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Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion

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[1] Field observations and numerical studies revealed that large scale deforestation in Amazonia could alter the regional climate significantly, projecting a warmer and somewhat drier post-deforestation climate. In this study we employed the CPTEC-INPE AGCM to assess the effects of Amazonian deforestation on the regional climate, using simulated land cover maps from a business-as-usual scenario of future deforestation in which the rainforest was gradually replaced by degraded pasture or by soybean cropland. The results for eastern Amazonia, where changes in land cover are expected to be larger, show increase in near-surface air temperature, and decrease in evapotranspiration and precipitation, which occurs mainly during the dry season. The relationship between precipitation and deforestation shows an accelerating decrease of rainfall for increasing deforestation for both classes of land use conversions. Continued expansion of cropland in Amazonia is possible and may have important consequences for the sustainability of the region's remaining natural vegetation. **Citation:** Sampaio, G., C. Nobre, M. H. Costa, P. Satyamurty, B. S. Soares-Filho, and M. Cardoso (2007), Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion, *Geophys. Res. Lett.*, *34*, L17709, doi:10.1029/2007GL030612.

1. Introduction

[2] Deforestation has reached an area of 560,000 km^2 (15% of the forest area) in Brazilian Amazonia alone (www.obt.inpe.br/prodes) due mostly to cattle ranching and agriculture, with soybean cropland expansion playing a major role in the last few years [*Morton et al.*, 2006; *Costa et al.*, 2007]. Agriculture has a major contribution for the economy in Brazil, which is increasingly becoming a leader in the meat, soy and biofuel international markets. If this trend continues into the future, about 40% of the Amazon forests will disappear by 2050 [*Soares-Filho et al.*, 2006]. Combining the types of land use that are currently observed and the fact that Amazonia represents a substantial fraction of the territorial extent indicates a strong potential for widespread expansion of pastures and agricultural areas in the place of original forests in the region.

[3] Several studies have shown the importance of the tropical rainforests for the Earth's climate. For example, field observations [*Gash and Nobre*, 1997] and numerical studies [e.g., *Dickinson and Henderson-Sellers*, 1988; *Nobre et al.*, 1991; *Hahmann and Dickinson*, 1997; *Costa and Foley*, 2000] reveal that large scale deforestation in Amazonia could alter the regional climate significantly. Generally, replacing forests with pastures reduces evapotranspiration and increases the surface sensible heat flux and, consequently, surface temperature. In specific, forest conversion increases the surface albedo, lowers the surface roughness, and reduces the leaf-area index (and associated canopy interception) and the available soil moisture (mainly because pasture plants often have shallower roots than rainforest trees) [*Gash and Nobre*, 1997].

[4] As a consequence, tropical deforestation is expected to lower the ability of the land surface to maintain a high rate of evapotranspiration throughout the year, leading to changes in the latent heating of the atmospheric boundary layer and the strength of tropical convection. In general it is expected that these changes in the surface energy and water balance lead to a significant reduction in rainfall and an increase in surface temperature [*Sud et al.*, 1993; *Costa and Foley*, 2000].

[5] In order to assess the effects of Amazonian deforestation on the regional climate, we used the CPTEC-INPE AGCM driven by land cover maps under a business-as-usual scenario. Previous studies [e.g., *Nobre et al.*, 1991; *Lean and Rowntree*, 1993, *Costa and Foley*, 2000; *Berbet and Costa*, 2003], in general, have considered a single scenario of degraded pasture. Here, the rainforest is gradually replaced by degraded pasture or by soybean cropland, allowing for analyses of transient states of the land cover and reflecting the potential for agricultural expansion in the region.

2. Model Description and Experiment Design

[6] The CPTEC-INPE global atmospheric model [*Cavalcanti et al.*, 2002] is used for the numerical simulations, with T062L42 spectral resolution (42 vertical levels, $\sim 2°$ lat/lon horizontal resolution). The land surface scheme is the SSiB [*Xue et al.*, 1991]. For each land grid point, a vegetation type (biome) is prescribed following the classification by *Dorman and Sellers* [1989] along with a set of physical, morphological, and physiological parameters. Based on the work of *Nobre et al.* [1991], *Xue et al.* [1996] and the ABRACOS experiment [*Gash et al.*, 1996], we create a new vegetation type called degraded grass (pasture). Based on *Costa et al.* [2007], we created another new vegetation type called soybean cropland (soy-

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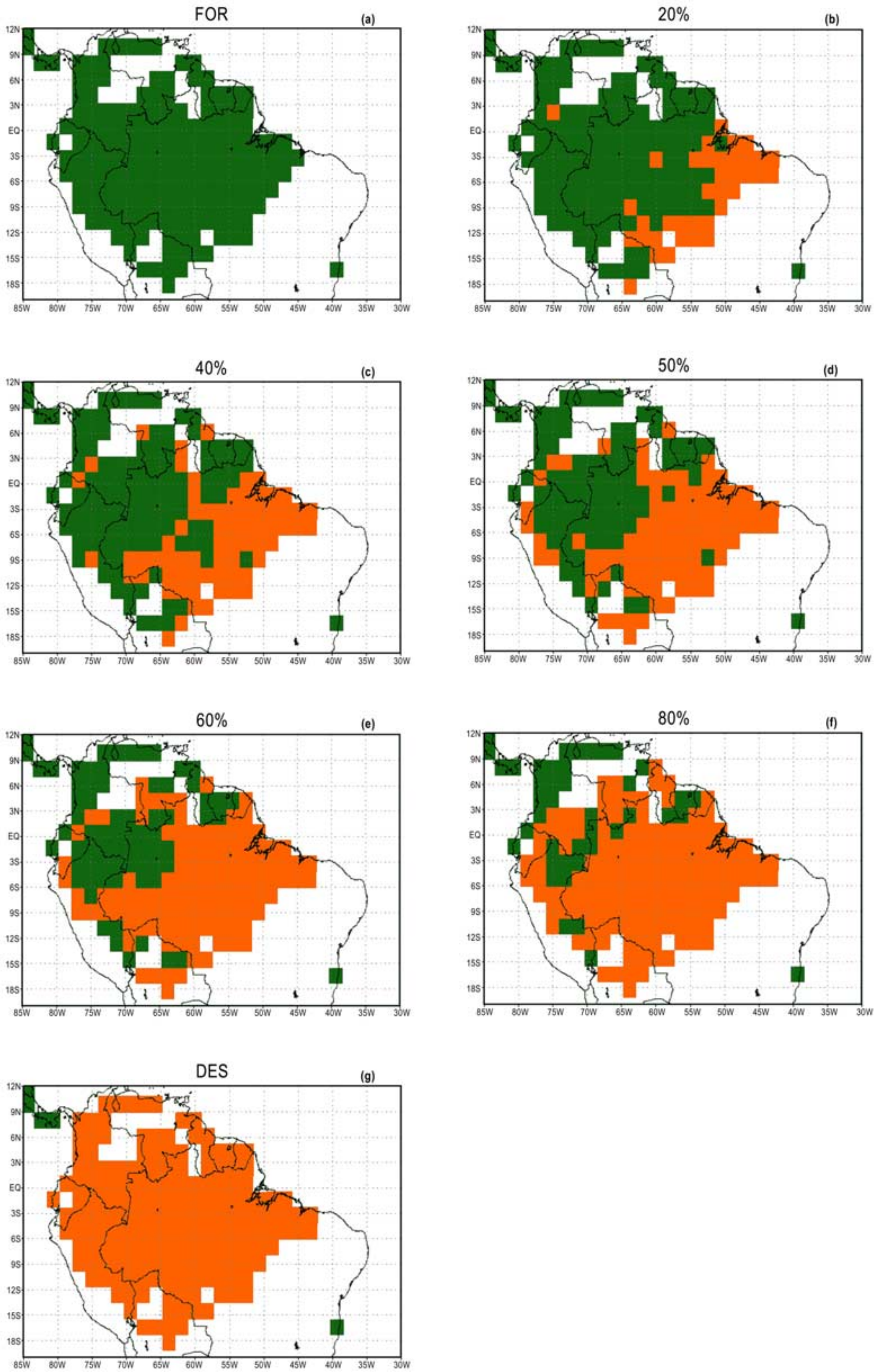

Figure 1. Deforestation scenarios for the Amazon on a ∼2° lat/lon grid: (a) control case; land cover scenario with (b) ∼20% of deforested area, (c) ∼40% of deforested area, (d) ∼50% of deforested area, (e) ∼60% of deforested area, and (f) ∼80% of deforested area; and (g) total deforestation case (green: tropical forest, red: pasture or soybean cropland).

bean), which has the physiology of a C3 plant and was parameterized with data from a soybean micrometeorological experiment performed in 2005 in Paragominas, eastern Amazonia.

[7] The modeled soybean crop was planted on 4 February, and harvested on 15 June, and in the remainder of the year the land cover type was bare soil. The simulated deforestation was converted to degraded grass (for land cover change

Table 1. Vegetation Parameters Used in CPTEC-INPE AGCM to Characterize Forest, Pasture and Soybean in the Amazon Basin

Parameter	Forest	Pasture	Soybean
Albedo[a]	0.13	0.19	0.18
Albedo[b]	0.12–0.13	0.17–0.21	0.17–0.25
Leaf area index[b]	5.0–5.0	1.2–2.2	0.13–5.9
Vegetation fraction[b]	0.98–0.98	0.50–0.90	0.0–0.90
Roughness length,[a] m	2.65	0.08	0.02
Height of canopy top, m	35.0	0.6	0.4

[a]Annual mean.
[b]Intra-annual variation.

scenarios with deforested areas equal to 20%, 40%, 50%, 60%, 80% and 100% of the original extent of the Amazon forest) or to soybean cropland (with deforested areas of 20%, 50%, 80% and 100%), and for each scenario a pseudo-equilibrium between the climate and vegetation was obtained.

[8] The land cover change scenarios with deforested areas smaller than 40% are from *Soares-Filho et al.* [2006]. Their model produces annual maps of simulated future deforestation under user-defined scenarios of highway paving, protected areas networks, protected areas effectiveness, deforestation rates and deforested land ceilings. The land cover change scenarios with deforested areas greater than 40% are obtained using the same methodology extending further into the future the simulation of deforestation under the business-as-usual scenario, which considers that recent deforestation trends will continue; highways currently scheduled for paving will be paved; compliance with legislation requiring forest reserves on private land will remain low; and protected areas will not be enforced (Figure 1). Though extreme, it is important to evaluate scenarios of complete deforestation. The Amazon has entered a new era as the growing profitability of cattle ranching and soy production increases deforestation rates and drives the expansion of the highway network into the region's core [*Soares-Filho et al.*, 2006]. According to *Nepstad et al.* [2006 references therein], "Brazil is the world's leading exporter of poultry, beef, oranges, and sugar cane and will soon be the leading exporter of cotton, soybeans, and biofuels." Large areas of the Amazon Basin have suitable soils, climate, and topography with strong potential for large-scale mechanized agriculture [*Morton et al.*, 2006]. The extreme scenario of total deforestation is used to provide insight into underlying physical principles of the functioning of the system, since it is unlikely that deforestation will affect all forests over western and northwestern Amazon.

[9] For the control run and for each treatment, the AGCM is integrated for 87 months, with five different initial conditions derived from five consecutive days of NCEP analyses, from 14 to 18 October 2002. We use climatological boundary conditions, including sea surface temperature, for treatments and control. In all simulations, atmospheric CO_2 concentrations are set to 370 ppmv. In the present work, the assessment of climate impacts is based on anomaly values (difference between treatment and control runs). Due to the existence of systematic errors, it is necessary to assign uncertainties to the calculated anomalies [*Oyama and Nobre*, 2003]. The first 27 months of each integration are neglected due to the soil moisture spin up. The results are the mean of the last 60 months (treatment–control).

[10] Table 1 shows the differences between rainforest, pasture and soybean parameters. Albedo is one of the most important controlling parameters to explain precipitation changes [*Berbet and Costa*, 2003; *Costa et al.*, 2007]. Other important differences between pasture and soybean are: leaf area, vegetation fraction and surface roughness. These differences arise mainly because the soybean crop was grown only during the first half of the year, becoming bare soil during the remainder of the year. Although this is a realistic agricultural management practice in Amazonia, it is also common in certain regions to grow a secondary crop, such as millet or sorghum, that would maintain the albedo at higher levels than specified for longer periods [*Costa et al.*, 2007].

3. Results and Discussion

[11] This paper focuses only on eastern Amazonia because of the higher climate predictability of the CPTEC-INPE AGCM for this region [*Marengo et al.*, 2003]. This spatial pattern of predictability is also present in the results of other major climate models, such as ECHAM [*Moron et al.*, 1998] and CCM3 [*Kiehl et al.*, 1998].

[12] The results for pasture show warmer near-surface air temperature (hereafter referred as surface temperature) in all deforestation cases compared to the control case (Table 2). For the scenario of complete conversion of forest to pasture (hereafter referred to as "PAS"), some areas can become warmer than 4°C. The higher surface temperature in all deforestation cases gives rise to more outgoing longwave

Table 2. Average Differences Between Annual Means of Pasture and Control Case for Eastern Amazonia

	Deforested Fraction[a]					
Variable	20%	40%	50%	60%	80%	100% Pasture
Precipitation, %	−0.2 (0.4)	−2.2 (0.7)	−5.8 (2.4)	−9.2 (0.8)	−14.9 (3.0)	−18.2 (1.9)
Temperature,[b] °C	0.8 (0.1)	1.7 (0.1)	2.2 (0.1)	2.6 (0.1)	2.8 (0.1)	3.1 (0.1)
Evapotranspiration, %	−4.7 (0.3)	−11.0 (0.8)	−15.1 (0.8)	−19.1 (0.5)	−22.1 (1.4)	−25.7 (1.0)
Sensible heat flux, %	3.9 (1.4)	12.9 (1.9)	19.6 (3.5)	28.4 (2.0)	35.6 (5.5)	42.8 (4.5)
Relative humidity, %	−2.8 (0.2)	−6.3 (0.4)	−8.4 (0.7)	−10.5 (0.3)	−12.0 (0.8)	−13.7 (0.6)
Outgoing longwave radiation, %	0.4 (0.2)	0.9 (0.1)	1.5 (0.4)	2.1 (0.1)	2.9 (0.5)	3.5 (0.3)
Net radiation, %	−2.4 (0.3)	−4.3 (0.2)	−5.4 (0.4)	−5.7 (0.2)	−5.8 (0.4)	−6.2 (0.3)
Cloud cover, %	−2.1 (0.2)	−5.1 (0.4)	−7.2 (0.6)	−8.9 (0.4)	−10.5 (0.8)	−12.4 (0.6)
CAPE, %	2.2 (0.7)	−1.7 (0.8)	−6.1 (1.8)	−10.4 (0.6)	−12.9 (2.2)	−16.1 (1.2)

[a]Standard deviation in parentheses.
[b]Deforested-control.

Table 3. Average Differences Between Annual Means of Soybean and Control Case for Eastern Amazonia[a]

Variable	Deforested Fraction 20%	50%	80%	100% Soybean
Precipitation, %	1.8 (2.2)	−4.6 (1.8)	−19.2 (1.7)	−25.8 (0.8)
Temperature,[b] °C	1.2 (0.1)	2.9 (0.1)	3.7 (0.1)	4.2 (0.1)
Evapotranspiration, %	−5.6 (0.8)	−18.1 (0.8)	−26.5 (1.2)	−31.2 (0.6)
Sensible heat flux, %	4.9 (1.2)	24.4 (2.6)	44.0 (2.6)	53.7 (2.0)
Relative humidity, %	−3.4 (0.5)	−10.4 (0.5)	−15.0 (0.6)	−17.5 (0.3)
Outgoing longwave radiation, %	0.3 (0.1)	1.7 (0.2)	3.7 (0.2)	4.9 (0.2)
Net radiation, %	−2.8 (0.4)	−6.2 (0.1)	−6.5 (0.3)	−7.0 (0.3)
Cloud cover, %	−2.1 (0.4)	−8.0 (0.5)	−12.9 (0.8)	−16.2 (0.5)
CAPE, %	5.2 (0.8)	−6.6 (1.6)	−16.8 (1.5)	−22.1 (1.2)

[a]Standard deviation in parentheses.
[b]Deforested-control.

radiation from the surface compared to the control case. This relative warming of the deforested land surface is consistent with the reduction in evapotranspiration, the lower leaf area and the lower surface roughness length (Table 2). Over eastern Amazonia the decrease of evapotranspiration is about 26% (~370 mm/year) in PAS (Table 2). All the factors-the higher surface albedo, the lower surface aerodynamic roughness, the lower leaf area, and the shallower rooting depth of pasture and soybean cropland compared with forest-contribute to reduce evapotranspiration [*Costa and Foley*, 2000]. To partially compensate the decrease in evapotranspiration (latent heating),

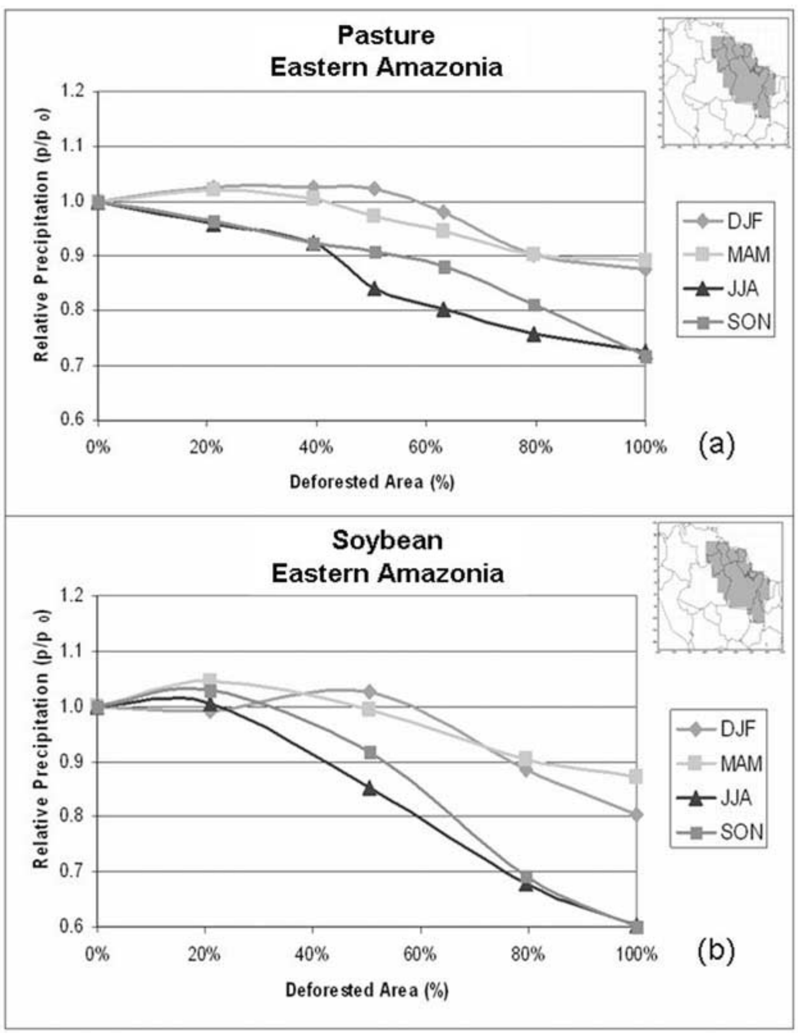

Figure 2. Mean seasonal precipitation of deforested cases compared to the control case over eastern Amazonia. Deforested areas are converted to (a) pasture and (b) soybean. Each point represents an average of 5 simulations (5 initial conditions) for each scenario.

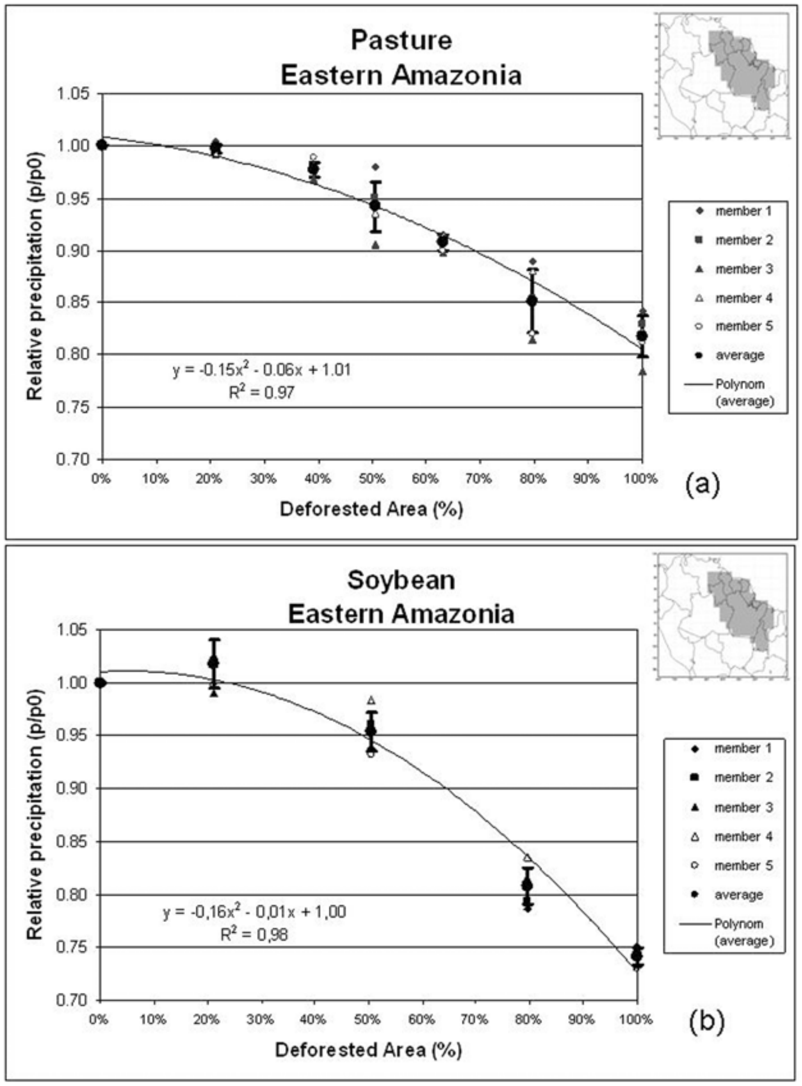

Figure 3. Annual mean precipitation of deforested cases compared to the control case in eastern Amazonia. Deforested areas are converted to (a) pasture and (b) soybean. Each point represents one simulation run for each scenario, and the black dots represent an average of 5 simulation runs. In both cases, the black line represents the parabolic best fit, in which the change in land surface explains the majority (R^2 = 0.97 and 0.98) of the precipitation variance. The bar represents the standard deviation.

sensible heat fluxes increase by about 43% (~20 W m^{-2}) in PAS, leading to the estimated increases in temperature. The results for soybean cropland (Table 3) show even warmer surface temperatures for all deforestation cases, higher reduction in evapotranspiration (31.2% for complete conversion of forest to soybean-hereafter referred to as "SOY") and increase in sensible heat flux (~54% for SOY).

[13] The annual precipitation is reduced by 18.2% (~346 mm) for the PAS case for eastern Amazonia, and there is a decrease in precipitation associated with pasture expansion (Table 2). The changes in precipitation for all experiments show reduction mainly over eastern Amazonia and increase in the western Amazonia. Figure 2 shows the seasonal averages for eastern Amazonia. The reduction in precipitation in this area is more evident when the deforestation exceeds 40% of the original forest extent. Small scale, patchy, heterogeneous deforestation pattern can, in principle, drive mesoscale circulations which might even enhance precipitation over deforested areas, as suggested by *Baidya Roy and Avissar* [2002]. However, as deforestation affects larger scales with more homogeneous land covers, then large-scale land-atmosphere processes are dominant. The reduction in precipitation occurs mainly during the dry season for that region in June–July–August (JJA) and September–October–November (SON). The same tendency is observed for the soybean cropland expansion case, showing even a higher reduction in precipitation (~40% in SOY case for JJA and SON). The tendency for decrease in precipitation associated with pasture expansion is similar to that of soybean cropland expansion for the same extent of deforested area. Still, the magnitude of precipitation decrease is higher over soybean than over pasture. This difference seems to be related to increase in land surface albedo, sensible heat flux and related increase in surface temperature, mainly because in soybean crops the land becomes bare soil during one half of the year.

[14] The underlying mechanism for the simulated changes in precipitation are linked to reduction of evapotranspiration associated with a decrease in leaf area index, a decrease in root depth, and reduction of roughness, which, in turn, decreases the surface latent heat fluxes through the decrease in drag coefficient [*Hahmann and Dickinson*, 1997; *Costa et al.*, 2007]. By reducing evapotranspiration, forest clearing diminishes the amount of water being pumped into the atmosphere, thereby contributing to reducing precipitation and relative humidity (Tables 2 and 3). The reduction in absorbed solar radiation, due to increases both in albedo and surface temperature, leads to a decrease in the net radiative heating of the land surface.

[15] In the deforested case, the solar and longwave radiation changes imply a decrease of 6.2% (~10 W m^{-2}) in the net radiation at the surface for PAS and decrease of 7.0% (~11.3W m^{-2}) for SOY, and this is dominated by the longwave part of the surface energy budget (Tables 2 and 3). Due to the reduction of latent heat flux, less energy fuels the atmospheric circulation, which ultimately results in a cooling of the upper atmosphere, followed by subsidence, less precipitation, reduction in convection and less cloudiness over the deforested areas [*Eltahir*, 1996; *Hahmann and Dickinson*, 1997]. *Dirmeyer and Shukla* [1994] have showed that the impact of an increase in continental albedo is a reduction in precipitation. In this work, for the case of replacing the entire Amazon forest by pastures (PAS case), there will be an increase of about 5% in continental albedo and a reduction of about 18.2% (~346 mm) in precipitation, and a reduction in precipitation of about 25.8% (~491 mm) for the SOY case (Tables 2 and 3).

[16] The results for pasture and soybean show reduction of evapotranspiration, warmer surface temperature and increase in sensible heat flux over eastern Amazonia (Tables 2 and 3). Thus, one can conceive of a negative feedback driven by enhanced sensible heating in the deforested case. That could generate both a more unstable vertical profile and a thermal low which, in turn, could enhance moisture convergence and precipitation. However, for that region one has to consider the aggregated effects of more sensible heating, increasing column instability, and less latent heating, drying out the boundary layer and decreasing instability. The calculation of the convective available potential energy-CAPE [*Moncrieff and Miller*, 1976] for eastern Amazonia shown in Tables 2 and 3 confirms a decrease of this instability index with increase of deforested area, which is consistent with reductions in precipitation.

[17] *Avissar et al.* [2002] discussed the impact of gradual deforestation on precipitation and proposed three hypothetical possible patterns: 1) a linear decrease of precipitation as a response of increasing deforested areas; 2) an initial sharp reduction of precipitation for a relatively small extent of deforestation, with further deforestation not having a significant impact; and 3) a possible increase of precipitation for a small extent of deforestation as a response to mesoscale circulations, followed by a catastrophic decrease in precipitation after the deforestation extent has passed a threshold value. Here, our results indicate a parabolic relationship between precipitation reduction and deforestation (Figures 3a and 3b) for both land uses (pasture and soybean) which explains ~98% of the precipitation variance.

4. Summary and Conclusions

[18] This paper assesses the climate impacts of converting the Amazon rainforest into pastures or soybean croplands using simulated land cover maps from a business-as-usual scenario of future deforestation. The results for eastern Amazonia show increase in surface temperature and decrease in evapotranspiration and precipitation. The precipitation change after deforestation over eastern Amazonia is associated with increase in albedo and reduction of evapotranspiration associated with the lower surface aerodynamic roughness, the lower leaf area, and the shallower rooting depth of pasture and soybean cropland compared with forest. The relationship between simulated precipitation and deforestation shows an accelerating decrease of rainfall for increasing deforestation for both classes of land use conversions. The reduction in precipitation in this region is more evident when deforestation exceeds 40% of the original forest cover, and this reduction in precipitation occurs mainly during the dry season. When we analyze the average change in precipitation for the entire Amazon (not presented here) we find the same tendency: reduction in precipitation in dry season of about 16% for the case of replacing the entire forest by pasture, and 24% for replacing by soybean. The reduction in precipitation can create favorable conditions to potentially alter the structure of the forests, and lead to a process of savannization, as suggested by some studies [e.g., *Nobre et al.*, 1991; *Oyama and Nobre*, 2003; *Hutyra et al.*, 2005].

[19] The ecosystems of Amazonia are subjected to various, but interconnected, environmental driving forces at the regional and global scales. Continuing trends of pasture and soybean cropland expansion over Amazon rainforests may have important consequences for the sustainability of the region's remaining natural vegetation.

[20] **Acknowledgments.** We thank Gordon and Betty Moore foundation and LBA.

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