GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 23, 2199, doi:10.1029/2003GL018600, 2003

A new climate-vegetation equilibrium state for Tropical South America

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Received 10 September 2003; revised 16 October 2003; accepted 29 October 2003; published 5 December 2003.

[1] The existence of multiple climate-vegetation equilibria in Tropical South America is investigated under present-day climate conditions with the use of an atmospheric general circulation model coupled to a potential vegetation model. Two stable equilibria were found. One corresponds to the current biome distribution. The second is a new equilibrium state: savannas replace eastern Amazonian forests and a semi-desert area appears in the driest portion of Northeast Brazil. If sustainable development and conservation policies were not able to halt the increasing environmental degradation in those areas, then land use changes could, per se, tip the climate-vegetation system towards this new alternative drier stable equilibrium state, with savannization of parts of Amazonia and desertification of the driest area of Northeast Brazil, and with potential adverse impacts on the rich species diversity in the former region and water resources in the latter. *INDEX TERMS:* 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 9360 Information Related to Geographic Region: South America. **Citation:** Oyama, M. D., and C. A. Nobre, A new climate-vegetation equilibrium state for Tropical South America, *Geophys. Res. Lett.*, *30*(23), 2199, doi:10.1029/2003GL018600, 2003.

1. Introduction

[2] The major land cover types of Tropical South America east of the Andes have been undergoing considerable anthropogenic changes. Currently, close to 15% of tropical forests of Brazilian Amazonia have already been deforested [*Instituto Nacional de Pesquisas Espaciais*, 2002], and more than 10% of the semi-arid vegetation of Northeast Brazil (dry shrubland known as *caatinga*) show a high degree of environmental degradation [*MMA*, 2000]. The influence of these land cover changes on climate has been assessed by Atmospheric General Circulation Model (AGCM) simulations [e.g., *Nobre et al.*, 1991; *Sud and Fennessy*, 1982]. The simulations revealed that large-scale vegetation changes - deforestation in Amazonia, desertification in Northeast Brazil - have the potential to affect regional climate, and the predicted impacts seem to be enough to sustain a savanna expansion into the Amazonia forest-savanna transition (northern, southern and eastern edges of Amazonia) and the presence of semi-deserts in the driest area of Northeast Brazil. On the other hand, some studies have provided theoretical evidence for the existence of alternative stable climate-vegetation equilibrium states in general [*Brovkin et al.*, 1998; *Scheffer et al.*, 2001], and in the forest-savanna transition over the Amazonia basin edges in particular [*Sternberg*, 2001; *Higgins et al.*, 2002]. Two stable equilibrium states would be possible: high/low dry season precipitation (and evapotranspiration) associated with forest/savanna cover.

[3] Despite AGCM sensitivity simulations and theoretical evidence suggest the existence of at least an alternative stable savanna equilibrium state in the forest-savanna transition at the Amazonia basin edges, climate simulations using coupled AGCM-vegetation models had not found any alternative equilibrium state for South America. For the southwestern Sahara (SW Sahara), two stable equilibrium states were found under present-day climate forcings [*Claussen*, 1997, 1998]: the first yields the present-day distribution of vegetation and climate (drier state), and the second shows a northward penetration of savanna and xerophytic shrub (wetter state). In this work, a new set of climate simulations is performed to further test the possibility of existence of an alternative equilibrium state for Tropical South America. The atmospheric (AGCM) and vegetation models are different from previous studies, and higher horizontal resolution is used to better represent the relatively sharp forest-savanna transitions in Tropical South America. To cope with the atmospheric model systematic errors, the vegetation model is driven by atmospheric model anomalies added to the present-day climatology [e.g., *Kutzbach et al.*, 1998].

2. Simulations

[4] To perform the simulations, the CPTEC/COLA AGCM on T62 spectral resolution (horizontal resolution of about 2 degrees) and 28 vertical levels [*Cavalcanti et al.*, 2002] is asynchronously coupled to a potential vegetation model (PVM), named CPTEC-PVM, which shows a good skill in reproducing the current natural vegetation distribution patterns both globally and for South America (M. D. Oyama and C. A. Nobre, A simple potential vegetation model for coupling with the Simple Biosphere Model - SiB, submitted to *Brazilian Journal of Meteorology*, 2003). Given a set of environmental variables derived from climatological values of monthly mean surface temperature and precipitation, CPTEC-PVM outputs a biome belonging to the vegetation classification used in the Simplified Simple Biosphere (SSiB) land surface scheme [*Xue et al.*, 1991; *Dorman and Sellers*, 1989] (SSiB is the land surface scheme of the CPTEC/COLA AGCM). The global vegetation distribution is updated every 3 years (the procedure of running the atmospheric model and updating the vegetation is called iteration). To avoid unrealistic biome placement due to the atmospheric model systematic errors, the 3-year

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0094-8276/03/2003GL018600$05.00

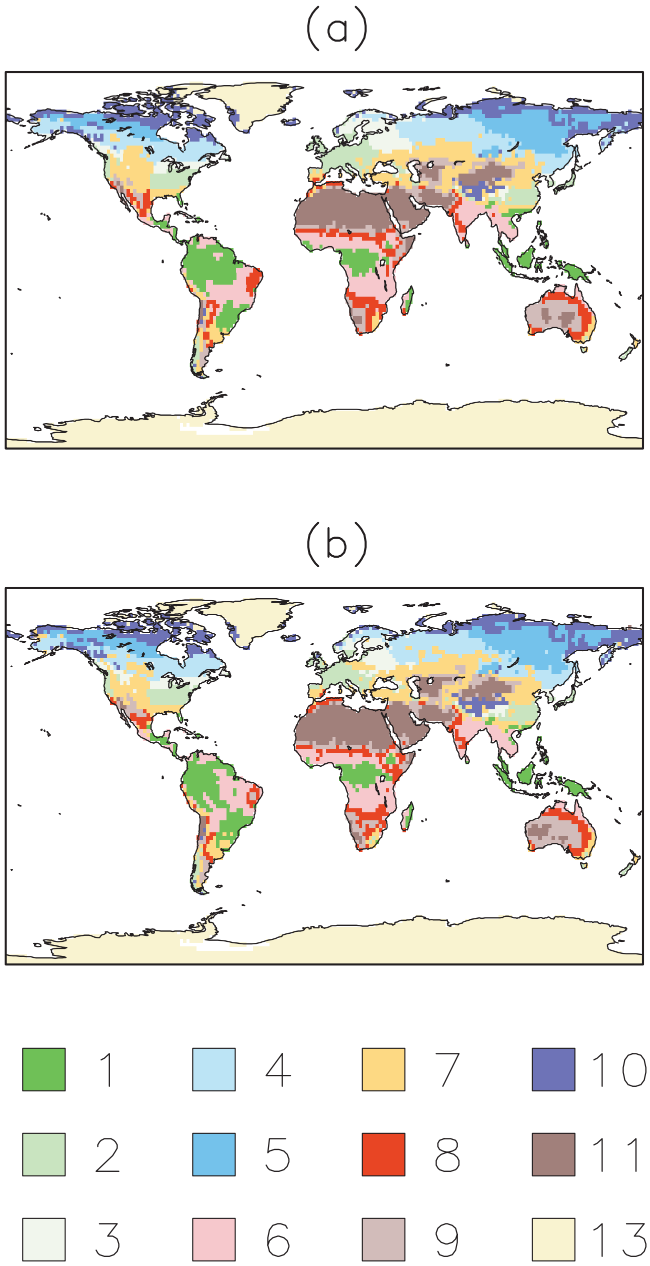

Figure 1. (a) Vegetation distribution in equilibrium with the current climate (potential vegetation distribution). (b) Last iteration vegetation distribution of the simulation initiated with all land cover (except ice) replaced by desert (bare soil; DES simulation). The vegetation type represented by each number is shown in Table 1.

model anomalies are added to the observed climatology to drive the vegetation model (anomaly coupling procedure) [e.g., *Kutzbach et al.*, 1998]. All forcings - sea surface temperature (SST), carbon dioxide concentration, solar radiation, sea-ice, among others - except vegetation distribution, follow the present-day climatology.

[5] Firstly, the present-day potential biomes (output of the CPTEC PVM forced by the present-day climate) are kept unchanged during a 10 year-integration to provide the model climatology (control run). Then, two 15-year (5 iterations) integrations are performed, named DES and FOR. In the initial condition, all land cover (except ice) is changed to desert vegetation in DES, and to tropical forest in FOR. After the 3rd iteration, the degree of agreement between successive iterations, measured by the kappa statistics [*Monserud and Leemans*, 1992], reaches a steady value. Thus, 5 iterations are sufficient to reach equilibrium of the climate-vegetation system. The vegetation distribution and the climate of the last iteration (5th iteration) of each simulation (DES and FOR) are regarded as a stable equilibrium state of the climate-vegetation system.

3. Results

[6] The FOR simulation leads to the present-day potential biomes (not shown). The DES simulation, however, leads to a different vegetation distribution particularly for Tropical South America (Figures 1b and 2b): savannas replace eastern Amazonia forests (hereafter referred to as regions A and C) and a semi-desert vegetation area appears in the driest area of Northeast Brazil (region B).

[7] To check the statistical significance of the vegetation changes, the last 3 iterations of DES and FOR (3rd, 4th and 5th iteration) are compared using the procedure described in *Claussen* [1998]. The area covered by each biome is calculated for the entire globe and the northern part of South America (NSA, 90°W–30°W, 15°S–15°N). The results are summarized in Table 1. Globally, significant changes in tropical forest, savanna and grassland area are

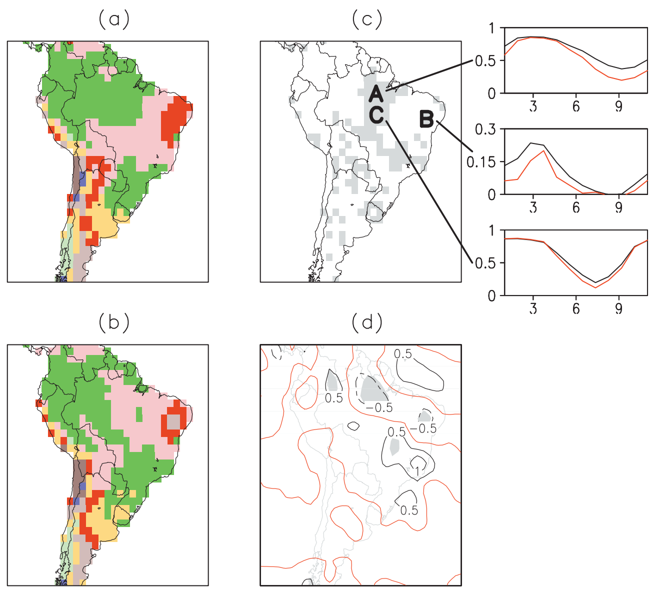

Figure 2. (a, b) Blow-up of Figure 1 for South America. Vegetation types are the same as in Figure 1. (c) Shaded regions are covered by different vegetation types when comparing 2a (control) and 2b (DES). Letters A, B and C refer to regions described in the text. For each region, the monthly soil moisture degree of saturation (ratio between the actual and the maximum volumetric soil moisture) for the present-day climate (black line) and for the alternative equilibrium state (red line) are shown. (d) Precipitation anomalies (in mm day^{-1}) between DES and control runs (red lines refer to zero values). Shaded areas indicate significant anomalies at 5 and percnt; level.

Table 1. Average difference of areal coverage (10^6 km^2) between the last 3 iterations of DES and FOR simulations (positive sign means more coverage in DES simulation) for the entire Globe (Global) and northern part of South America (NSA, 90°W–30°W, 15°S–15°N)

Biome number	Biome name	Global	NSA
1	tropical forest	−1.9	−2.3
2	temperate forest	0.0	0.0
3	mixed forest	−0.2	–
4	boreal forest	−0.7	–
5	larch	+0.4	–
6	savanna	+1.6	+2.4
7	grassland	+1.1	0.0
8	*caatinga*	−0.2	−0.4
9	semi-desert vegetation	+0.5	+0.3
10	tundra	−0.8	–
11	desert	+0.2	0.0

Shaded values mean significant differences at 5% level. The vegetation classification follows *Dorman and Sellers* [1989].

found. While most of the tropical forest and savanna area changes take place in regions A and C, grassland expansion is more scattered. In Polland and Central Asia, where the grassland expansion is more organized (Figure 1b), the change in area is not significant on regional level (not shown). For the NSA, significant changes in *caatinga* and semi-desert vegetation area are found. These changes are related to replacement of *caatinga* by semi-desert vegetation in region B. For each simulation (DES or FOR), corroborating the statistical significance results, the vegetation patterns in A, B and C remain almost the same for the last 3 iterations (not shown).

[8] Therefore, for the present-day climate forcings, a second stable equilibrium state does seem to exist for Tropical South America. Figure 2c shows that this new alternative state is related to soil moisture decrease in A, B and C. In regions A and B, there is a weakening of the hydrological cycle: precipitation, evapotranspiration and atmospheric moisture convergence decrease (see Figure 2d for the precipitation anomalies). In region C, despite the decrease in evapotranspiration, there is a slight increase in precipitation. There is a belt extending from A to B where precipitation decreases, and from C to Southeast Brazil where it increases. The precipitation decrease in A and B is significant at 5% level.

4. Discussion

[9] It is important to verify how the alternative equilibrium state could be sustained by changes in the Amazonian rain-producing systems. Our simulations are not suitable to address this issue, due to atmospheric model systematic errors [*Cavalcanti et al.*, 2002] and resolution (higher resolution is necessary to resolve mesoscale convective systems). Therefore, the following discussion is an attempt to support the predicted changes for the northern part of eastern Amazonia (region A) based on the current knowledge of the Amazonian rain-producing systems. A negative precipitation anomaly belt parallel to the Brazilian northern coast and an hydrological cycle weakening in A could result from changes in precipitating efficiency as squall lines propagate inland [*Cohen et al.*, 1995]. In the dry season, when the frequency of squall lines is larger, forests sustain evapotranspiration by extracting water from deep soil layers [*Nepstad et al.*, 1994], thus supplying moisture (through the atmospheric boundary layer) to squall line propagation. Several studies indicate that 40–60% of precipitation in Amazonia may be recycled [e.g., *Salati and Vose*, 1984], and squall line propagation is an important process for it. Savannas would not be able to supply moisture (since evapotranspiration is markedly reduced), thus confining the squall lines and preventing precipitation from reaching region A. Therefore, in the forest/savanna equilibrium state, more/less evapotranspiration would favor/block squall line inland propagation, decreasing/increasing the dry season length in region A and, thus, favoring the presence of forests/savannas in this region. This mechanism, however, needs to be further confirmed by additional simulation studies.

[10] For SW Sahara, a wetter stable equilibrium state (hereafter referred to as "green Sahara state", GSS) was found in AGCM simulations performed by *Claussen* [1997, 1998], and the existence of this state is supported by simulations with atmospheric models of intermediate complexity [e.g., *Zeng and Neelin*, 2000]. Our results do not show the GSS (Figure 1b): both DES and FOR simulations converge to the present-day vegetation in SW Sahara. A state similar to GSS emerges as the output of the 1st iteration of FOR simulation: there is northward expansion of *caatinga* and savanna in the SW Sahara (not shown). This state, however, is unstable in our simulations. From the 1st to the 2nd iteration, summer monsoon strength decreases and less moisture is carried to SW Sahara. The albedo decrease (of about 10%) is unable to keep the atmospheric moisture convergence and the GSS disappears. The present-day vegetation state is found in SW Sahara from the 2nd until the last (5th) iteration. Therefore, our results do not show a stable GSS due to a weaker monsoon dynamics response to albedo change in the SW Sahara. An unstable GSS was also found due to similar reasons by *de Noblet-Ducoudré et al.* [2000].

[11] On global scale, the lack of alternative equilibrium states outside Tropical South America - i.e., the similarity between DES and FOR simulated biomes - may be due to two main reasons. The first is to force the climate system with present-day climatological fields (except vegetation), thus precluding bidirectional interactions among its various subsystems. The second is the anomaly coupling procedure. Adopting it means that the climate inputs to the vegetation model do carry the memory of the present-day climatology. Both methodologies strongly constrain climate state excursions from the present-day equilibrium state. Therefore, the alternative climate state found for Tropical South America may be regarded as the stable equilibrium state closest to the present-day state.

5. Concluding Remarks

[12] Natural ecosystems in Tropical Brazil have been under increasing land use change pressure. Amazonia deforestation and Northeast Brazil desertification are two examples of the ongoing anthropogenic environmental degradation. As showed by theoretical and simulation studies, these land use changes would weaken the hydrological cycle in both Amazonia and Northeast Brazil. If

sustainable development and conservation policies are not able to halt this increasing environmental degradation, then land use changes could, per se, tip the biome-climate system towards a new alternative drier stable equilibrium state with savannization of parts of Amazonia and desertification of the driest area of Northeast Brazil. This second equilibrium state would be associated with reduced species diversity in eastern Amazonia and more severe water scarcity in Northeast Brazil. Further studies are necessary to ascertain at which level Amazonia deforestation and Northeast Brazil desertification could tip the biome-climate system to the alternative drier equilibrium state.

[13] **Acknowledgments.** This work is part of first author's doctoral thesis under the guidance of the second author. The authors would like to thank Drs. B. J. Turcq, M. H. Costa, H. R. Rocha, S. H. Franchito and J. A. Marengo for useful comments and suggestions.

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