally. If the vegetation is human managed, like crops, the results are different, as now discussed.

3.2 Agriculture and Climate Variability

About one third of the Earth's land surface is currently occupied by croplands or pastures (Ramankutty and Foley, 1998), and more land has been disturbed in some way by human beings. Cropland as a human managed land surface is greatly influenced by planting, fertilization, irrigation, and harvesting. Its energy partition, seasonal cycle, and long-term variability can be very different from that of natural vegetation (Adegoke et al., 2003; Shen et al., 2004). Recent studies have been mainly concerned about observed and model simulated climate changes cause by agricultural practices (Segal et al., 1989; Lyons et al., 1993; Bonan, 2001; Govindasamy et al., 2001; Boucher et al., 2004; Cooley et al., 2005). Farming is a long-term continuous human activity on the land surface, it certainly can change the local mean climate to some extent, but it also may influence climate variability. For example, agricultural drought has been a long-term concern (e.g., Glantz, 1994), but whether agriculture can cause drought is still unknown. The community has realized the importance of cropland and is better

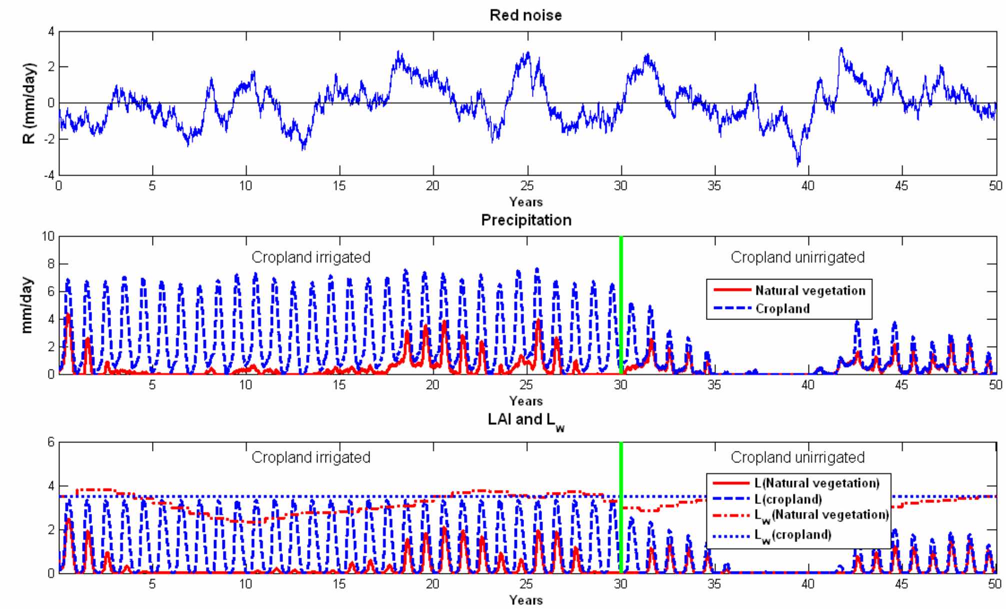

Figure 2. Precipitation, LAI and L_w from two 50-year runs for natural vegetation (interactive L_w) and cropland (L_w fixed at 3.5). The precipitations are forced by a red noise R, and forcing strength σ =3. The cropland is irrigated for first 30 years (left of the vertical green line), and the last 20 years is unirrigated. Initial L_w for natural vegetation is 3.5, and fractional vegetation cover f =75% for both.

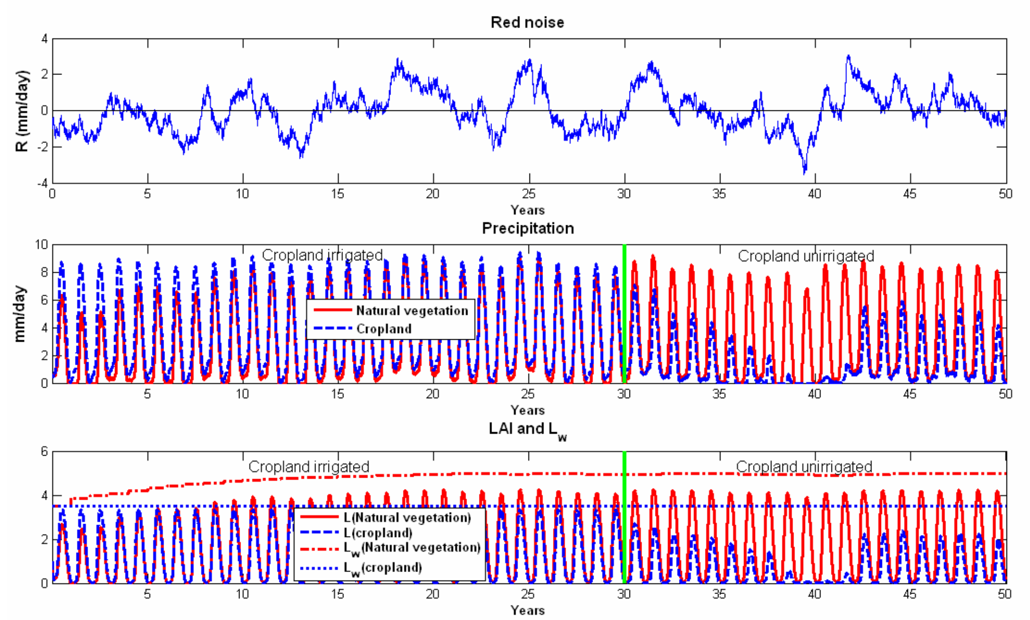

Figure 3. Same as Figure 2 except fractional vegetation cover f =98%.

incorporating it into climate system models (Kucharik, 2003; Gervois et al., 2004; Scholze et al., 2005). This is a complex long-term work. Here we use our simple model to address this problem.

Several 50-year runs are carried out for natural vegetation and cropland. For natural vegetation, L_w is interactive; while for human managed cropland, the LAI cannot exceed a certain limit, so we fix L_w at 3.5 here. For the first 30 years of the 50-year integration, the cropland is irrigated by setting the soil wetness of the vegetated land at 95% of field capacity. The last 20 years is unirrigated due to overwithdrawal of groundwater or other reasons. There are two experiments. In the first experiment, the fractional vegetation cover is set as 75% for both natural vegetation and crops (Figure 2), while in the second experiment we increase it to 98% (Figure 3). The first experiment corresponds to a dry climate, and the second one corresponds to a wet climate because without outside forcing the climate in the two cases will finally go to dry and wet equilibriums, respectively. When irrigated, the crops maintain a high peak LAI in both dry and wet climates, and the agricultural area can get more rainfall than the natural area in dry climate when water is the main stress for ET. However, cropland is vulnerable to drought if not irrigated, and it is more vulnerable than natural vegetation in the wet climate because of its small LAI from the L_w limit, while natural vegetation has larger L_w and LAI in the wet climate.

In conclusion, croplands are vulnerable to drought in both dry and wet climates if irrigation is not sufficient because of their small vegetation amount and limited control on climate. Clearing the land for agriculture can change the local dry climate by bringing more rainfall if it is well irrigated, or change the local wet climate by decreasing the rainfall if irrigation is not sufficient. These hypotheses need to be confirmed by GCMs coupled with complex ecosystem models with crops.

4. DISCUSSION AND CONCLUSIONS

This study develops a simple model of land-atmosphere interaction to study the role of land surface processes in long-term climate variability. Although it is simple, the model is able to capture the basic features of land surface control on ET at seasonal timescale and simulate long-term biosphere-atmosphere interactions. It is used to study several important problems involving long-term land-atmosphere interaction. The major findings are: 1) The impact of land cover on local climate is influenced by outside variability; 2) Human managed cropland is vulnerable to climate fluctuations if irrigation is not sufficient, but it can alleviate the local dry climate if well irrigated.

The model has many advantages due to its simplicity; for example, it can be easily integrated for a long time to estimate the trend of climate variation, it can clearly separate variability from different sources and analyze their individual influence on climate variability, and different climate conditions can be easily represented by changing a few model parameters. However, disadvantages can also come from its simplicity; for instance, it has no variability from energy balance and related processes, no boundary layer processes, which are important for the surface fluxes and convection, and no atmospheric dynamics. Although these disadvantages can limit the application of this model, it is especially suitable for study of interannual to interdecadal climate variability and it can give some prospective results before a long-term GCM integration. Although this model is not realistic as GCMs by not taking in account nonlocal variability, it is on the other hand a good tool to study the variability in the local land-atmosphere system without the "noise" from outside.

Sensitivity experiments with the model emphasize the role of vegetation because of its importance in long-term climate variability. A previously less considered aspect is the role of cropland on climate variability. With increasing human disturbance of the land surface, it will become more and more important. The connections to climate variability on natural and human managed land are very different, and determined by many factors like vegetation type difference and human disturbance. The agricultural processes modeled here are very simple; real agriculture is more complex and may be quantitatively or even qualitatively different for different crop types. This study only provides some suggestions for further study. The impact of agricultural harvest (e.g., winter wheat in June) is also considered by suddenly decreasing the LAI and stopping the irrigation for some time during the harvest. The simulated LAI and rainfall are smaller than the cropland without harvest but do not change the results of this paper. However, there is no atmospheric dynamics in this model. Study of dynamic systems has shown that short-periodic variations can lead to significant long-term variability (Pielke and Zeng, 1994). Can such year after year agricultural activity cause long-term variability in the land-atmosphere system?

ACKNOWLEDGMENTS. This work was supported by NSF Grant ATM-03433485 and DOE grant DE-FG02-01ER63198.

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