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Land use change exacerbates tropical South American drought by sea surface temperature variability

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[1] Observations of tropical South American precipitation over the last three decades indicate an increasing rainfall trend to the north and a decreasing trend to the south. Given that tropical South America has experienced significant land use change over the same period, it is of interest to assess the extent to which changing land use may have contributed to the precipitation trends. Simulations of the National Center for Atmospheric Research Community Atmosphere Model (NCAR CAM3) analyzed here suggest a non-negligible impact of land use on this precipitation behavior. While forcing the model by imposed historical sea surface temperatures (SSTs) alone produces a plausible north-south precipitation dipole over South America, NCAR CAM substantially underestimates the magnitude of the observed southern decrease in rainfall unless forcing associated with human-induced land use change is included. The impact of land use change on simulated precipitation occurs primarily during the local dry season and in regions of relatively low annual-mean rainfall, as the incidence of very low monthly-mean accumulations (<10 mm/month) increases significantly when land use change is imposed. Land use change also contributes to the simulated temperature increase by shifting the surface turbulent flux partitioning to favor sensible over latent heating. Moving forward, continuing pressure from deforestation in tropical South America will likely increase the occurrence of significant drought beyond what would be expected by anthropogenic warming alone and in turn compound biodiversity decline from habitat loss and fragmentation. **Citation:** Lee, J.-E., B. R. Lintner, C. K. Boyce, and P. J. Lawrence (2011), Land use change exacerbates tropical South American drought by sea surface temperature variability, *Geophys. Res. Lett.*, *38*, L19706, doi:10.1029/2011GL049066.

1. Introduction

[2] Analyses of past precipitation over tropical South America have demonstrated strong sensitivity of regional rainfall to remote sea surface temperature (SST) forcing from both the Atlantic and Pacific Oceans [*Nobre and Shukla*, 1996; *Enfield*, 1996; *Liebmann and Marengo*, 2001]. For example, on interannual timescales, the occurrence of droughts over northern South America during El Niño/Southern Oscillation (ENSO) warm years (El Niños) is well-known [*Liebmann and Marengo*, 2001; *Chiang et al.*, 2000]. On longer (interdecadal) timescales, precipitation over the northern and southern parts of tropical South America has often exhibited opposing trends [*Marengo*, 2004; *Li et al.*, 2008]: over the last ~30 years, annual-mean precipitation has shown an upward trend to the north and a downward trend to the south (see Figure 1a).

[3] Given that human activity has substantially altered the land surface over tropical South America and that further land use change is expected to occur in the future [*Nepstad et al.*, 2008], it is critical to consider how altered surface conditions associated with large-scale land use practices like deforestation or agricultural conversion may impact South American hydroclimate. While isolating the influence of changing land surface conditions on precipitation is challenging, there are several potential pathways through which this may occur. For example, the direct decrease of moisture flux resulting from deforestation might be anticipated to decrease precipitation [*Oyama and Nobre*, 2004]. Since trees can tap large reservoirs of deep soil moisture that are otherwise unavailable to the atmosphere, tropical forests with deep roots can support relatively high rates of transpiration even during the dry season and thus provide a moisture source for rainfall [*Nepstad et al.*, 1994; *Oliveira et al.*, 2005; *Lee et al.*, 2005]. The residual dry season moisture flux from the land surface has been shown to be especially important for early onset of the rainy season [*Fu and Li*, 2004; *Lintner and Neelin*, 2009], so a reduction in this flux could significantly increase the length of the dry season, with potentially devastating impacts on biodiversity [e.g., *Kreft and Jetz*, 2007; *Lee and Boyce*, 2010; *Boyce and Lee*, 2010; *Lewis et al.*, 2011].

[4] In this paper, we focus on understanding the decadal-scale precipitation change over tropical South America during the period of available satellite observations (here 1979–2006) by considering differences between two consecutive 14-year periods, 1979–1992 and 1993–2006. Our principal objective is to demonstrate how the combined effects of remote SST forcing and local land use change may have contributed to the observed decadal precipitation change through climate model simulations with a version of the National Center for Atmospheric Research Community Atmospheric Model (NCAR CAM3) [*Collins et al.*, 2006]. A key finding here is that inclusion of plausible land use changes over the last 30 years significantly increases the incidence of the driest monthly rainfall accumulations as simulated by the NCAR model. As we discuss below, this particular manifestation of land use change impact on precipitation is likely to have substantial implications under

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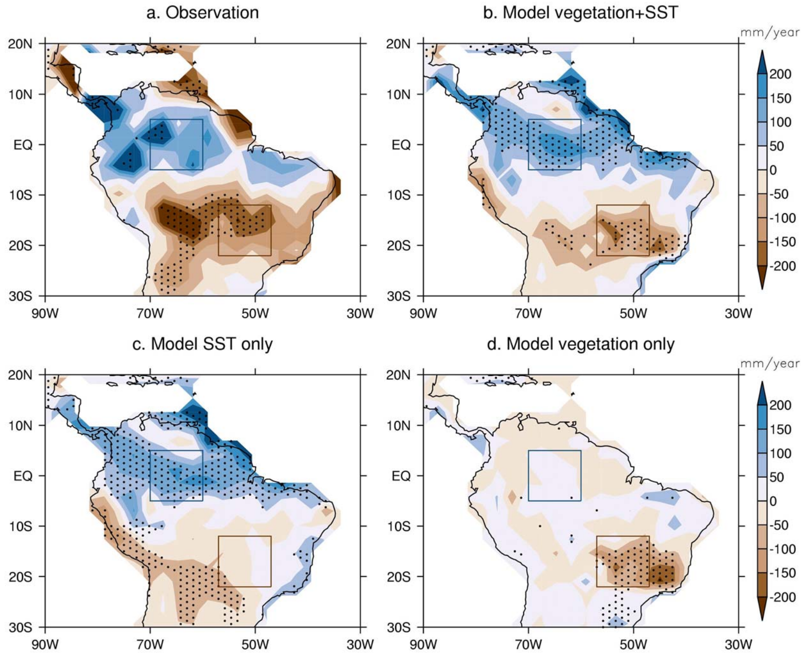
a. Observation b. Model vegetation+SST c. Model SST only d. Model vegetation only

Figure 1. Precipitation difference from (a) Global Precipitation Climatology Project (GPCP) precipitation [*Adler et al.*, 2003], and from CAM simulations due to (b) SST and vegetation differences, (c) SST differences, and (d) vegetation differences between the average of 1993–2006 and of 1979–1992. Stippled area shows area where the difference is statistically significant ($P < 0.05$) with a student t-test. The effect of SST only is the ensemble mean differences from the control run differences from 1993–2006 to 1979–1992, and the effect of vegetation only is the ensemble mean differences from the present-day vegetation to pre-land use vegetation cases for the whole period (1979–2006). The combined effect of SST and vegetation is the ensemble mean difference from 1993–2006 with present-day vegetation to 1979–1992 pre-land use vegetation cases.

projections of warmer conditions associated with greenhouse gas forcing in the current century.

2. Models

[5] We analyze simulations from NCAR CAM3 coupled to the Community Land Model (CLM) [*Oleson et al.*, 2008] and forced with mean-monthly observed SSTs from the Hadley Centre's HadISST dataset. These simulations were performed at T42 resolution (~3° by ~3°) for the period January 1979–December 2006 for two distinct land vegetation scenarios. One scenario imposed "present-day" vegetation cover derived from MODIS satellite observations for the period 2001–2003 [*Lawrence and Chase*, 2007]. The other scenario imposed "pre-land use" vegetation [*Lawrence and Chase*, 2010], which effectively represents the vegetation distribution expected in the absence of human disturbance. Pre-land use vegetation is constructed using the land-use change history [*Ramankutty and Foley*, 1999] and is incorporated into CLM vegetation parameters [*Lawrence and Chase*, 2010]. For each vegetation scenario, an ensemble of five runs initialized from independent conditions on September 1st 1975 was performed. The effects of SST alone, vegetation alone, and SST and vegetation combined on precipitation are compared between the earlier (1979–1992) and later (1993–2006) periods. For more information on the model, see auxiliary material.[1]

[6] We should point out that a more consistent approach for addressing the role of land-use changes on precipitation over recent decades would be to impose the observed temporal evolution of land use (or vegetation) changes. However, CLM3.5 has 16 plant functional types, and modifications to each of these are nontrivial. Our interest here is to use the extremes represented by present day and potential vegetation to assess how large the impacts of land use change on precipitation may be: since our analysis demonstrates substantial changes, it motivates the development of more realistic vegetation change scenarios for application in the future work. We also note that, compared to previous studies using hypothetical vegetation scenarios [e.g., *Shukla and Mintz*, 1982; *Oyama and Nobre*, 2004], our analysis makes use of land use changes based on historic estimates (albeit likely exaggerated).

3. Results and Discussion

[7] The SST differences between the two periods exhibit a La Niña-like pattern, with larger temperature increases over the western Pacific and smaller increases, or even weak decreases, over the eastern Pacific (Figure 2). The North Atlantic also exhibits a pronounced increase in SST during the 1993–2006 period. It has been suggested that a transient, La Niña-like SST pattern may develop in response to global warming because the atmosphere, land surface, and mixed layer of the ocean all warm on time scales of less than a decade, while the deep ocean and the surface upwelling regions strongly coupled to the deeper ocean, e.g., the

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL049066.

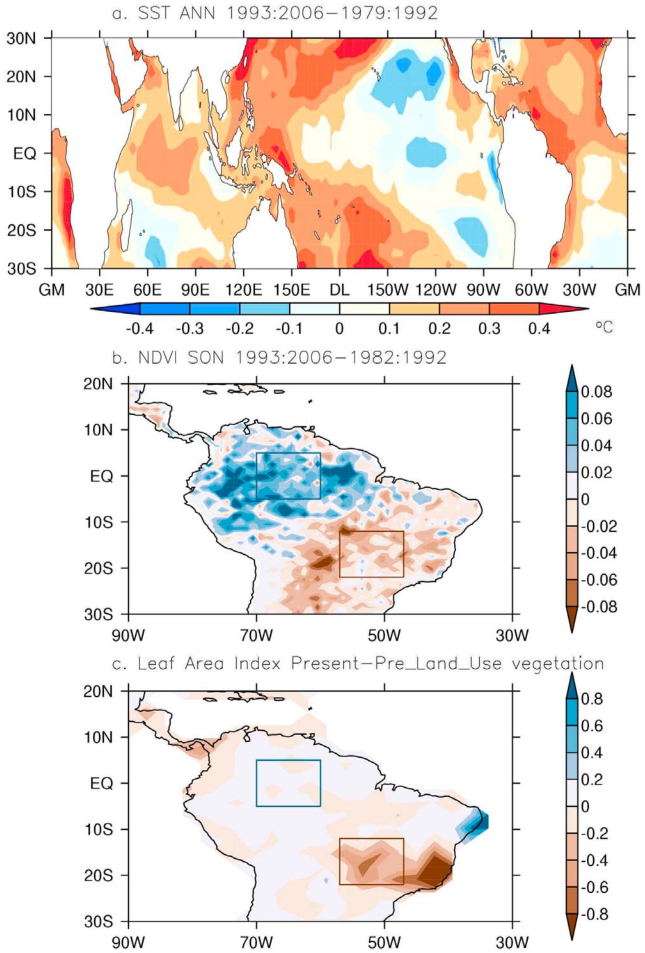

Figure 2. The differences in (a) HadSST (28) difference between the averages of 1993–2006 and of 1979–1992 and (b) Normalized Difference Vegetation Index (NDVI) [*Tucker et al.*, 2005] difference between the averages of 1993–2006 and of 1982–1992, and (c) leaf area index (LAI: the ratio of projected leaf area to surface ground area) difference between present-day and pre-land use vegetation runs. Tropical forest has a leaf area index close to 7 [*Clark et al.*, 2008]. Pre-land use vegetation adds historical land use change to present-day vegetation, and reflects vegetation before human modification.

equatorial Pacific cold tongue, require much longer to warm [*Clement et al.*, 1996; *Held et al.*, 2010; *Lintner and Neelin*, 2008]. Another characteristic of the decadal La Niña-like pattern of Pacific SSTs is its association with warmer conditions in the tropical troposphere, which contrasts to the tendency for a cooler-than-normal tropical troposphere during La Niña conditions on interannual timescales.

[8] Over northern tropical South America, the simulated precipitation field from the present-day vegetation run manifests an increase of 127 mm/year between 1979–1992 and 1993–2006. A comparable increase in northern precipitation occurs in the pre-land use vegetation run, suggesting that the change is dominated by remote SST forcing (Figures 1b and 1c and Table S1 in the auxiliary materials). Diagnosis of the tropospheric moisture budget terms from the model (Table S2 in Text S1) suggests that most of the annual-mean northern precipitation increase is balanced by enhanced low-level wind and associated column moisture convergence. In contrast to the northern increase of precipitation, the southern portion of tropical South America experiences a reduction during the later period under this pattern of decadal-scale SST forcing. Prior studies have postulated a warmer tropical Atlantic as the principal driver for drought over this region [*Zeng et al.*, 2008; *Marengo et al.*, 2008], which is consistent with the behavior simulated by NCAR CAM3. However, Figure 1 suggests that vegetation plays a more significant role in the decrease over the southern tropical South America.

[9] How does land use change influence the regional precipitation changes over southern tropical South America? The principal biophysical effect of land use change involves a decrease of the leaf area index, i.e., leaf area divided by land surface area (Figure 2b). CO_2 assimilation and H_2O transpiration occur through the surface pores on leaves (stoma); thus, decreasing leaf area decreases CO_2 and H_2O exchange. Over tropical South America, the largest recent deforestation has occurred along the periphery of the Amazon basin [*DeFries et al.*, 2002] where continental evapotranspiration provides the main moisture source for precipitation: over the southern region (brown box in Figure 1) evapotranspiration (1280 mm/year) is far more important in an annual-mean sense than is moisture convergence (97 mm/year). Changes in the various terms associated with moisture convergence terms tend to cancel, underscoring the significance of evapotranspiration (Table S2 in Text S1).

[10] Considering the temperature response, land use change accounts for the bulk of the simulated warming to the south, with SST forcing playing a secondary role (Figure 3, bottom). Land use change is expected to alter the partitioning between sensible and latent heating: in particular, the decrease (increase) of latent (sensible) heating with land use change increases the Bowen ratio (the ratio of sensible to latent heat) during the dry season (Figure S3 in Text S1). Although decreased leaf area leads to decreased incoming shortwave absorption, temperature increases because increased sensible heating dominates over the cooling tendency of reduced surface shortwave heating in the Tropics. Although previous studies [*Fu and Li*, 2004] have shown that precipitation onset over tropical South America is very sensitive to boundary layer moisture, many model convection schemes are known to be too sensitive to the moisture in the boundary layer [*Donner and Phillips*, 2003]. Such high sensitivity could account for the large change in rainfall with the relatively small change in the simulated Bowen ratio seen in our simulations.

[11] It is worth noting that the total annual mean total (SST + land use); use temperature increase between the two periods in our simulations over the southern part (0.7°C) is larger than observed (0.5°C) (Table S1 in Text S1). However, it is likely that the model overestimates the effects of deforestation and land use change because pre-land use rather than actual vegetation is assumed for the early period. Of course, it has been shown that Amazonian deforestation increased dramatically between the 1980s and 1990s [*DeFries et al.*, 2002]; thus, while the vegetative change implied by our simulations may be larger than what occurred over the last three decades, it is probably not unreasonable over the principal area of interest in the south. Indeed, the satellite-derived Normalized Difference Vegetation Index (NDVI) [*Tucker et al.*, 2005] indicates a decrease in biomass over

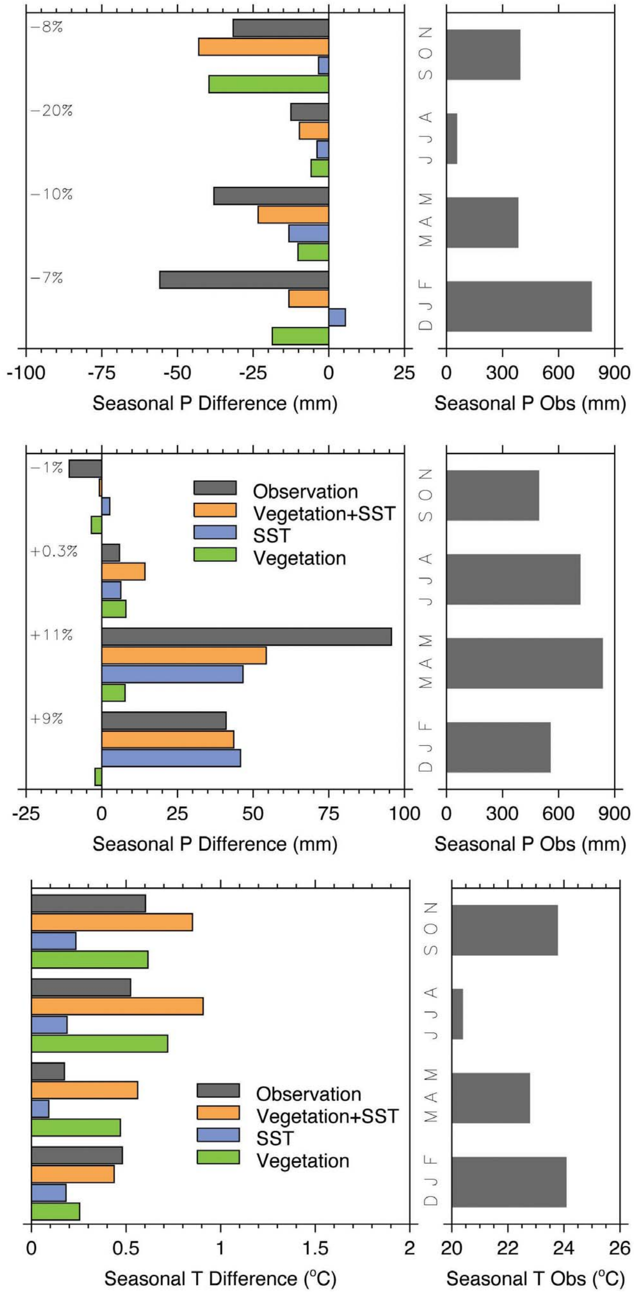

Figure 3. (left) Seasonal precipitation difference for observations between the later (1993–2006) and earlier (1979–1992) periods (grey), model results between the later period with control vegetation and earlier period with pre-land use vegetation (orange), model results between the later and earlier periods (light blue), and model results between the present-day and pre-land use vegetation for the whole period (green) over (top) southern (brown box in Figure 1) and (middle) northern (blue box in Figure 1) parts of tropical south America. (bottom) Temperature changes between the two periods. (right) Mean seasonal precipitation from GPCP data for the (top) northern and (middle) southern tropical South America, and (bottom) mean seasonal temperature from Global Historical Climatology Network (GHCN) over the southern part. Northern part temperature is not available from GHCN data because of the lack of the observation. Numbers on the left represent % change during the later period compared with the earlier period from the observations.

the southern portion of tropical South America over the period of available measurements (Figure 2): the difference of observed NDVI averaged over 1993–2006 and 1982–1992 (there are no NDVI data prior to 1982) over the southern region is 0.052 (or ~10%) during austral spring (September through November) when moisture stress is highest.

[12] The simulated precipitation changes, on the other hand, are typically smaller than observed, especially during the dry season. At least part of this difference may be attributed to a known dry bias in the NCAR model climatology in the southern region (Figure S1 in Text S1). Moreover, vegetation changes occur not only through anthropogenic mechanisms such as deforestation but also naturally through climate variability, and it is difficult to deconvolve SST forcing from vegetation because some of the vegetative change may be driven by SST forcing. Underestimation of the precipitation change over southwestern tropical South America (Figure 1) likely occurs because this natural response is not included (Figure 2). Note, too, that our simulation did not include other potentially important drivers of regional precipitation change such as aerosols [*Cox et al.*, 2008] that are expected to change with land use.

[13] Although precipitation is lower throughout the year in the later period, the evapotranspiration (and Bowen ratio) differences due to vegetation change are in fact quite small during the wet season (December–April) when there is significant exposed water on the soil surface and canopy rainfall interception is high. In contrast, evapotranspiration decreases sharply during the drier months. At this time, extraction of deep soil moisture by plants (transpiration) represents the major component of evapotranspiration [*Lee et al.*, 2005]; thus, the sensitivity to leaf area differences are likely strongest during the dry season. Moreover, even while the absolute magnitudes of the precipitation changes are smallest during the driest months (June to August), the dry season changes in precipitation are proportionally the largest, with simulated decreases approaching 20% (Figure 3). From an ecological perspective, dry season precipitation is thought to be the most important determinant of forest productivity and biodiversity [*Saatchi et al.*, 2007]. Simulated gross primary productivity decreases ~7% annually, but up to 20% by the end of the dry season when moisture stress is highest (Figure S4 in Text S1).

[14] The observations further reveal that the incidence of low precipitation months, here comprising accumulated monthly precipitation <10 mm has increased over tropical South America for the later period (1993–2006) relative to the earlier period (1979–1992) (Table 1). The 10 mm per month benchmark is considered here as this is the minimum monthly accumulation necessary for viable large-scale soybean production [*Sombroek*, 2001], and soybean production has driven much of the recent agricultural land use change [*Nepstad et al.*, 2008]. While our simulations indicate both SST and vegetation forcing have increased the likelihood of low precipitation months, the vegetative changes contribute more strongly to the increase.

4. Conclusion

[15] In this paper, we explore the roles of remote SST forcing and local land use change in explaining the observed north-south dipole precipitation change that has occurred over tropical South America during recent decades. Based

Table 1. Changes in the Occurrence of Low Precipitation (P < 10 mm/month) from 1993–2006 to 1979–1992 Over Tropical South America Excluding Regions Near the Andes[a]

	Precipitation
Model	
SST	+84 (+2.4%)
Vegetation	+278 (+8.9%)
Total	+362 (+11.7%)
Observation	+230 (+9.4%)

[a] Location: 30°S–10°N; 70°W–30°W; 164 grid points; GPCP data is regridded in 2.8° × 2.8° resolution from its original 2.5° × 2.5°. The occurrence in low precipitation months shows a larger increase when SST forcing and vegetation forcing are combined than expected from the linear combination of each forcing. Model occurrence of low precipitation is larger than the observations because the model underestimates precipitation (e.g., Figure S2 in Text S1).

on simulations performed with NCAR CAM3, it is shown that decadal scale warming of tropical SSTs in the equatorial Pacific and northern Atlantic, and attendant warming in the troposphere, can create the dipole pattern. While the precise mechanism for this remote SST forcing impact requires more detailed study, we note that enhancement of the gross climatological north-south gradient in precipitation over tropical South America is consistent with expectations of warming-induced intensification of the hydrologic cycle as posited in a number of studies [e.g., *Held and Soden*, 2006]. However, while SST may account for the spatial structure of the opposing trends, local land use appears to be critical in simulating the southern decrease, particularly the increased frequency of the driest monthly extremes (i.e., precipitation less than 10 mm/month) during the latter period.

[16] Climate models exhibit many biases in simulating regional precipitation climatology and variability [*Dai*, 2006], and they show differential sensitivity to imposed vegetation changes [*Pitman et al.*, 2009]. However, both observations and model studies have documented interannual precipitation sensitivity to SSTs in the northern part of tropical South America [*Liebmann and Marengo*, 2001; *Chiang et al.*, 2000], so it is plausible that the decadal La Niña-like SST changes would increase precipitation there. For southern tropical South America, the local contribution of evapotranspiration to precipitation is large, so it is conjectured that decreased leaf area index as a result of land use change would decrease evapotranspiration and thus precipitation. One point worth mentioning is that the largest decadal-scale precipitation decrease in the model occurs over to the southeast and not the southwest as was observed (Figure 1d). In southwestern tropical South America, recent deforestation has been large [*DeFries et al.*, 2002] while recent drought has caused decreased vegetation cover. The pre-land use vegetation scenario we have used in this study is the map of vegetation before human modification, taking into account human modification [*Ramankutty and Foley*, 1999].

[17] What do these results imply for future climate change? Over tropical South America, the ensemble of current generation models projects decreasing precipitation under global warming over much of the southern tropical South America, most notably during the dry season [*Intergovernmental Panel on Climate Change*, 2007]. At the same time, it is anticipated that the southern tropical South America region in particular will continue to be subject to extreme deforestation and land use pressures that accelerated during the last few decades of the 20th century because of rising global demand for biofuels and meat production [*Nepstad et al.*, 2008]. Our analysis suggests that the combination of global warming and land use are likely to produce warmer and drier conditions and favor more frequent and more intense droughts over southern tropical South America throughout the 21st century. Such climate stresses are likely to result in decreased carbon assimilation [*Cao and Woodward*, 1998] and the loss of biodiversity, which could in turn feed back onto, and accelerate, the warming and drying.

[18] **Acknowledgments.** We thank I. Fung, T. Kubar, and R. Pierrehumbert for providing many useful suggestions for the improvement of the manuscript and also thank the researchers who made GIMMS NDVI, GPCP precipitation, GHCN temperature, and HadSST data available. The runs were performed at NERSC. JEL acknowledges support from National Science Foundation grant EAR-090919. BRL acknowledges support from National Science Foundation grant AGS-1035968 and New Jersey Agricultural Experiment Station Hatch grant NJ07102.

[19] The Editor thanks the two anonymous reviewers.

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