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The response to deforestation and desertification in a model of West African monsoons

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Abstract. Since Charney proposed his theory on the dynamics of deserts and droughts in the Sahel [*Charney*, 1975], there has been significant scientific interest in the interaction between vegetation and climate in this region. The essence of this interaction is that the atmospheric circulation, and therefore rainfall, over this region may be sensitive to changes in vegetation cover near the desert border. Here we describe simulations of the West African monsoons with a simple zonally-symmetric model. The results suggest that the potential impact of human induced change of land cover on regional climate depends critically on the location of the change in vegetation cover. That is, desertification along the border with the Sahara (*e.g.*, in Chad, Niger, Mali and Mauritania) leaves a relatively minor impact on monsoon circulation and regional rainfall; deforestation along the southern coast of West Africa (*e.g.*, in Nigeria, Ghana and Ivory Coast) may result in complete collapse of monsoon circulation, and a significant reduction of regional rainfall.

Introduction

West Africa has been experiencing intense change in land cover throughout this century. The nature of this change varies from desertification at the northern border to deforestation at the southern border. These changes in land cover are driven primarily by increases in population. Expansion of agricultural land at the expense of humid forests, substantial growth of the timber industry, overgrazing, and domestic use of wood from dry woodlands, have been causing some of the most intense changes in land cover. Early in this century, rain forests covered a large area, about 500,000 square kilometers, along the Atlantic coast. Today, less than 10% of the primary rain forest is left, with credible predictions that hardly any primary forest is likely to be left by the year 2000 (Figure 1) [*Aldhous*, 1993; *Gornitz*, 1985; *Myers*, 1991].

During the last two decades, there have been numerous studies that explored the impact of changes in land cover on rainfall and the role of land-atmosphere interaction in the climate of West Africa [*Charney et al.*, 1975; *Charney et al.*, 1977; *Cunnington and Rowntree*, 1986; *Walker and Rowntree*, 1977; *Xue and Shukla*, 1993; *Yeh et al.*, 1984]. However, most of these studies focus on changes in land cover at the desert border (Sahel). Relatively little attention has been given to the impact of coastal deforestation on the regional climate. In contrast to this, there have been several studies on the impact of Amazonian deforestation on the regional climate [*Dickinson and Henderson-Sellers*, 1988; *Lean and Warrilow*, 1989; *Shukla et al.*, 1990]. The fraction of the primary forest that has been cleared in West Africa is significantly larger than the corresponding fraction for the Amazon region (~ 0.9 versus ~ 0.1). Figure 1 shows that deforestation in West Africa may introduce a significant change in land cover which is likely to cause substantial changes in energy fluxes from the surface [*Eltahir*, 1996]. Our goal here is to use a mechanistic model to study the role of vegetation distribution in the dynamics of West African monsoons.

Model

Based on observations that rainfall and other atmospheric variables in West Africa are basically zonally uniform [*Griffiths*, 1972], due to the significant east-west orientation of the southern Atlantic coast and lack of topography, a zonally symmetric model (without longitudinal variation) should be sufficient to represent the essential features of the West African monsoon on seasonal time scales. It is worth noting that the actual rain-producing systems in West Africa are zonally-asymmetric easterly waves with the life cycle of several days. Since the time scale of interest in this study is the summer season and we are actually more interested in the ensemble effect of all these disturbances, the use of a

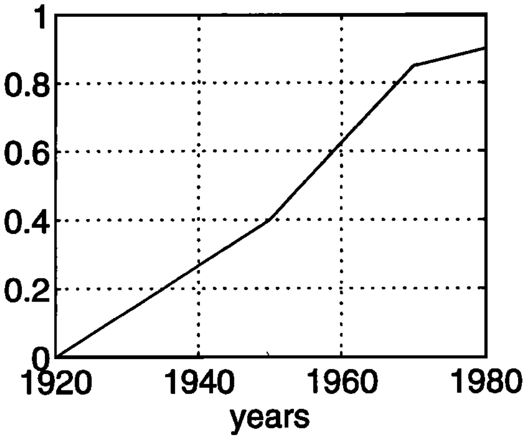

Figure 1. The time evolution of the ratio of the deforested area to the total area of the primary forest in 1920 (~ 500,000 km^2) in West Africa estimated based on the data reported by several studies [*Gornitz*, 1985; *Myers*, 1991]. The highest annual rates of deforestation are in Ivory Coast (16%), Nigeria (14%), and Ghana. Indeed, these are the highest annual rates of deforestation compared to any other region of the world.

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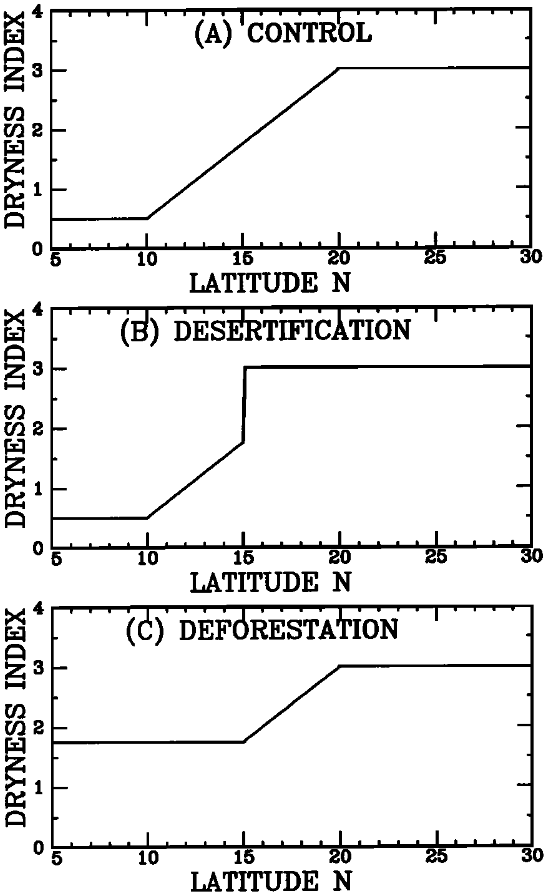

Figure 2. The distribution of vegetation in (a) the control experiment, described by the Budyko [1974] dryness index (nondimensional); (b) the desertification experiment, which is identical to that of the control experiment except that the vegetation cover in the region between 15°N and 25°N is removed resulting in expansion of the desert; (c) the deforestation experiment, which is identical to that of the control experiment except that the vegetation cover for the region 5°N to 15°N is replaced by savanna. In the control experiment, this region is covered by tropical forest between 5°N and 10°N and by savanna for the subregion between 10°N and 15°N.

zonally-symmetric model is sufficient for our purposes. For example, [*Webster and Chou*, 1980] used a zonally-symmetric model to simulate the seasonal structure of the Indian monsoon successfully although the rainfall in the actual Indian monsoon is associated with monsoon depressions (zonal asymmetries). On the other hand, relatively well developed theories [*Eltahir and Gong*, 1996; *Emanuel*, 1995; *Plumb and Hou*, 1992] of zonally-symmetric circulations will guide our interpretation of the model simulations and our search for a clear understanding regarding the impact of desertification and deforestation.

We have developed a moist zonally-symmetric model and used it to simulate the steady state solutions (under the same perpetual summer insolation) of atmospheric response to different perturbations in vegetation distribution (Figure 2). The model represents zonal average between 15°W to 15°E. Since the observed maximum Sahel rainfall occurs in August, we fix the solar insolation on August 15. The model solves the primitive equations and includes explicit representations for the hydrological cycle. The moist convection in this model is parameterized by Emanuel scheme [*Emanuel*, 1991]. Large-scale condensation occurs whenever the model atmosphere is supersaturated. The radiative processes are represented by a physically-based code [*Chou et al.*, 1984]. The land surface temperature is computed by satisfying surface energy balance. The surface fluxes of momentum, heat and moisture are calculated by bulk formulae. The land-sea boundary is set at 5°N. The model horizontal resolution is about 2.0°, vertical resolution is 1 km and time step is 20 minutes.

We use Budyko dryness index (D) as an indicator of the vegetation type [*Budyko*, 1974]. The relationships between the dryness index (therefore vegetation) and albedo (α), and between the dryness index and water availability (w) from the surface are similar to those of [*Gutman et al.*, 1984]. The expressions are as follows:

$$\alpha = \begin{cases} \min(0.25, 0.07 + 0.06D), & D \ge 1 \\ 0.10, & 0 < D < 1 \end{cases}$$

$$w = \max(0.0, 1.23\frac{tanhD}{D} - 0.33), D \ge 0$$

The specification of the dryness index in Fig. 2a to mimic the corresponding vegetation distribution in West Africa (from tropical forest near the coast, grassland in the Sahel to desert near the Sahara) therefore determines how much of the solar insolation is reflected at the surface, and how the net surface radiation is partitioned between latent heat flux and sensible heat flux.

Although variability in Sea Surface Temperature (SST) distribution plays an important role in the dynamics of rainfall and drought in West Africa [*Folland et al.*, 1977; *Lamb*, 1978; *Lamb and Peppler*, 1992; *Lough*, 1986; *Owen and Ward, 1989*], this important issue is not the focus of this paper. Hence, the distribution of SST in the tropical Atlantic south of 5°N is speci-

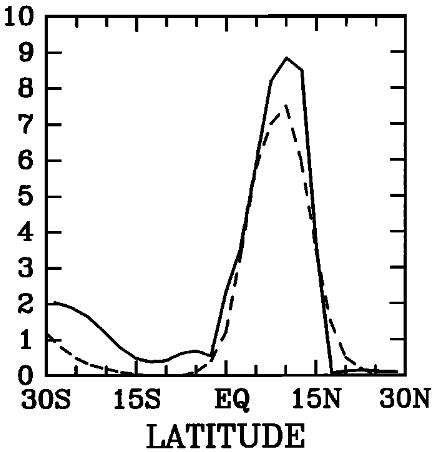

Figure 3. The August rainfall meridional profiles of the model with seasonal cycle (solid) and the observed GPCP 1987-1994 climatology averaged from 15°W to 15°E, in mm/day.

fied according to the observed August climatology from 1981-1995 [*Reynolds and Smith*, 1994], consistent with the assumed solar forcing.

Results and Conclusions

We would like to point out that since we are concerned with steady state solutions, a comparison of the model control rainfall with the observed rainfall is inappropriate. To show the credibility of the model, we ran the same model with seasonal cycle. The model August rainfall agrees reasonably well with that of the Global Precipitation Climatology Project (GPCP) rainfall data, in particular, the location of maximum rainfall and the north-south gradient of the rainfall (Figure 3). We now describe our steady-state experiments. The control experiment shows a well-developed monsoon circulation. The maximum rainfall occurs at the latitude of about 12.5°N, coinciding with the location of the maximum large-scale moisture convergence (Figure 4). In addition, results not shown here indicate a strong upper-level easterly jet, and a surface westerly over the land. This monsoon circulation is nonlinear in nature, characterized by almost zero absolute vorticity at the tropopause, as predicted by Plumb and Hou [1992]. Overall, these features are consistent with the development of a healthy monsoon [*Ramage*, 1971].

The desertification experiment is similar to the case considered by Charney [1975] and several other studies [*Charney et al.*, 1975; *Charney et al.*, 1977; *Xue and Shukla*, 1993]. Even with desertification, the monsoon circulation still exists and is strong. The rainfall decreases substantially within the perturbation region (15°N to 25°N) due to the decrease of both moisture convergence and local evaporation. However, south of 15°N, rainfall increases, mainly due to the increase in moisture convergence (Figure 4). The location of the maximum rainfall, and hence ITCZ (Intertropical Convergence Zone) does not change significantly. In short, desertification near the southern edge of the Sahara reduces the rainfall within the perturbation region but enhances rainfall south of it. The atmospheric response to desertification is not significant enough for the monsoon to collapse. These results are consistent with those of the previous studies mentioned above.

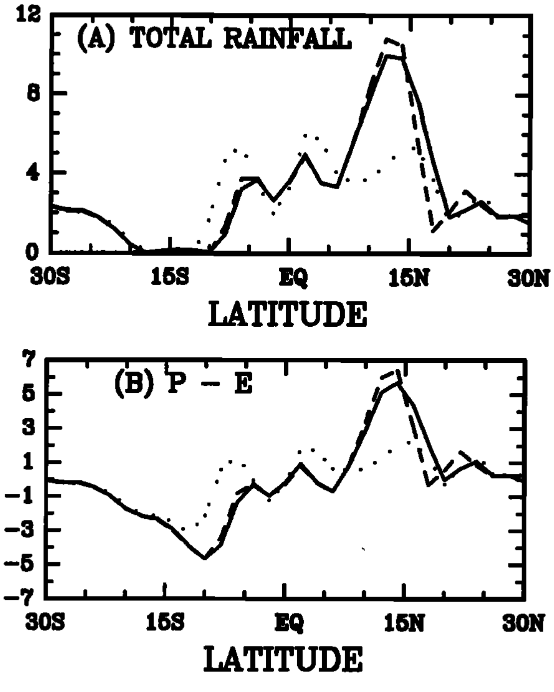

Figure 4. The meridional distribution of (a) total rainfall in mm/day, for the control (solid line), desertification (dashed line), and deforestation (dotted line); (b) the same as (a) but for large-scale moisture convergence.

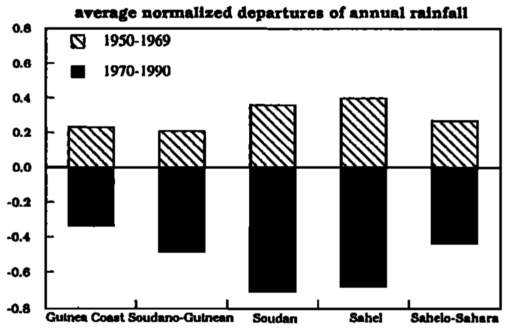

Figure 5. The standardized annual departures of African rainfall averaged for periods 1950-1969 and 1970-1990 for different regions. The five regions are Guinea Coast (5), Soudano-Guinean (4), Soudan (3), Sahel (2) and Sahelo-Sahara, as defined in Nicholson [1994].

The changes in land cover that we assumed in deforestation experiment describes the worst possible scenario for tropical deforestation in West Africa with all the forests replaced by savanna. Unlike the desertification experiment, the influence of deforestation is dramatic. The monsoon circulation collapses; ITCZ stays over the ocean and does not move onto the land (Figure 4). The collapse of the monsoon can be explained by the impact of deforestation on surface net radiation and entropy flux. The boundary layer entropy is important for the dynamics of moist atmospheres [*Emanuel*, 1995]. Deforestation reduces the net surface radiation and entropy flux [*Eltahir*, 1996], resulting in a decrease of boundary layer entropy and rainfall over the coastal land and thus limiting the northward extension of ITCZ. Therefore, the monsoon collapses.

The results of this study shed some light on the relation between the dynamics of West African monsoons and the distribution of vegetation. The impact of the land cover change on monsoon circulation depends critically on the location of the change in vegetation cover. We are confident that this conclusion is robust. Other experiments that considered perturbations of vegetation cover with different latitudinal extents (5° patches instead of 10° patches) have been performed and we have reached similar conclusions.

The standardized annual rainfall departures in various regions in West Africa for periods 1950-1969 and 1970-1990 are shown in Figure 5. It is very clear that for the past two decades the rainfall over the whole West Africa is relatively low compared to the period 1950-1969, similar to the anomalous rainfall pattern of deforestation, if land cover is indeed responsible for the observed rainfall variability. But this is not warranted because the West African drought in general is related to both land cover transformation and global SST variability [*Rowell et al.*, 1995]. This paper investigated the role of land cover change (SST fixed) on the West African rainfall. Our simulations show clearly that in comparison to desertification near the desert border, deforestation of the humid rain forests near the West African coast may have a more significant impact on the monsoon circulation, rainfall and the regional climate. This result warrants further study of the role of tropical deforestation in West Africa using a more realistic model (*e.g.*, a 3-D regional model for West Africa, along with a more sophisticated land surface scheme).

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