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Theoretical Impact of Changing Albedo on Precipitation at the Southernmost Boundary of the ITCZ in South America

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ABSTRACT: South America has undergone a large increase in albedo over the past decade as forests have been converted to crops and wetlands have been drained. Recent modeling literature and paleoclimate precipitation proxies have highlighted how changes in surface energy balance could affect the position of the intertropical convergence zone (ITCZ) in South America. Here, the authors investigate whether large continental increases in albedo in South America can likewise affect the southward migration of the ITCZ into South America using the NCAR Community Atmosphere Model, version 3.0 (CAM3.0) coupled with the Community Land Model, version 3.5 (CLM3.5) and a slab ocean model. Moderate Resolution Imaging Spectroradiometer (MODIS) albedo data show that between 2001 and 2008 average albedo increased by 0.0025 albedo units across all South America and by 0.0032 albedo units between 0° and 24° latitude in South America and, because of this effect, the authors' simulations

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estimate an average $\sim 23 \text{ mm yr}^{-1}$ decrease in rainfall in the southern migration of the ITCZ (SMI) and an average $\sim 9 \text{ mm yr}^{-1}$ decrease in the entire Amazon basin. Large increases in albedo in South America decrease the northward atmospheric energy transport at the equator during the months the region of increased albedo is south of the ITCZ (May–July), leading to an apparent delay in its arrival to the SMI region and reduced rainfall in this region. However, because changing albedo is often associated with changing surface roughness, the authors model this separately and find that decreased surface roughness will have an opposite, increasing effect on precipitation. Therefore, they expect increasing albedo in South America associated with the drainage of wetlands to decrease precipitation, especially in the SMI region; however, in the case of deforestation, some of the decrease in precipitation from increased albedo may be offset by a corresponding decrease in surface roughness.

KEYWORDS: Albedo; Surface roughness; Amazon; ITCZ; South America

1. Introduction

Several modeling studies have indicated that changes in surface energy budgets may affect the movement of the intertropical convergence zone (ITCZ), the region of convection between the two cells of the Hadley circulation. An early study found that increasing albedo north of the ITCZ from 14% to 35% decreased rainfall during the wet season in the Sahel by 40% because the ITCZ shifted several degrees to the south (Charney 1975). More recently, large-scale simulated afforestation experiments in the midlatitudes of the Northern Hemisphere have reduced the surface albedo, leading to tropical circulation changes and a drying at the southern edge of the Amazon forest (Swann et al. 2012). Other papers demonstrate how ice (Chiang and Bitz 2005) or anthropogenic aerosol forcing (Rotstayn et al. 2000) may cause changes in midlatitude energy budgets and tropical circulation. Rainfall in South America is dependent on the southward movement of the ITCZ, which allows wet monsoonal Atlantic storms and the trade winds to enter and cross the continent as part of the Hadley cell circulation (Riehl 1979).

Tropical forests are increasingly recognized as major resources for mitigating climate change (Canadell and Raupach 2008). Any change in precipitation to these regions may have a detrimental effect on tropical forests (Phillips et al. 2009) and global atmospheric CO_2 concentrations. Previous modeling efforts have shown that Amazonian deforestation can affect rainfall patterns throughout South America (Henderson-Sellers et al. 1988) and the world through hydrometeorological tele-connections (Avissar and Werth 2005). The Amazon region is characterized by high rates of recycling of precipitation through the land surface (Nobre et al. 1991), making downwind regions particularly susceptible to changes in precipitation patterns upwind. Deforestation can decrease evapotranspiration and increase surface temperatures by 3° - 5° C (Dickinson and Henderson-Sellers 1988). Previous simulations of deforestation have shown either decreased precipitation due to the weakening of precipitation recycling or increased precipitation due to the intensification of convection over areas of land surface heterogeneity (D'Almeida et al. 2007).

Considering albedo alone, increases in albedo over South America will reduce convection and precipitation as surface latent and sensible heat fluxes decrease due to reduced energy absorbed at the surface (Dirmeyer and Shukla 1994). Both forest



Figure 1. Change in MODIS white-sky albedo product for South America between 2001 and 2008. For further details, see Loarie et al. (Loarie et al. 2011). The blue oval shows the SMI region. The black solid outline shows the region of interest. The black dashed line shows the average position of the ITCZ in January.

and pasture albedo show seasonal variability, with the forest albedos higher in the dry period (June–November) and lower in the rainy period (December–May), whereas the pasture albedo is lower in the dry season (Berbert and Costa 2003). Certain crops, such as soybean, have a higher albedo and therefore can decrease precipitation more than lower albedo pasture land (Costa et al. 2007).

There has been much variation in the amount and extent of rainfall in South America over the past few thousand years. The Amazon basin was $\sim 40\%$ dryer during the Younger Dryas [$\sim 12~000$ years before present (YBP)] than today during a period of low summer insolation (Maslin et al. 2000). Precessional cycles are well correlated with precipitation over southern Brazil with the maxima and minima of the last five precessional cycles in solar radiation aligning with the maxima and minima of precipitation in southern Brazil (Cruz et al. 2005). The southern migration of the ITCZ (SMI) region of South America (blue oval in Figure 1) has experienced particularly large changes in precipitation in the past 12 000 years. Long sediment cores from Lake Titicaca indicate maximum aridity 8000–5500 YBP during a time of low summer insolation (Baker et al. 2001). The humid evergreen rain forests of eastern Bolivia have been expanding southward over the past 3000 years, suggesting that their present-day limit represents the southernmost extent of Amazonian rain forest over at least the past 50 000 years (Mayle et al. 2000).

The inferred changes in precipitation may be due to a shift in the southern boundary of the ITCZ in South America. It has been hypothesized that the southernmost position of the ITCZ is controlled by the temperature gradient between the equator and the pole, whereas the strength of the rainfall is controlled by the precessional cycles (Maslin 2008). In South America, the position of the ITCZ may be controlled by Atlantic sea surface temperatures (Nobre and Shukla 1996) and summer insolation absorbed by the land surface (Cruz et al. 2005).

Absorbed solar energy is controlled by both solar insolation and albedo. The main driver of albedo change in South America in the present day is deforestation-associated land-use change and the drainage of wetlands (Loarie et al. 2011). Deforestation modifies not only albedo but other important climate-driving variables as well, such as canopy height and rooting profile, which will affect surface roughness and evapotranspiration. Most studies conclude albedo dominates surface energy budgets during land-use change (Berbert and Costa 2003), but other studies have found a large role for an ecophysiological/aerodynamic component for controlling land surface temperature (Dickinson and Henderson-Sellers 1988; Juang et al. 2007). Trees are rougher surfaces than crops or pasture, and they have very deep roots, which enable them to access deep soil water reserves and act as better conduits for water vapor to the atmosphere (Nepstad et al. 1994), thus increasing evaporative fluxes to the atmosphere (Bala et al. 2007).

There have been large increases in albedo in South America as dark forests are replaced by bright crops and wetlands are drained (Loarie et al. 2011). By 2050, agricultural expansion is predicted to eliminate a total of 40% of Amazon forests (Soares et al. 2006), which will result in further increases in albedo. Large-scale albedo changes in South America could theoretically alter continental heating and convection rates causing similar changes to the ITCZ that were seen during periods of low summer insolation 8000 YBP. We are interested in how large, theoretical changes in albedo can impact rainfall patterns, specifically in the SMI region of the Amazon basin. However, albedo will often change along with other parameters such as surface roughness and rooting profiles, and we model these affects separately. We combine GCM climate simulations with MODIS albedo data to ask the following questions:

- 1) How do large increases and decreases in albedo and their location control rainfall patterns in South America?
- 2) How does changing albedo compare to other noncarbon climate forcing from deforestation, such as changes in rooting profile and canopy height in driving precipitation?

2. Methods

We determined the change in surface albedo between 2001 and 2008 using a Moderate Resolution Imaging Spectroradiometer (MODIS) white-sky albedo (MOD43B3) 16-day 1-km product. Further details of this study are published in Loarie et al. (Loarie et al. 2011). For each pixel, we calculated the mean monthly value over the 8-yr period and then subtracted the actual value from the mean value. We then compared the average differential from 2001 to 2004 to the average differential from 2005 to 2008.

To simulate climate, we used the National Center for Atmospheric Research (NCAR) Community Atmosphere Model, version 3.0 (CAM3.0; http://www.ccsm. ucar.edu/models/atm-cam/), coupled with the Community Land Model, version 3.5 (CLM3.5; http://www.cgd.ucar.edu/tss/clm/) and a slab ocean model (Collins et al. 2006; Kiehl et al. 2006). This model is among the most accurate GCM in predicting current rainfall in the Amazon basin (Malhi et al. 2009). The simulations were run at a 20-min time step at T42 resolution (2° by 2.5° at the equator) for 60 years, with no dynamic vegetation response and atmospheric CO_2 held constant at 385 ppm. Results were calculated as the average of the final 30 years and significance was determined using a paired Student's t test comparing each pixel for each of the 30 years to the same pixel from control runs. We modified the land surface in two regions of South America; one region replicates an area in the central Amazon with high rates of deforestation known as the arc of deforestation (33 pixels in an arc shape at $0^{\circ}-8^{\circ}S$, $65^{\circ}-47.5^{\circ}W$). The second region is centered on central South America (40 pixels in a rectangular shape at 8°–24°S, 62.5°–50°W). From now on, we will refer to the combined arc of deforestation and central South America as the region of interest (black outlines in Figure 1). These areas are not meant to represent realistic areas of deforestation or albedo change but instead to understand the sensitivity of the system.

We simulated climate by modifying just the land surface albedo in the region of interest without changing rooting profiles or canopy height. To do this, we converted the entire region of interest to the crop plant functional type and modified the surface level albedo by reducing leaf albedo by 5%, 10%, and 20% and increasing it by 10% and 20%. This resulted in average surface albedos across the region of interest of 0.065, 0.10, 0.146, 0.18, 0.27, and 0.29, where 0.18 is the average surface albedo of unmodified crops. Averaged across all of South America between 0° and 24°S, land surface albedos were 0.131, 0.142, 0.157, 0.168, 0.197, and 0.200, where 0.168 is the control albedo.

We tested the impact of geographic location of an albedo shift on rainfall patterns by converting a large rectangular region of South America $(4^{\circ}-20^{\circ}\text{S}, 50^{\circ}-65^{\circ}\text{W})$ to the crop land surface type and sequentially increasing surface level albedo by 0.1 in four equally sized quadrants of 12 pixels (4 by 3) (black outlines in Figure 4). We then compared rainfall, cloud cover, and latent heat fluxes between the control and increased albedo simulations to see if increases in albedo had larger impacts on precipitation in certain regions.

With deforestation, albedo is modified in conjunction with canopy height (thereby altering surface roughness) and rooting profiles (thereby altering evapotranspiration). To separate these effects, we ran simulations where we modified each variable separately. In the first simulation, we modified only albedo by increasing leaf level albedo by 10% in the region of interest, keeping canopy height and rooting profile the same between simulations. In the next, albedo and canopy height were constant between simulations but rooting profiles were modified to that of broadleaf evergreen tropical trees. Root distribution parameters adopted from Zeng (Zeng 2001) were modified from the crop values of 6 and 3 to the average broadleaf evergreen tropical forest values of 7 and 1.

In the final simulation, albedo and rooting profiles were constant between simulations, but canopy height was modified so the land surface had the stature and aerodynamic properties of trees but the albedo and rooting profile of crops. We

converted all aerodynamic properties from those similar to broadleaf evergreen tropical trees to those similar to grasses by changing the top of canopy height from 0.5 to 35 m, the ratio of momentum roughness length from 0.12 to 0.075, and the ratio of displacement height to canopy top height from 0.68 to 0.67.

3. Results

MODIS albedo data show that South America has brightened over that past 8 years by an average of ~ 0.0025 albedo units over the entire continent and by ~ 0.0032 albedo units between 0° and 24°S. There is much regional disparity, and albedo increased by between 0.01 and 0.1 in many regions of South America (Figure 1). We focus on two geographic regions with large historic albedo changes: the arc of deforestation (an arc shape at 0°–8°S, 47.5°–65°W; black outlines in Figure 1, top), which increased by an average of 0.0050 albedo units and a region incorporating central South America (a rectangular shape at 8°–24°S, 50°–62.5°W; black outlines in Figure 1, bottom), which increased by an average of 0.0044 albedo units.

Paleoclimate studies demonstrate a link between changing summertime solar insolation and precipitation in South America. Maslin and Burns (Maslin and Burns 2000) estimate that, on average, precipitation decreased by $\sim 40\%$ between present day and 12 000 years ago, which they attribute to a 70 W m⁻² decrease in summer 10°S solar insolation from 940 to 870 W m⁻². This is approximately a 0.57% reduction in precipitation for each watt per square meter decrease in solar insolation, if we assume a linear relationship. We modify land surface albedo to see if increased reflected solar radiation has a similar effect on South American rainfall as decreased downwelling solar insolation. We increase and decrease albedo in the region of interest that has undergone large recent albedo changes. We average total continental albedo for South America between 0° and 24°S, including regions with both modified and unmodified albedo. If we assume a linear relationship between albedo and precipitation, there is a 1.1% reduction in annual rainfall per watt per square meter decrease in absorbed solar insolation (Figure 2). Paleoclimate data show that precipitation decreased more strongly in the SMI region of South America than other regions of South America. In our simulations, precipitation also decreased most strongly in the SMI region where precipitation decreased by 4% per watt per square meter decrease in absorbed solar radiation. With a 0.0032 increase in surface albedo between 0° and 24°S, a linear relationship would predict a decrease in precipitation of 9 mm yr⁻¹ for the Amazon basin and 23 mm yr⁻¹ in the SMI region.

Precipitation was significantly lower (P < 0.05) in the high albedo simulation than the control simulation in most pixels of the SMI region in the months at the start of the dry season in March–May and at the end of the dry season in October– November (Figure 3). An increase in albedo delayed the onset of the wet season and extended the dry season, and a decrease in albedo advanced the onset of the wet season and delayed the dry season. The total maximum rainfall in the wet season was higher at lower albedos. The Amazon basin showed similar but smaller trends compared to the SMI region.

The location of an albedo change also influenced precipitation patterns. Changing albedo in the northeast quadrant resulted in the greatest average decline



Figure 2. Change in total average percent precipitation in the Amazon basin and SMI region as a function of the change in absorbed shortwave solar radiation from climate simulations across South America between 0° and 24°S.

in precipitation in the Amazon basin of 3.5%, followed by the northwest quadrant and southwest quadrant, both at 2.4%, and the southeast quadrant at 1% (Figure 4). Changing albedo in the southwest decreased precipitation in the SMI region by the greatest amount (14%), followed by the northwest (8%), the northeast (6%), and the southeast (5%). When we increased albedo in the southeast quadrant, there were significant changes (P < 0.05) in monthly precipitation in most pixels of the SMI region at the onset of the dry season (March through May) and the end of the dry season (October–November) (Figure 5).

We calculate the total northward atmospheric transport of energy from the top of atmosphere net radiative flux in order to estimate the shift in the Hadley circulation associated with the albedo change. This proxy is diagnostic of changes in circulation and is associated with the location of the ITCZ (Swann et al. 2012). We expected a brightening of South America to reduce the hemispherical energy imbalance and reduce the average northward atmospheric energy transport. Contrary to our expectations, there was almost no change in northward energy when averaged over the year between our high albedo simulation and the control, which indicates no annually averaged northward shift of the ITCZ. However, we find that, in months when the ITCZ is north of the high albedo region, such as in May–July, there is a net reduction of northward energy compared to the control. In other months, such as November–January, there is no net increase in northward energy compared to the control. This indicates that the ITCZ is shifted slightly northward during the time of the year when it is north of the high albedo zone, and this delays its arrival to its southernmost point in the SMI region.

Decreasing canopy height from 35 to 0.5 m in the region of interest increased precipitation significantly (P < 0.05) in most pixels of the SMI region between November and March by an average of 14% in the SMI region and 6% in the Amazon basin in our simulations (Figure 6). Switching from the rooting profiles



Figure 3. (top left) Change in precipitation (mm month⁻¹) in the Amazon basin with an average land surface albedo change of -0.037 (black solid line), -0.026 (gray solid line), -0.011 (black dashed line), 0.029 (black dotted line), and 0.033 (gray dashed line) between 0° and 24°S in South America. (top right) Change in precipitation in the SMI region with albedo. Absolute precipitation by month with modified albedo in (bottom left) the Amazon basin and (bottom right) the SMI region.

of broadleaf evergreen trees to those of crops did not significantly change precipitation in most pixels (P > 0.05). During the middle of the rainy season (December–January), modifying canopy height (and thus surface roughness) had a similar impact on precipitation as changing surface albedo, but with opposing sign (Figure 7). Decreasing the average canopy height from 35 to 0.5 m reduced atmospheric mixing, which increased mean temperatures in the region of interest by ~1.2°C. This increase in temperature increased latent heat fluxes by ~7 W m⁻² and may have contributed to the increased precipitation in Figure 6.

4. Discussion

There is an emerging literature on how changes to surface energy budgets can impact the position of the ITCZ and rainfall within the Hadley circulation (Broccoli et al. 2006; Chiang and Bitz 2005). One such study found Northern Hemisphere afforestation may lead to drying at the southern boundary of the Amazon as the ITCZ is shifted northward (Swann et al. 2012). Such simulations are supported by paleoclimatological studies where there is a relationship between South American summer insolation and total precipitation in South America (Cruz et al. 2005; Maslin and Burns 2000). Pollen records and lake sediment cores indicate



Figure 4. Change in average yearly precipitation (mm month⁻¹) between a control simulation and simulations where we consecutively increased surface albedo by 0.1 in (bottom left) the southwest, (top left) the northwest, (top right) the northeast, and (bottom left) the southeast. Black squares show the region where albedo was modified.

that the SMI region seems especially prone to ITCZ-driven changes in rainfall (Baker et al. 2001; Maslin and Burns 2000).

Our simulations indicate that, over a wide range of surface albedos (0.13–0.19 albedo units), precipitation in the SMI region varied linearly with albedo in the central Amazon (Figure 2). These changes in precipitation with albedo were strongest in the SMI region and were concentrated at the beginning and the end of the dry season, leading to an extended dry season with increased albedo, which may have a negative impact on forest physiology (Phillips et al. 2009). The location of the albedo change was also important, because increasing albedo in the southwest quadrant had the largest impact on precipitation in the SMI region. This quadrant is especially important in controlling precipitation rates in



Figure 5. (top) Change in average monthly precipitation (mm month⁻¹) for (left) the Amazon basin and (right) the SMI region between a control simulation and simulations where we consecutively increased surface albedo by 0.1 in the southwest (black solid line), the northwest (gray solid line), the northeast (black dashed line), and the southeast (gray dashed line). Total monthly precipitation (mm month⁻¹) with land surface modifications in (bottom left) the Amazon basin and (bottom right) the SMI region.

the SMI region possibly because of the prevailing low pressure and high convection (Maslin and Burns 2000).

A previous study using the same model (CAM3.0 plus CLM3.5 and a slab ocean model) darkened the Northern Hemisphere by increasing tree cover in the midlatitudes and found that atmospheric circulation redistributed the anomalous energy absorbed in the Northern Hemisphere toward the south, which altered the Hadley circulation and resulted in a northward movement of the ITCZ and a drying of the southern Amazon (Swann et al. 2012). Climatologically, we would expect a similar result as we reduce the energy absorbed in the Southern Hemisphere, causing a similar redistribution of energy toward the south and a northward movement of the ITCZ. We indeed find a similar northward transport of energy in May–July, when the high albedo region is south of the ITCZ. However, in November–January, the energy transfer stops as the high albedo region is now north of the ITCZ. This dynamic causes an apparent delay of the arrival of the ITCZ in the SMI region and reduced total precipitation in this area.

During deforestation, albedo increases in conjunction with other meteorological properties. We separate the effect of albedo, canopy height, and rooting profile in our simulations. Tropical forests have very deep roots capable of accessing water in the dry season and keeping transpiration rates similar in both the wet and dry seasons



Figure 6. (top) Change in average monthly precipitation (mm month⁻¹) for (left) the Amazon basin and (right) the SMI region between a control simulation and a simulation with increased leaf level albedo by 10% (black solid line), between a simulation with canopy height of 35 m to one of 2 m (gray solid line), and between a simulation with rooting profile of tropical broadleaf evergreen trees to one of crops (black dashed line) in the region of interest. (bottom) Total monthly precipitation (mm month⁻¹) with land surface modifications in (left) the Amazon basin and (right) the SMI region.

(Goulden et al. 2004; Nepstad et al. 1994), but these deep root profiles are not reflected in the model, so our estimates likely underestimate the impact of changes in rooting profile between crops and forests.

In our simulations, decreasing surface roughness by decreasing canopy height can warm the land surface and increase precipitation. This emphasizes the importance of surface roughness on climate in this region (Dickinson and Henderson-Sellers 1988). Field studies that have separated out the albedo effect from the aerodynamic/ecophysiological effect have found similar results with a 2.1°–2.9°C cooling during the transition from grass fields to tree plantations from only aerodynamic/ecophysiological effects (Juang et al. 2007).

Between 0° and 24°S, South American albedo increased by 0.0032 over the past 8 years. Our simulations indicate that this increase in albedo would decrease precipitation by \sim 23 mm yr⁻¹ in the SMI region and \sim 9 mm yr⁻¹ in the entire Amazon basin. This larger decrease in precipitation in the SMI region is likely due to a delay in the arrival of the ITCZ due to large-scale circulation effects. However, if the increases in albedo are mainly due to deforestation as opposed to the draining of wetlands, then we would expect the decrease in precipitation from albedo to be partially offset by an increase in precipitation due to surface roughness effects.



-90 -45 0 45 90 mm month ⁻¹

Figure 7. Change in average yearly precipitation (mm month⁻¹) (left) between a control simulation and a simulation with increased leaf level albedo by 10%, (middle) between a simulation with canopy height of 35 m to one of 2 m, and (right) between a simulation with rooting profile of tropical broadleaf evergreen trees to one of crops in the region of interest.

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