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Climate change in Amazonia caused by soybean cropland expansion, as compared to caused by pastureland expansion

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[1] In the last two decades, the strong increase of pasturelands over former rainforest areas has raised concerns about the climate change that such change in land cover might cause. In recent years, though, expansion of soybean croplands has been increasingly important in the agricultural growth in Amazonia. In this paper we use the climate model CCM3 to investigate whether the climate change due to soybean expansion in Amazonia would be any different from the one due to pastureland expansion. The land component of the model has been updated with new findings from the Large-Scale Biosphere Experiment in Amazonia (LBA), and a new soybean micrometeorological experiment in Amazonia. Results show that the decrease in precipitation after a soybean extension is significantly higher when compared to the change after a pastureland extension, a consequence of the very high albedo of the soybean. **Citation:** Costa, M. H., S. N. M. Yanagi, P. J. O. P. Souza, A. Ribeiro, and E. J. P. Rocha (2007), Climate change in Amazonia caused by soybean cropland expansion, as compared to caused by pastureland expansion, *Geophys. Res. Lett.*, *34*, L07706, doi:10.1029/2007GL029271.

1. Introduction

[2] In August 2005, the Brazilian Amazon deforestation was approximately 560,000 km^2, equivalent to 15% of the total original rainforest cover, and is increasing at the average rate of 19,350 km^2 a year (www.obt.inpe.br/prodes). Although historically most of the changes in land cover are conversions from rainforest to pasturelands, in recent years the expansion of soybean croplands has been increasingly important in the agricultural growth in Amazonia. Official statistics from the Brazilian Government (www.conab.gov.br) indicate that soybean planted area in Amazonian states expanded at the rate of 14.1% a year from 1990 to 2005, but the rate is increasing: 12.1% a year during the 1990s (from 1.11 M ha in 1990 to 2.76 M ha in 1999), and 16.8% a year from 2000 to 2005 (to 7 M ha) (Figure 1). The average expansion in the latter period ($\sim$0.7 M ha year^{-1}, or $\sim$7,000 km^2 year^{-1}) is roughly one-third of the average increase in agricultural land (pastureland and cropland) in the period. Several factors may contribute to maintain the exponential expansion of soybean in Amazonia in the future, including improvements in infra-structure for soybean export (roads, harbors) and an increasing demand for biofuels like biodiesel, which can be obtained from the soybean oil.

[3] Although the climate effects of Amazon deforestation have been studied by many scientists [see, e.g., *Nobre et al.*, 1991; *Costa and Foley*, 2000], virtually all of these studies have considered a pasture land cover as a replacement for the original rainforest.

[4] In this study we use the climate model CCM3 to investigate whether the climate change due to soybean expansion in Amazonia would be any different from the one due to pastureland expansion. We initially describe the models used, the early results from the first soybean micrometeorological experiment, which are used to parameterize the model, and the numerical experiment design. Then, we present results of an Amazon partial deforestation experiment, using both pasture and soybean as replacement for the fallen rainforest, concluding with a discussion relevant to the future climate change in Amazonia, and suggestions for future research.

2. Model Description and Soybean Parameterization

[5] In this study, we use the National Center for Atmospheric Research (NCAR) Community Climate Model version 3 (CCM3) [*Kiehl et al.*, 1998] coupled with an updated version of the Integrated Biosphere Simulator (IBIS) of *Foley et al.* [1996]. We refer to this coupled model as CCM3–IBIS [*Delire et al.*, 2002]. CCM3 is an atmospheric general circulation model with spectral representation of the horizontal fields. In this study, to allow longer runs and the several required simulations, we choose to operate the model at a resolution of T42L18 (the spectral representation of the horizontal fields is truncated at the 42nd wavenumber using a triangular truncation; horizontal fields are converted to a 2.81° × 2.81° grid; 18 levels in the vertical), with a 20-min time step. This resolution allows for a reasonable representation of the major climate features of the region, although it is not sufficient to represent sub-synoptic or mesoscale processes associated to the climate dynamics of the region and to the deforestation patterns.

[6] The global terrestrial biosphere model IBIS (version 2.6) is a comprehensive model of terrestrial biospheric processes, representing two vegetation layers (i.e., trees and short vegetation) and simulates land surface physics, canopy physiology, and plant phenology. Although IBIS also includes a dynamic vegetation component, in this study it is disabled, so vegetation land cover is fixed. Land surface physics and canopy physiology are calculated with the time step used by the atmospheric model. The plant phenology algorithm has a daily time step. In

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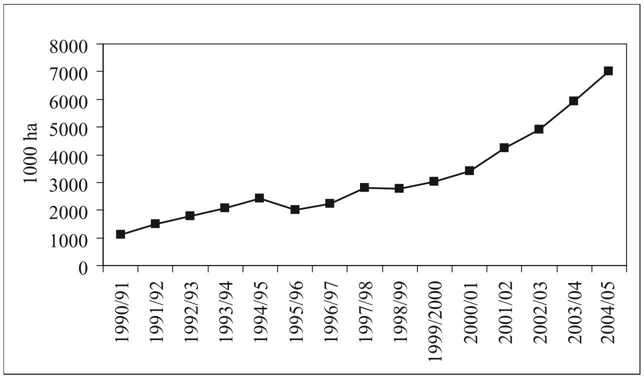

Figure 1. Soybean expansion in Brazilian Amazonia.

these simulations, IBIS operates on the same T42 spatial grid as the CCM3 atmospheric model. We have updated the rainforest representation in IBIS with a new calibration against flux data from four different Amazonia flux tower sites [*Imbuzeiro*, 2005], using data from the Large-Scale Biosphere Experiment in Amazonia (LBA), and from a new soybean micrometeorological experiment in Amazonia.

[7] We also modified the IBIS model to introduce a new land cover type, the soybean. This new land cover type is based on the physiology of a C3 plant, but has specific phenology parameterizations that emulate a soybean crop that grows in Amazonia. These parameterizations are based on data collected at a soybean micrometeorological experiment that has been setup in late 2005 in Paragominas, eastern Amazonia. Although most of the soybean expansion in Amazonia is taking place in northern Mato Grosso and Rondônia, and the Paragominas region represents a small enclave of the soybeans in Amazonia, this micrometeorological experiment is the only one available in Amazonia and is therefore the best reference available for the region. The IBIS soybean parameterization uses standard parameterizations for C3 plants, but used local data on leaf area index (LAI) and surface albedo (Figure 2). Albedo is one of the most important determiners of precipitation in the tropics, and the albedo data obtained at this site is fundamental to parameterize this numerical experiment, and to explain the climate differences between the soybean land cover and the pasture land cover, as discussed later. Other parameterizations, including the rooting depth and the physiological parameters, are the same for the soybeans and other C3 plants. Although soy plants are substantially shallower in their rooting than pasture plants, we understand that this difference has little influence on the crop latent heat flux, because the growth of the soy crop happens during the wet season. The use of default physiological parameterizations may cause variations in the Bowen ratio which we are unable to evaluate at the moment, due to lack of flux data in the first soybean field data collection season.

[8] Figure 2a shows the LAI data collected on the field and the actual model representations. Forest and pasture LAI representation are consistent with other values in the literature [*Wright et al.*, 1996]. Soybean LAI indicates the characteristic annual crop cycle. Although in our field experiment the soybean crop was planted on February 4 2006 and harvested on June 15 2006, in the model we assume a planting date of January 5, more characteristic of the region. For appropriate comparison, the observation dates are shifted by 31 days. After harvest on May, it is assumed that low leaf area vegetation like weeds grows.

[9] Figure 2b shows the soybean albedo data collected on the field and the actual model representations for the average forest, average pasture and the two individual soybean simulations (see details in the experiment design in the next section). Forest and pasture albedo follow the ABRACOS (Anglo-Brazilian Amazonian Climate Observation Study [*Gash et al.*, 1996]) recommendation [*Wright et al.*, 1996] and several numerical experiments [*Costa and Foley*, 2000; *Berbet and Costa*, 2003]. While one of the soybean simulations follow the observed data on the field, the other simulation aims at reproducing the peak values (0.26) observed elsewhere in the literature [*Blad and Baker*, 1972*; André and Viswanadhan*, 1983; *Fontana et al.*, 1991]. The soybean albedo observed on the field indicates an increasing albedo as the crop grows, and decreasing albedo as the crop drops leaves and dries out. For the period between growing seasons, we choose an average albedo of 0.20, characteristic of the presence of crop residues (straw) on the ground [*Horton et al.*, 1996].

[10] This phenological representation of the croplands considers a single growing season through the year, although it is common in Amazonia to grow a secondary crop, such as millet or sorghum, which would maintain the albedo at higher levels than specified for longer periods. Due to lack of phenological and albedo data on the double

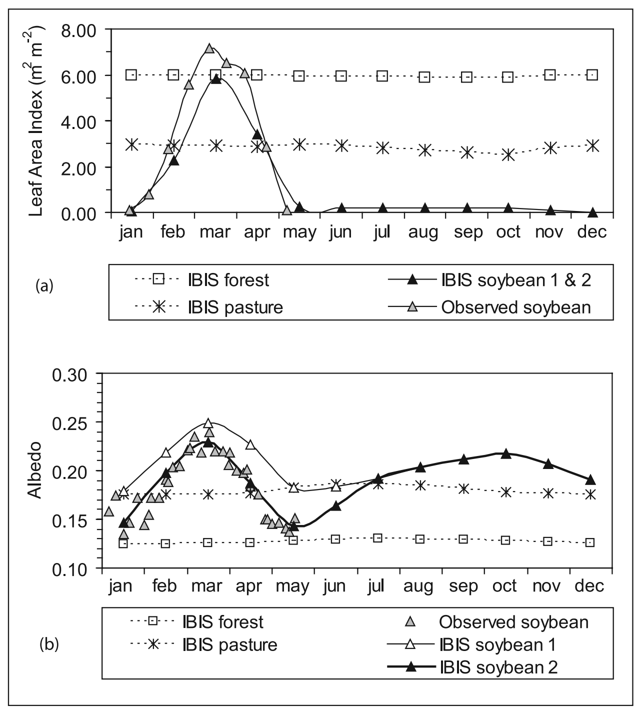

Figure 2. Seasonal variation of soybean crop LAI and albedo data collected on the field and IBIS representations of soybean, pasture and rainforest LAI and albedo. The soybean growing season is clearly represented.

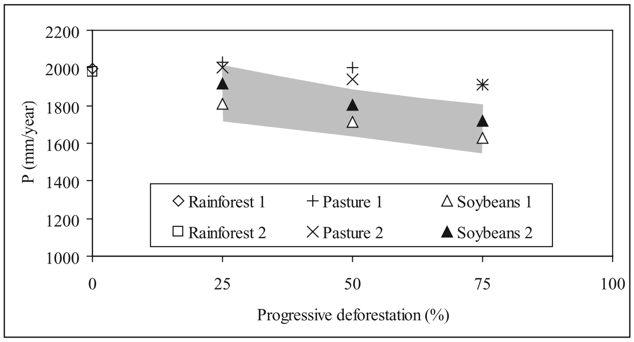

Figure 3. Annual mean results of precipitation for the control experiment and after increasing levels of pastureland and soybean cropland expansions. The grey area indicates the confidence interval for the soybeans mean, at the 95% level of significance.

cropping system, we set up our simulations using a single growing season.

3. Experiment Design

[11] The following set of simulations is designed to elucidate the climate effects of expansion of soybean cropland, compared to the climate effects of pastureland expansion. In all simulations, atmospheric CO_2 concentrations are set to 355 ppmv, and sea surface temperatures are set to a climatological seasonal cycle. All of the simulations are run for 20 years, using the same initial conditions; the last 10 years are averaged to analyze the results. The first ten years are left for the model to approach an equilibrium state, specifically with respect to soil moisture. To account for the variability in land surface albedo, for the control run and each of the pasture and soybean simulations, we run two repetitions, described below.

[12] In this study, we conduct three groups of simulations, in a total of 14 runs:

[13] (a) Control runs. Original rainforest land cover. We run two repetitions, where the only difference between them is the albedo of the rainforest, which is set to 0.125 and 0.129, inside the range of values measured by *Culf et al.* [1996]. LAI of the rainforest is set to 5.9 $m^2\ m^{-2}$, and forest biomass is set to 10.4 kg C m^{-2}.

[14] (b) Pastureland expansion. In three different simulations, pasture land cover in each Amazonia grid cell partially replaces the original rainforest, increasing from 0% in the control run, to 25%, 50% and 75%. In each grid cell, both land covers are treated separately, and the radiation and heat fluxes are averaged according to their land cover fraction. Variation of pasture LAI and albedo through the year are given by Figure 3. For each level of pastureland expansion, we run two repetitions, where the only difference between them is the albedo of the pastureland, which is set to 0.177 and 0.182, inside the range of values measured by *Culf et al.* [1996]. Albedo and LAI of the remaining rainforest patches are set to 0.125 and 5.9 $m^2\ m^{-2}$, respectively.

[15] (c) Soybean cropland expansion. In three different simulations, soybean cover in each Amazonia grid cell partially replaces the original rainforest, increasing from 0% in the control run, to 25%, 50% and 75%. In each grid cell, both land covers are treated separately, and the radiation and heat fluxes are averaged according to their land cover fraction. Variation of soybean LAI and albedo through the year are given by Figure 2. For each level of cropland expansion, we run two repetitions, where the only difference between them is the albedo of the soybean, which is set according to Figure 2b. Albedo and LAI of the remaining rainforest patches are set to 0.125 and 5.9 $m^2\ m^{-2}$, respectively.

4. Results and Discussion

[16] Figure 3 shows the annual mean results of precipitation after partial deforestation, showing two repetitions for the control run, the pastureland and soybean deforestation. This figure, which summarizes all experiments, shows at least three interesting results: climate response for partial deforestation, an increase in precipitation for small levels of deforestation, and the most remarkable ones, the difference between soybeans and pastures. This paper discusses only the effects of land use, i.e., soybean cropland expansion versus pastureland expansion. The other results will be discussed in companion papers.

[17] The decrease in precipitation associated with an expansion of soybean is considerably different from the decrease in precipitation associated with a pastureland expansion: for the same amount of deforestation, the precipitation decrease is much higher over soybean than over pastures, when compared to the rainforest control runs. The change in precipitation for 25%, 50% and 75% deforestation is, respectively, −123, −230 and −312 mm $year^{-1}$ (−6.2%, −11.6% and −15.7%) for the soybean land cover, significantly different than the +27, −16 and −77 mm $year^{-1}$ (+1.4%, −0.8% and −3.9%) for the pasture land cover (Figure 3).

[18] This difference in results seems to be directly related to the change in land surface albedo and water balance. Figure 4 shows the linear relationship between the annual mean precipitation, latent heat flux and sensible heat flux anomalies, against the annual mean albedo anomalies, where the change in land surface albedo explains about

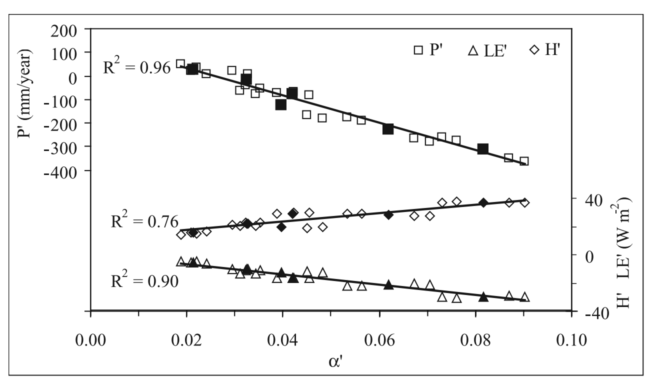

Figure 4. Annual mean anomalies in precipitation (P′), latent heat flux (LE′) and sensible heat flux (H′) as a function of annual mean anomalies in surface albedo (α'). The white symbols represent the original values for each simulation difference, and the black symbols represent the average of each condition.

96% of the precipitation variance. There are two mechanisms that reduce precipitation: one is the suppression of precipitation due to the cooling of the atmospheric column, but the other is the reduction of moisture from local evapotranspiration resulting in a drying of the column.

[19] The mechanisms that relate precipitation anomalies to surface albedo anomalies have been explained by several theoretical and modeling studies [*Dirmeyer and Shukla*, 1994; *Zeng and Neelin*, 1999; *Berbet and Costa*, 2003]. In summary, deforestation is characterized by an increment in albedo (α), a decrease in atmospheric turbulence (lower z_0), a decrease in leaf area index (LAI), and a decrease in root depth (z_R). Initially, consider only the non-radiative effects of deforestation (which is equivalent to assume $\alpha' = 0$). Decreases in z_0, LAI and z_R all contribute to a decrease in latent heat flux, and an increase in surface temperature, sensible heat flux, atmospheric instability, cloudiness and precipitation. As the reflected radiation increases (due to increases in surface albedo and to cloud-radiative feedbacks), surface latent and sensible heat fluxes decrease due to reduced radiation absorbed by the surface, resulting in a cooling of the atmospheric column, which induces a thermally-driven circulation that results in subsidence, with subsequent reduction in convection, cloudiness and precipitation. The cloud-radiative feedback is an important component of the entire process, as it modulates the amount of incident solar radiation at the surface [*Berbet and Costa*, 2003].

[20] Although in this study we see essentially the same mechanism acting, these results demand our attention because the difference in surface albedo, in the soybean case, is very large (up to 0.09 for the 75% deforestation case).

5. Summary and Conclusions

[21] Although historically most of the changes in Amazonia land cover are from rainforest to pasturelands, in recent years expansion of soybean croplands has been increasingly important in the agricultural expansion in Amazonia. The precipitation change after deforestation has been linearly related to the increase in surface albedo. While rainforest albedo is around 12.5% and pasture albedo is around 18% (difference 5.5%), soybean albedo peaks at 24–26%, and averages about 20.5% through the year (average difference 8.0%). Following the larger increase in surface albedo and decrease in evapotranspiration, decrease in precipitation is significantly higher after a soybean expansion when compared to the change after a pastureland expansion.

[22] Soybeans will certainly not expand uniformly across the Amazon because of severe edaphic constraints imposed by rocky soils, poor drainage, and because of climatic constraints (generally, of too much rainfall). Most likely, it will stay below 30% of the Amazon area, with higher proportions concentrated in Mato Grosso, Rondônia, southern Pará and along major roads or ports [*Soares-Filho et al.*, 2006]. The results presented here suggest the need to further study of the role of soybeans, and croplands in general, on the physical climate system of Amazonia. Future research needs include additional field experiments to measure the different land use parameterizations, the geographical aspects of agricultural expansion, and global as well as regional climate experiments that evaluate its influences on climate.

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References

André, R. G. B., and Y. Viswanadhan (1983), Radiation balance of soybeans grown in Brazil, *Agric. Meteorol.*, *30*, 150–173.

Berbet, M. L. C., and M. H. Costa (2003), Climate change after tropical deforestation: Seasonal variability of surface albedo and its effects on precipitation change, *J. Clim.*, *16*, 2099–2104.

Blad, B. L., and D. G. Baker (1972), Reflected radiation from a soybean crop, *Agron. J.*, *64*, 277–280.

Costa, M. H., and J. A. Foley (2000), Combined effects of deforestation and doubled atmospheric CO_2 concentrations on the climate of Amazonia, *J. Clim.*, *13*, 18–34.

Culf, A. D., J. L. Esteves, A. O. Marques Filho, and H. R. da Rocha (1996), Radiation, temperature and humidity over forest and pasture in Amazonia, in *Amazonian Deforestation and Climate*, 1st ed., edited by J. H. C. Gash et al., pp. 175–191, John Wiley, Hoboken, N. J.

Delire, C., J. A. Foley, and S. Thompson (2002), Evaluating the carbon cycle of a coupled atmosphere-biosphere model, *Global Biogeochem. Cycles*, *17*(1), 1012, doi:10.1029/2002GB001870.

Dirmeyer, P. A., and J. Shukla (1994), Albedo as a modulator of climate response to tropical deforestation, *J. Geophys. Res.*, *99*, 20,863–20,877.

Foley, J. A., I. C. Prentice, N. Ramankutty, S. Levis, D. Pollard, S. Sitch, and A. Haxeltine (1996), An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics, *Global Biogeochem. Cycles*, *10*, 603–628.

Fontana, D. C., M. A. Berlato, and H. Bergamaschi (1991), Soybean radiation balance in subtropical region (in Portuguese with abstract in English), *Pesqui. Agropecu. Bras.*, *26*, 411–418.

Gash, J. H. C., C. A. Nobre, J. M. Roberts, and R. L. Victoria (1996), *Amazonian Deforestation and Climate*, 1st ed., 611 pp., John Wiley, Hoboken, N. J.

Horton, R., K. L. Bristow, G. J. Kluitenberg, and T. J. Sauer (1996), Crop residue effects on surface radiation and energy balance—Review, *Theor. Appl. Climatol.*, *54*, 27–37.

Imbuzeiro, H. M. A. (2005), Calibration of the IBIS model in the Amazonian forest using multiple sites, M.S. thesis (in Portuguese with abstract in English), 67 pp., Fed. Univ. of Viçosa, Viçosa, Brazil.

Kiehl, J. T., J. J. Hack, G. B. Bonan, B. A. Boville, D. L. Williamson, and P. J. Rasch (1998), The National Center for Atmospheric Research Community Climate Model: CCM3, *J. Clim.*, *11*, 1131–1149.

Nobre, C. A., P. J. Sellers, and J. Shukla (1991), Amazonian deforestation and regional climate change, *J. Clim.*, *4*, 957–988.

Soares-Filho, B., D. C. Nepstad, L. M. Curran, G. C. Cerqueira, R. A. Garcia, C. A. Ramos, E. Voll, A. McDonald, P. Lefebvre, and P. Schlesinger (2006), Modelling conservation in the Amazon basin, *Nature*, *440*, 520–523.

Wright, I. R., C. A. Nobre, J. Tomasella, H. R. da Rocha, J. M. Roberts, E. Vertamatti, A. D. Culf, R. C. S. Alvalá, and M. G. Hodnett (1996), Towards a GCM surface parameterization for Amazonia, in *Amazonian Deforestation and Climate*, 1st ed., edited by J. H. C. Gash et al., pp. 473–504, John Wiley and Sons, Hoboken, N. J.

Zeng, N., and J. D. Neelin (1999), A land-atmosphere interaction theory for the tropical deforestation problem, *J. Clim.*, *12*, 857–872.

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