Climate change consequences on the biome distribution in tropical South America

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Received 15 February 2007; revised 28 March 2007; accepted 9 April 2007; published XX Month 2007.

[1] We study the consequences of projected climate change on biome distribution in South America in the 21st century forcing a potential vegetation model with climate scenarios from 15 climate models for two emission scenarios (A2 and B1). This analysis was carried out for the savanna and tropical forest biomes, which are the predominant biomes in tropical South America. In both scenarios, the results indicate reduction of tropical forest cover areas which would be replaced by savannas. This reduction of tropical forests increases with the time through the end of the 21st Century, mostly over southeastern Amazonia. Considering the biome changes from current potential vegetation in the case when at least 75% of the calculations agree on the projected biome change (consensus), the decrease of the tropical forest area in South America is 3% for the period 2020–2029, 9% for 2050–2059 and 18% for 2090–2099 for the A2 emission scenario. **Citation:** Salazar, L. F., C. A. Nobre, and M. D. Oyama (2007), Climate change consequences on the biome distribution in tropical South America, *Geophys. Res. Lett.*, *34*, LXXXXX, doi:10.1029/2007GL029695.

1. Introduction

[2] Climate and the vegetation interact bidirectionally on many time and spatial scales. One clear manifestation of such interaction is the global pattern of vegetative land cover and climate. Climate may be regarded as the single factor that exerts the largest influence on vegetation distribution and its characteristics on a global context [*Prentice*, 1990]. Thus, deserts, tropical forests, savannas, and other types of vegetation are determined to a first approximation by climate. Climate change has affected the global distribution of vegetation from the distant past and will likely affect it into the future. On the other hand, changes in the distribution and structure of the vegetation may influence climate [*Nobre et al.*, 2006]. The geographical distribution of the vegetation communities and their relationship with the climate has been examined with biogeographical models or biome models. These models use as central paradigm the assumption that climate has a dominant control over the distribution of vegetation. Numerous 'Potential Vegetation Models' (PVM) are found in the literature (e.g., BIOME of *Prentice et al.* [1992], MAPSS of *Neilson* [1995], CPTEC-PVM of *Oyama and Nobre* [2004], etc.). Recently, dynamic vegetation models (e.g., IBIS of *Foley et al.* [1996] and LPJ-DGMV of *Sitch et al.* [2003]) provide the possibility to evaluate vegetation response to transient and long-term climate change. Due to the simplicity of the biome models and the existence of empirical global rules linking natural vegetation and the climate, biome models have been used in many climate studies [e.g., *Claussen and Esch*, 1994; *Nobre et al.*, 2004].

[3] Field observations [*Gash and Nobre*, 1997] and numerical studies [e.g., *Nobre et al.*, 1991] reveal that large scale deforestation in Amazonia could alter the regional climate significantly. Evapotranspiration is reduced and surface temperature is increased when rainforests are replaced by pasturelands. That effect alone might lead to a 'savannization' of portions of the tropical forest domain [*Nepstad et al.*, 2001]. Recently, *Oyama and Nobre* [2003] showed the existence of a second stable biome-climate equilibrium state with savannas covering eastern Amazonia and semi-deserts in Northeast Brazil. However, there have been few studies on the impact of global climate change on South America, particularly on its biomes [e.g., *Cox et al.*, 2004; *Scholze et al.*, 2006; K. H. Cook and E. K. Vizy, Effects of 21st century climate change on the Amazon rainforest, submitted to *Journal of Climate*, 2007, hereinafter referred to as Cook and Vizy, submitted manuscript, 2007]. In all of these studies, tropical South America emerges as a region of possible conversion of significant amounts of forest to nonforest areas as a result of global warming.

[4] This study addresses this question further by assessing, with CPTEC-PVM model [*Oyama and Nobre*, 2004], how natural biomes could change in response to various scenarios of climate change prepared for the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4). The application of ensemble analysis, which is rarely done in studies like this, is an attempt to provide a robust assessment of climate-change consequences on biome distributions.

2. Model, Data and Experiments

[5] This study uses standard output, available through the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset, from fifteen Coupled Ocean-Atmosphere GCMs for the IPCC AR4: BCCR-BCM2.0, CCSM3, CGCM3.1(T47), CNRM-CM3, CSIRO-Mk3.0, ECHAM5/MPI-OM, ECHO-G, GFDL-CM2.0, GFDL-CM2.1, GISS-ER, INM-CM3.0, IPSL-CM4, MIROC3.2(MedRes), MRI-CGCM2.3.2, and UKMO-HadCM3. These models have a resolution around 1.4°–5°, and simulate the climate

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0094-8276/07/2007GL029695$05.00

in the 21st Century according to the changes in climate forcing, including increase of atmospheric carbon dioxide. We have examined the biome distribution in the 21st Century under the emission scenarios A2 and B1 (that represent the plausible range of conditions over the next century). In scenario B1, the atmospheric CO_2 concentration in the year 2100 reaches a level of 550 ppm, about twice the preindustrial level; in A2 the corresponding value is 860 ppm [*Intergovernmental Panel on Climate Change*, 2000]. Climate simulation for the end of the 20th century (20CM3) of each model is used to evaluate the models' anomalies. The precipitation and surface temperature monthly climatology (1961–1990) are obtained from work by *Willmott and Matsuura* [1998]. The climatology data, originally on 0.5° resolution, and the models scenarios utilized are interpolated to T62 spectral resolution (about 2°), which is the resolution used for the calibration of the CPTEC-PVM [*Oyama and Nobre*, 2004].

[6] The potential vegetation model used is CPTEC-PVM [*Oyama and Nobre*, 2004]. Given a set of environmental variables derived from climatological values of monthly mean surface temperature and precipitation – namely, growing degree-days (G), temperature of the coldest month (Tc) and two moisture indexes (one to distinguish between wet and dry climates, H, and the other to represent the soil moisture seasonality, D) – CPTEC-PVM outputs a biome belonging to the vegetation classification of *Dorman and Sellers* [1989]: Tropical forest, temperate forest, mixed forest, boreal forest, larch, savanna, grassland, caatinga, semi-desert, tundra and desert. The CPTEC-PVM is similar in structure to other PVM in use, such as the BIOME model [*Prentice et al.*, 1992], but it does not account for ecological competition between plants. Only one biome is assigned to each grid cell. The CPTEC-PVM shows a good skill in reproducing the current natural vegetation distribution pattern on a global scale and, on a regional level in South America, the model is able to reproduce the principal biome types: the tropical forest in Amazonia and Atlantic coastal region, the savannas in Central Brazil, the dry shrubland vegetation ('caatinga') in Northeast Brazil and Chaco region, the grasslands in the Pampas, and the semi-desert vegetation in Patagonia [*Oyama and Nobre*, 2004].

[7] In order to evaluate the biome redistribution over South America for future scenarios of climate change, the CPTEC-PVM was used in three 10-year time-slice of the 21st Century: 2020–2029, 2050–2059 and 2090–2099, and for the A2 and B1 scenarios of Greenhouse Gas Emissions (GHG). To avoid unrealistic biome placement due to the atmospheric model systematic errors, the anomalies of precipitation and temperature (with respect to each model's average precipitation and temperature for the base period 1961–1990, for each time-slice analyzed) are added to the observed climatology to drive the vegetation model (anomaly coupling procedure) [e.g., *Kutzbach et al.*, 1998; *Oyama and Nobre*, 2003]. For each 10-year time-slice climatology, the model is run until the soil water seasonal cycle difference between successive years is close to zero. Comparing the potential vegetation of each 21st century time-slice and the current potential vegetation (output of the CPTEC-PVM forced by the present-day climate), it is possible compute de areas where the biome has changed.

3. Results

[8] Analyses of precipitation and temperature anomalies (not shown) reveal larger differences among models than among emission scenarios for the same model. As expected, the main source of uncertainty for regional climate change scenarios is associated to different projections from different AOGCMs. The projected temperature warming for South America range from 1° to 4°C for emissions scenarios B1 and from 2° to 6°C for A2. The analysis is much more complicated for rainfall changes. Different climate models show distinct patterns, even with almost opposite projections. Figure 1 shown the current potential vegetation and the projected biome distributions for the A2 scenario and the 2090–2099 time slice for all the models analyzed. The major differences in biome distributions are found among different models (Figure 1) rather than from the two emissions scenarios (not shown) for the same model.

[9] Figure 2 shows the grid points where more than 75% of the models (>11 models) coincide in projecting the future condition of the tropical forest and the savanna in relation with the current potential vegetation (consensus) for the three 10-year time-slices and the A2 and B1 GHG scenarios. For tropical South America, the results indicate that for the B1 scenario, the models show consensus regions of tropical forest being replaced by savanna. This reduction of tropical forest increases with time through the 21st Century. For the 'caatinga' biome in the Northeast of Brazil, a consensus of its future condition was not found, especially for the 2090–2099 time-slice. This non-consensus was related to the differences in projections of temperature and precipitation among models in this region (not shown). For the A2 scenario, the reduction of tropical forest which is replaced by savanna is greater than for the B1 scenario, and the magnitude of the area also increases with the time. As expected, this is mainly because the warming anomaly of South America is greater for A2 than for B1 scenario, that in turn could result in greater reduction in the amount of soil water. The area for which consensus of the future condition of the forest biome was not reached also increases with time. For the period 2090–2099 in both scenarios, the tropical forest in Colombia and western Amazon is maintained and the Atlantic tropical forest extends to south in southern Brazil (Figures 2c and 2f).

[10] The lost of tropical forest is related with the moisture, H, and seasonality, D, parameters. The moisture parameter can be considered as an integrated measure of the annual amount of growth-limiting drought stress on plants. The seasonality parameter represents explicitly the soil moisture seasonality (related with the dry season length). It is necessary high values of H and D in the model for tropical forest vegetation, that is, short dry season and water availability through the year. In the experiments where the tropical forest is replaced by savanna, the annual moisture is too low and/or the dry season is too long to support tropical forest (not shown).

[11] Natural ecosystems in tropical South America have been under land use change pressure not only recently, but for centuries. Amazonia deforestation and land use change

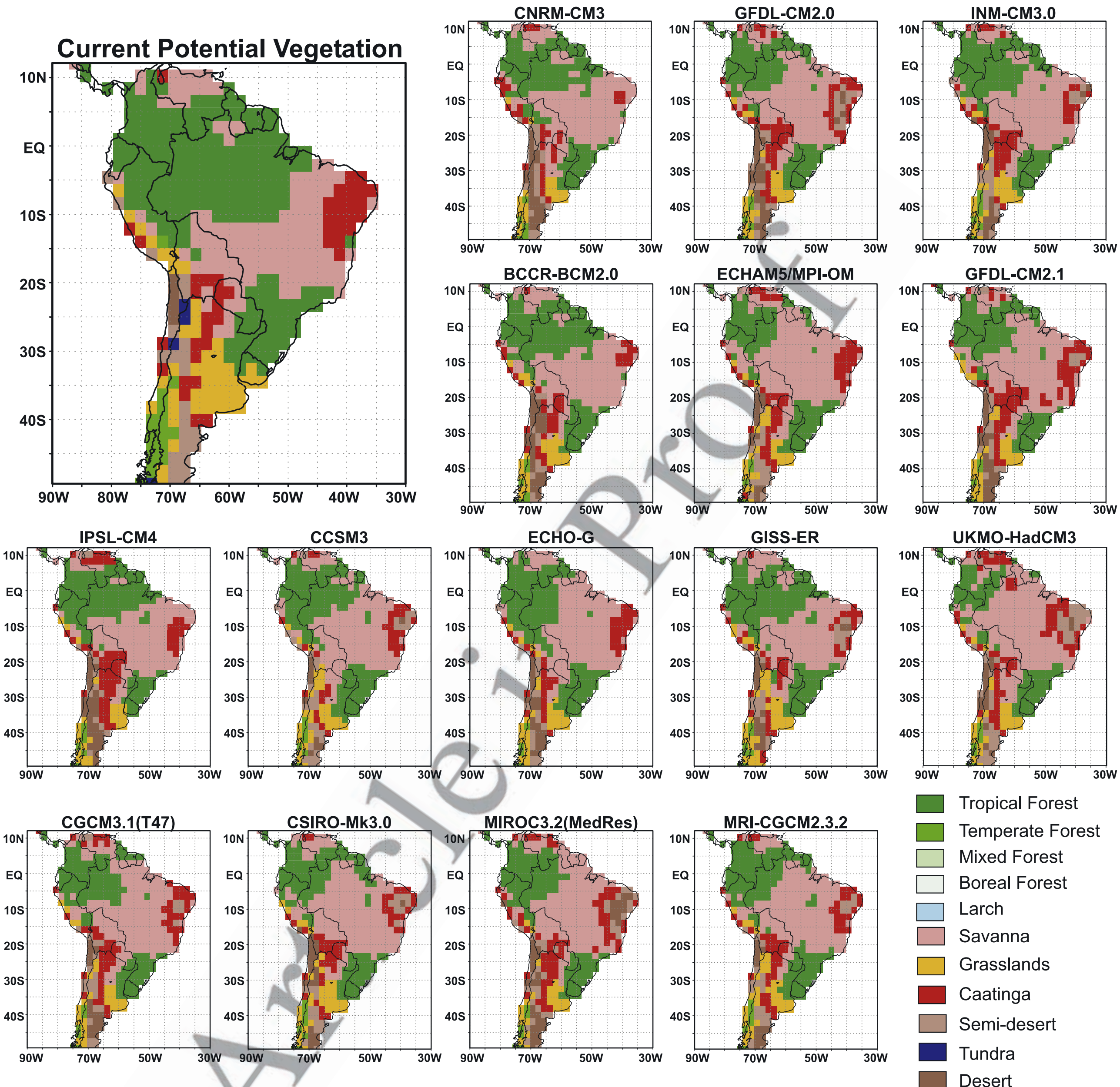

Figure 1. Projected distribution of natural biomes in South America for 2090–2099 from 15 AOGCMs for the A2 emissions scenarios. The top left plot represents the current potential biomes (they represents the potential biomes, but not the actual vegetation distribution, which is a result of historical land use and land cover change).

in the Atlantic tropical forest from southern to northeastern Brazil are examples of the anthropogenic environmental degradation. The Atlantic tropical forest (shown in the current potential biomes map, Figure 1), and that really existed in the past, has been converted into agricultural land, with only 7% of the original forest remaining [*Tabarelli et al.*, 2005]. Figure 2 indicates that these regions under projected conditions could maintain the areas of tropical forest, that is, future climate change due to global warming would cause much less biome change than the direct effect of land use change.

[12] Figure 3 shows the changes in model-calculated South American tropical forest and savanna land cover area. There is a consistent increase in reduction of areas covered by tropical forests (18% [8%] disappear, 30% [23%] inconclusive results for the A2 [B1] scenario and the 2090–2099 time slice) and a corresponding increase of areas covered by savannas. By and large, other similar projections of vegetation changes in response to climate change lend credence to a substantial reduction of forest areas [e.g., *Scholze et al.*, 2006; Cook and Vizy, submitted manuscript, 2007] or a complete forest die-back [e.g., *Jones et al.*, 2003; *Cox et al.*, 2004].

4. Conclusions

[13] Climate change scenarios arising from IPCC AR4 global climate models and also from regional models point

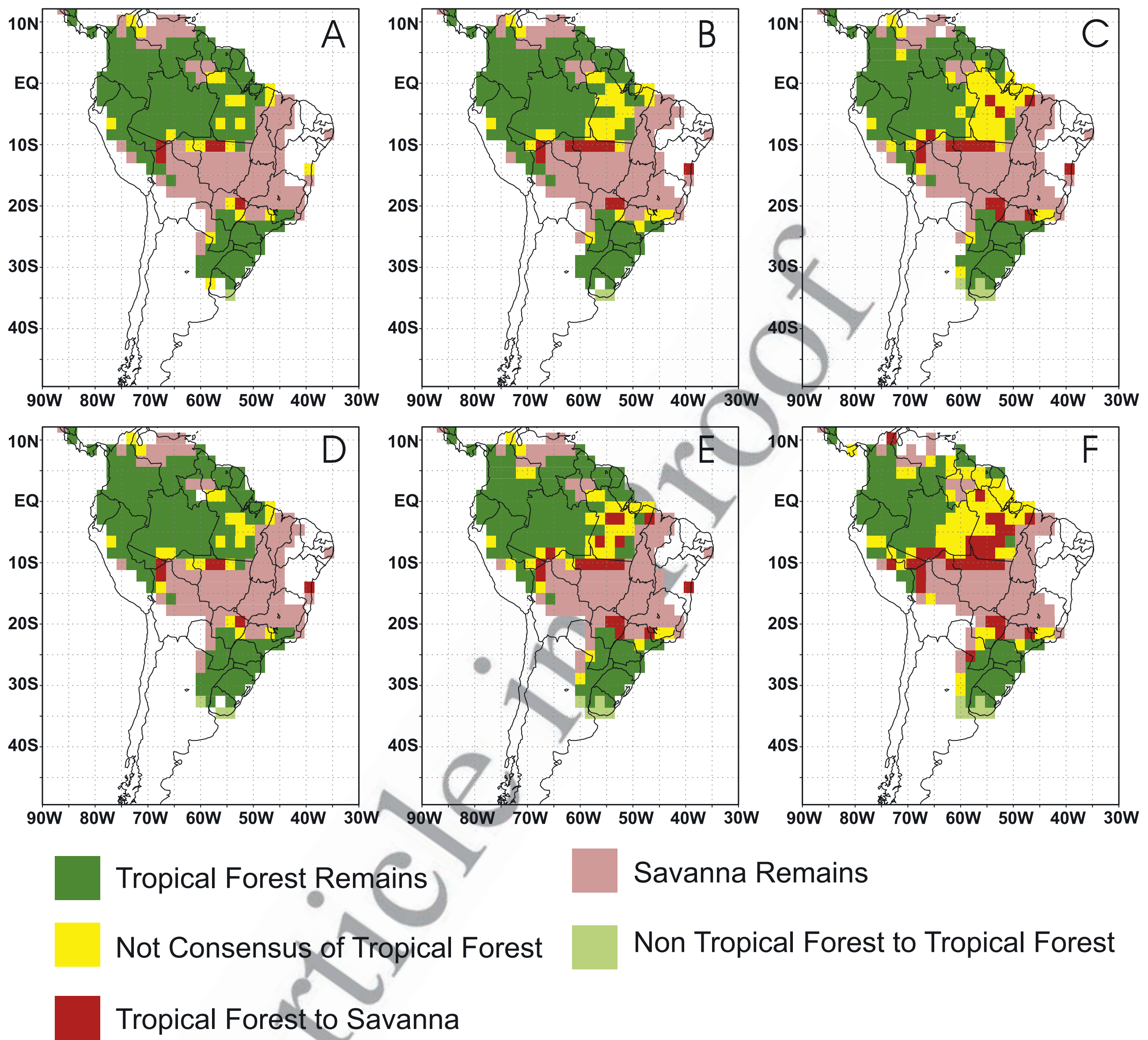

Figure 2. Grid points where more than 75% of the models used (>11 models) coincide as projecting the future condition of the tropical forest and the savanna in relation with the current potential vegetation, resulting in the following possibilities: tropical forest remains; savanna remains; tropical forest to savanna shift; non tropical forest to tropical forest shift. The figure also shows the grid points where a consensus amongst the models of the future condition of the tropical forest was not found for the periods (a) 2020–2029, (b) 2050–2059 and (c) 2090–2099 for B1 GHG emissions scenario and (d, e and f) similarly for A2 GHG emissions scenario.

towards a much warmer future for South America, with projected air temperature increases in the range of 2 to 6°C through 2100. However, there is still considerable uncertainty with respected to rainfall changes, mainly for Amazonia and Northeast Brazil. The increase in temperature may induce larger evapotranspiration in tropical regions. That, in turn, could result in reduction in the amount of soil water, even when rainfall does not change significantly. That factor by itself can trigger the replacement of the present-day potential biomes by other vegetation types which may be more adapted to less soil water. That is, tropical savannas replacing tropical forest in Amazonia. If severe droughts become more frequent in the future, which is a common projection for a warmer planet, then the process of 'savannization' of eastern Amazonia can further accelerate, since there is a higher probability of that area be stricken by droughts in the forest-covered areas of Amazonia [*Hutyra et al.*, 2005].

[14] The consensus analyses project for tropical South America a 18% (8.2%) reduction of areas covered by tropical forest for the A2 (B1) GHG emission scenarios, and a corresponding 30.4% (13.9%) increase of areas covered by savannas for the 2090–2099 time-slice. The reduction of tropical forest that is replaced by savanna is concentrate principally in the Southeastern Amazonia. These changes in vegetation are due to decrease of the annual soil moisture or/and increase of the dry season. The area for which consensus of the future condition of the

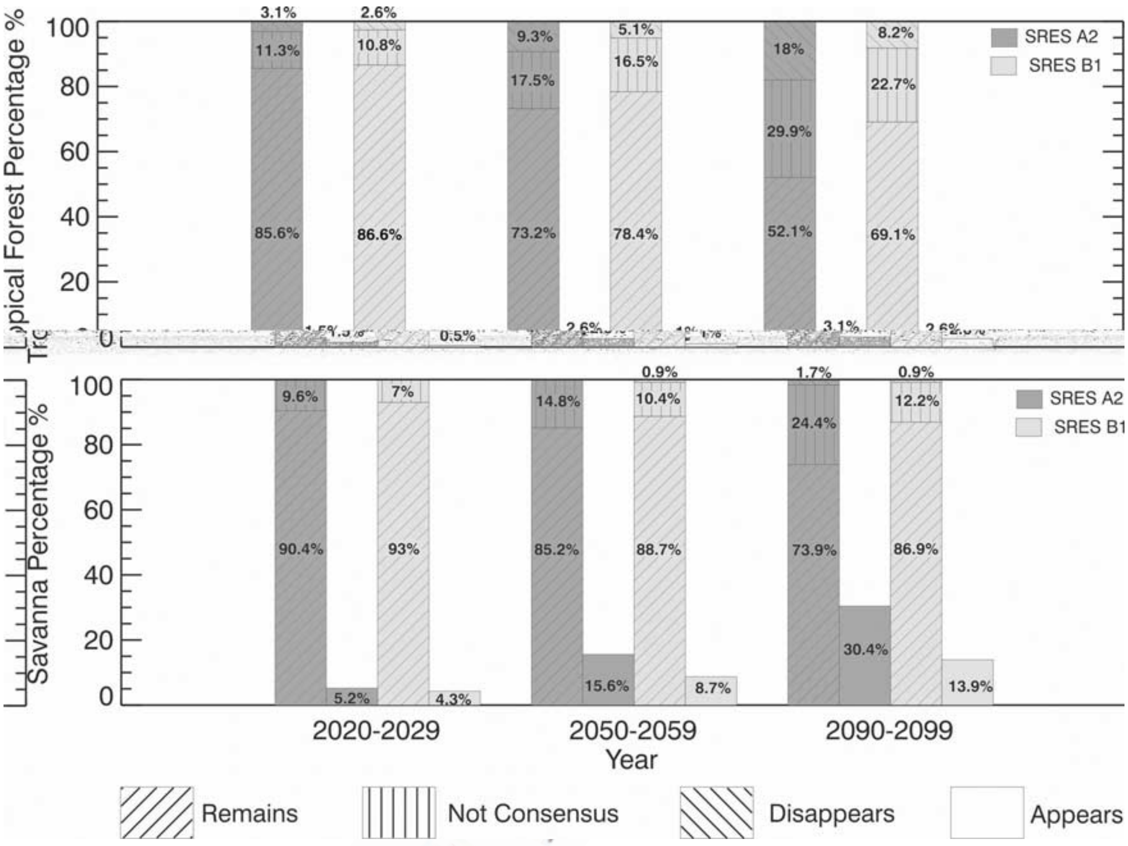

Figure 3. Percentage of the area where more than 75% of the experiments for the SRES A2 and the B1 GHG scenarios, coincide as projecting the permanence, disappearance or appearance of (top) the potential tropical forest and (bottom) savanna, and where there is not a conclusive consensus amongst models. The percentage is calculated in relation with the actual potential vegetation (approximate potential natural area of tropical forest is 8.39 * 10^6 km^2 and savanna is 4.98 * 10^6 km^2).

forest biome was not reached is concentrated in the eastern Amazonia.

[15] The future of biome distribution in tropical South America in face of the synergistic combination of impacts due to both land cover (deforestation, forest fires and fragmentation) and climate changes, resulting in warmer and possibly drier climates, points out to 'savannization' of portions of the tropical forests of Amazonia and possibly 'aridization' of parts of Northeast Brazil. Our results support these trends. For Amazonia that trend would be greatly exacerbated by fires [*Nepstad et al.*, 1999, 2001]. The more adapted species that may be able to withstand the new conditions are typically those of the tropical and subtropical savannas. These are naturally more adapted to hotter climates with marked seasonality in rainfall and long dry seasons and where fire plays an important ecological role. Considering that the time scale for natural ecosystem migration of centuries to millennia is much larger than the expected time scale of decades for both GHG-induced climate and land use changes, these have the potential of profoundly impacting ecological diversity of plant and animal species on a mega-diverse region of the planet. In sum, one cannot really expect effective adaptation policies when there is the potential for massive ecosystem disruptions brought about by projected climate changes of this century. Our findings reinforce the case for mitigating climate change to avoid a dangerous interference with the ability of natural ecosystems to adapt to it.

[16] **Acknowledgments.** This work is part of the first author's doctoral thesis at the Meteorology Graduate Program of the Brazilian Institute of Space Research (INPE), under the supervision of the second author. We acknowledge the modeling groups for making their simulations available for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the CMIP3 model output, and the WCRP's Working Group on Coupled Modelling (WGCM) for organizing the model data analysis activity. The WCRP CMIP3 multi-model dataset is supported by the Office of Science, U.S. Department of Energy.

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