The local and global effects of Amazon deforestation

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[1] To quantify the effects of land cover changes in the Amazon on local and global climate, numerical simulation experiments using the Goddard Institute for Space Studies Model II global climate model are conducted. An ensemble approach is adopted, in which a group of six control simulations is compared with a group of six deforested simulations. The deforestation effect in the Amazon is strong, with reductions in precipitation, evapotranspiration, and cloudiness. We also detect a noticeable impact in several other regions of the world, several of which show a reduction in rainy season precipitation that exhibits a high signal-to-noise ratio (determined by the *t* statistic). To determine the significance of the deforestation signal, we create several "false" ensembles, combining control and deforested members randomly, for comparison with the actual "true" ensemble. Such an analysis has not been used previously in deforestation studies and is useful for verifying the significance of a purported effect. The globally averaged precipitation deficits for the true ensemble are generally high in comparison with the false ensembles. Furthermore, changes in the Amazon due to the deforestation correlate significantly with remote changes in several areas. This suggests that the Amazon deforestation is producing a detectable signal throughout the Earth, and this finding underscores the importance of human activity in that region. *INDEX TERMS:* 1803 Hydrology: Anthropogenic effects; 1854 Hydrology: Precipitation (3354); 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; *KEYWORDS:* Amazon, deforestation, teleconnection, precipitation, climate, model

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1. Introduction

[2] Located as it is in the tropics, Amazon rain forest precipitation is dominated by convection. The rainy season (December through March) sees the advection of moisture from the Atlantic, which supplies about half of the moist air used for precipitation over the region [*Salati*, 1987]. The remainder is supplied through evapotranspiration (ET), primarily driven by the deep-rooted Amazon rain forest. Hence the Amazon rain forest plays an important role in maintaining the hydrologic balance of the region.

[3] As deforestation of the Amazon continues at an alarming pace (1.5×10^4 km^2/yr in the Brazilian Amazon from 1978 to 1988 [*Skole and Tucker*, 1993]), it is important to quantify the effects of such a reduction in rain forest area on local and global climate. Several modeling experiments have already been conducted to study Amazon deforestation. *Henderson-Sellers et al.* [1993] reviewed several earlier studies in which various models were run with different resolutions, parameterization schemes, and simulation lengths to examine the effects of deforesting the Amazon [*Henderson-Sellers and Gornitz*, 1984; *Dickinson and Henderson-Sellers*, 1988; *Lean and Warrilow*, 1989; *Shukla et al.*, 1990]. While the results vary, most studies agree that deforestation causes a local reduction in precipitation (-220 to -640 mm/yr, although the 1988 study showed no local precipitation change), evaporation (-164 to -500 mm/yr), a slight increase in surface temperature (0°C to 3°C), and a reduction in vertically averaged moisture convergence over the area. The latter change implies a connection between deforestation and the large-scale atmospheric flow, and models have indicated a reduction in large-scale vertical motion over the Amazon in response to deforestation (∼10 mbar/s [*Nobre et al.*, 1991; *Henderson-Sellers et al.*, 1993]). *Eltahir* [1996] developed a conceptual model in which a reduction in net radiation at the surface in response to deforestation (due to the increase in surface albedo) reduces convective precipitation. This change is accompanied by a reduction in convectively induced vertical motion and in the convection-convergence feedback.

[4] Because a mechanism exists for the propagation of a deforestation signal to the large-scale flow, this signal can possibly propagate outside the Amazon and leave a signature elsewhere in the world. *Trenberth et al.* [1998] reviewed several observed and simulated Rossby wave induced interactions between tropical sea surface temperatures (SST) and the midlatitudes. *Ting* [1996], for example,

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imposed a steady, deep tropical heat source to a multilevel baroclinic model, where it served as a Rossby wave source, and the resulting planetary wave train extended deep into the midlatitudes. *Kousky* [1984] noted an enhanced North American subtropical jet that coincided with a period of strong Amazon precipitation, and a modeling study by *Hou* [1998] revealed that an artificially enhanced Hadley cell could induce greater baroclinicity in the midlatitudes. In another modeling study, *Zhang et al.* [1996] observed changes in 500-mbar geopotential values in response to global (as opposed to Amazon) deforestation. The affected areas were mostly in the tropics, but an area over eastern North America and the North Atlantic experienced a statistically significant decrease in July geopotential. The question arises as to whether the changes induced by deforestation can result in reductions in precipitation elsewhere, in addition to altering atmospheric dynamics. *Henderson-Sellers and Gornitz* [1984] noticed no change in globally averaged precipitation in their deforestation simulation, but localized decreases are still possible.

[5] A deforestation of the Amazon was simulated with the Goddard Institute for Space Studies (GISS) global climate model (GCM). Unlike the earlier studies, we use an ensemble approach, creating six control and six deforested simulations. An ensemble of several multiyear simulations is needed to verify the robustness of the local and global effects of deforestation, along with a way to determine the significance of the changes. We look for changes in precipitation in the Amazon and other areas of the world and determine their statistical significance with Student's t test. We also generate a set of false ensembles, in which controls and deforested members are combined randomly, and the global precipitation deficits compared with that of the true ensemble. A correlational analysis between the Amazon and several remote areas is also done. This will reveal if the observed precipitation deficits are due to the deforestation or a model artifact. The latter two analyses provide a more quantitative method for determining the significance of the remote effect of deforestation. What we find is a strong signal in the Amazon and adjacent areas, a weaker signal downstream in the western Pacific, and a noticeable signal in North America. Europe and Asia see little change due to the deforestation.

2. The Model

[6] The simulations were conducted with the NASA-GISS model II GCM, configured with 12 layers and at a $4° \times 5°$ grid size [*Hansen et al.*, 1983]. Recently, Werth and Avissar (The regional evapotranspiration of the Amazon, submitted to *Journal of Geophysical Research*, 2002) evaluated the capability of this model to simulate the Amazon region and concluded that it is performing appropriately, though slightly underestimating precipitation. The GISS model has been used for deforestation experime nts before [*Henderson-Sellers and Gornitz*, 1984] but at a much coarser resolution ($8° \times 10°$) and with a more primitive surface scheme.

[7] Control runs with the vegetation held at its 1950 level (a mixture of several vegetation types) and deforested runs in which the Amazon rain forest is replaced with a mixture of shrubs and grassland were performed. An ensemble of six 12-year simulations each is generated for both the control and the deforested cases. The initial conditions of each run are identical, being the output of an unperturbed 12-year run, and so we can assume an initial equilibrium. After the deforestation (at t = 0), the model requires a spin-up time to achieve a new equilibrium between the surface and the atmosphere; so the first 4 years of each run are discarded. Heat and humidity are advected with a quadratic upstream scheme, and momentum is advected with a second-order scheme. The model has both shallow and deep convection, and a second-order closure planetary boundary layer scheme for moisture and heat transfer is applied at the surface. The model uses six soil layers and a hydrology scheme that accounts for soil moisture transfer and root extraction [*Rosenzweig and Abramopoulos*, 1997], the latter of which depends on the vegetation specified within a grid box. Climatological sea surface temperatures are used in all simulations, so that the same annual cycle is repeated each year, and no oceanic teleconnection can be confused with the effects of deforestation. This also means that no long-term memory exists, and each model year can be considered independent of the others.

3. Changes in the Annual Mean Cycle

[8] Ensembles of monthly means (six realizations, 8 years each) were calculated for both the deforested and the control runs, and the effect of the Amazon deforestation was detected through its effect on the annual precipitation cycle. The differences between the deforested and control monthly mean precipitation in the Amazon region (Figure 1) were calculated, and the annual cycle of the two ensembles was then compared to estimate the impact of local deforestation (Figure 2).

[9] Amazon precipitation follows a fairly regular cycle, with a summer rainy season and a winter dry season (note that the area in question lies entirely south of 3°S). As has been seen in previous modeling studies [e.g., *Henderson-Sellers et al.*, 1993], Figure 2 shows that the Amazon suffers a significant decrease in rainy season precipitation when the rain forest is eliminated, while the dry season precipitation experiences little change. The region also sees a reduction in evaporation that lasts throughout the year, with a consequent reduction of latent heat release aloft, possibly generating a propagating signal. Strong annual reductions in total Earth water and total cloud were seen, and a slight increase in summertime surface temperature was realized. We also see a summertime decrease in moisture convergence (as determined by precipitation-evaporation) and a winter decrease in flux divergence. This suggests that rain forest removal can have effects that extend throughout the atmospheric column and which can occur all year. These results are consistent with what has been seen in the modeling studies described earlier and enhances our confidence in those results.

[10] To detect any remote effect of the Amazon deforestation, we first created a global map of precipitation differences between the deforested and control ensemble means for each month. Several areas were qualitatively selected in which the differences were relatively large and occurred over a widespread area (Figure 1). The annual

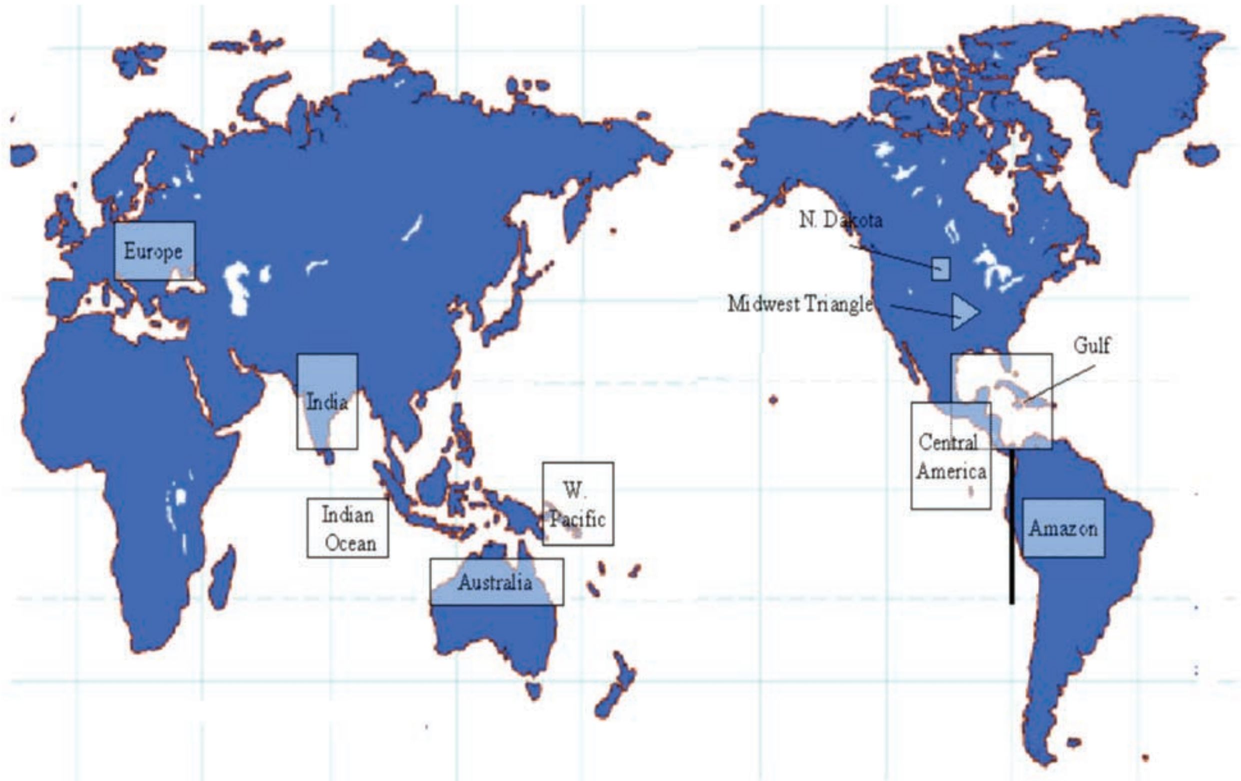

Figure 1. Areas within which monthly averages of precipitation were taken. Easterly Amazon winds at 787 mbar were averaged along the black solid line for the correlational analysis. Map courtesy of www.theodora.com/maps; used with permission.

precipitation cycles of these areas were plotted for the control and deforested simulations, and the results are seen in Figure 2.

[11] Two areas in relative proximity to the deforested area in which we see a signal are the Gulf of Mexico and off the west coast of Central America. These areas experience annual cycles that are less regular than those over the Amazon, but they do show peak months in annual precipitation in the late summer and early fall. In both areas, we see a small decrease in precipitation in almost every month, with the August and September precipitation decreasing significantly in the deforested runs. Central America also experiences summertime reductions in evaporation and total cloud, with smaller reductions in the Gulf of Mexico (not shown). The gulf also sees a weak increase in sensible heat flux (not shown).

[12] Across the Pacific, we encounter areas with noticeable decreases in precipitation when the Amazon is deforested. An area over the West Pacific shows an annual precipitation cycle with peaks in winter and summer, both of which are reduced in the deforested runs. Changes in evaporation and total cloud are weak. A region over the Indian Ocean has its precipitation maximum in late winter, with steady precipitation throughout the rest of the year. Interestingly, the greatest decrease in precipitation occurs not during the rainy period but during October, toward the end of the long, drier period. Total cloud also undergoes a strong reduction in October. Proceeding further west, an examination of Europe and Asia revealed little change when the Amazon was deforested.

[13] Several areas over North America were studied to see if any signal can propagate from the tropics into this midlatitude area. A search of the continent turned up two small areas, each comprising four grid points, as experiencing a noticeable reduction in precipitation. The Dakotas region and the Midwest Triangle in the United States experience an annual cycle of precipitation with summertime peaks. The effect of deforestation is to reduce the precipitation in each area during the summer months, with the largest reduction occurring during July. Weak reductions in evaporation and total cloud accompany the precipitation decrease in both areas throughout the year, especially in summer, and summertime increases in sensible heat flux are also observed, concordant with the idea of a drier, warmer surface.

4. Relative Strength of Change

[14] How do these deforestation-induced perturbations compare to the natural year-to-year variability of the model? To compare the two, we use the Student's t statistic. By considering each of the six realizations as a set of eight measurements, we have two (unpaired) 48-member data sets for each month. The month of maximum precipitation reduction is selected for each area, resulting in 48 measurements for that area (January in the Amazon, July for the

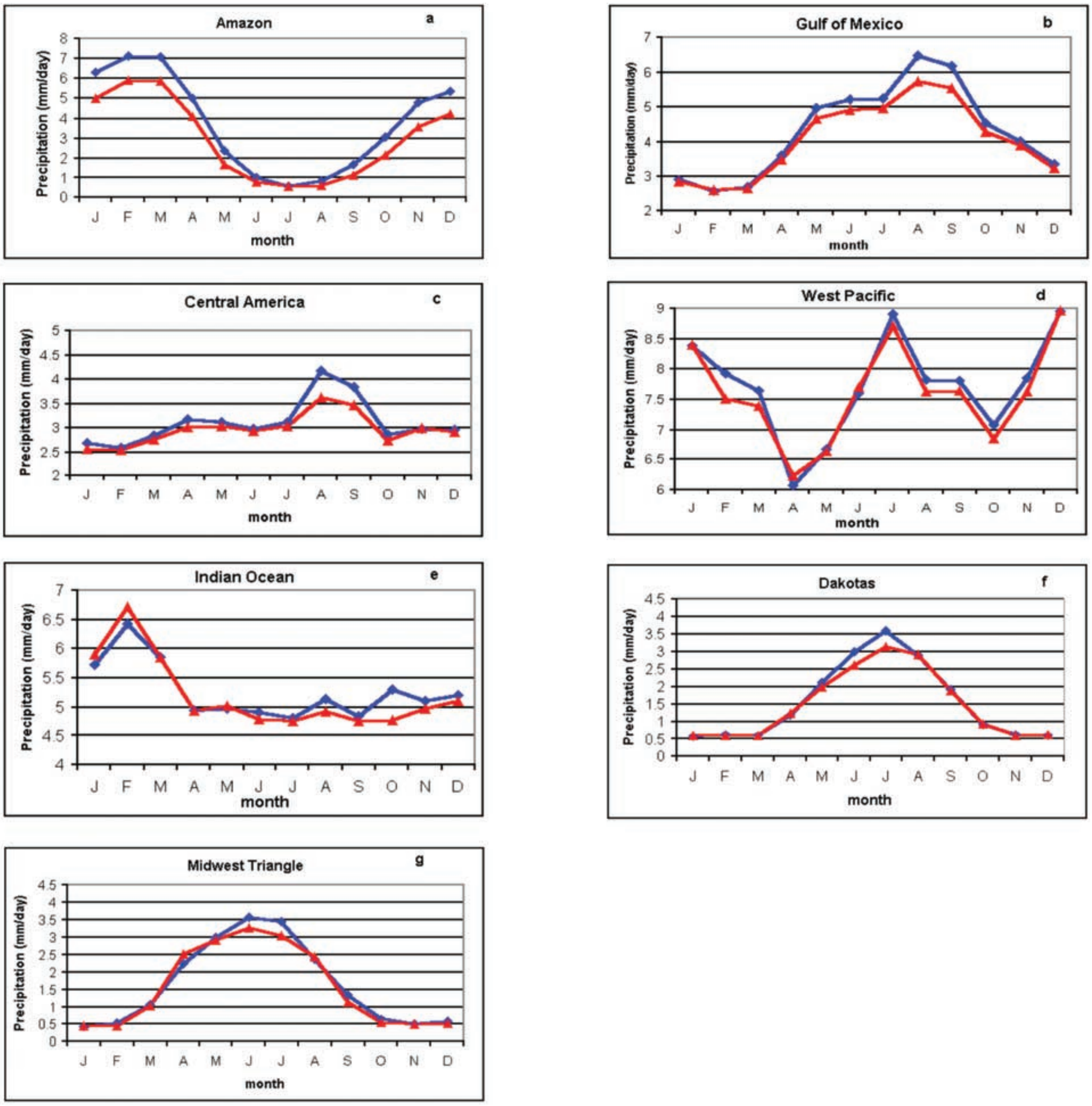

Figure 2. Annual cycle of precipitation, ensemble mean, 8-year average for the control (diamonds) and the deforested (triangles) for (a) Amazon, (b) Gulf of Mexico, (c) Central America, (d) West Pacific, (e) Indian Ocean, (f) Dakotas, and (g) Midwest Triangle.

Dakotas, etc.). By using the control data set as one array and the deforested data set as the other, we can calculate the means and standard deviations of precipitation, and the one-tailed t statistic can be calculated (Table 1). We can reject with 97.5% certainty the null hypothesis for all areas except the West Pacific in August, and we can be 99% certain about the three tropical areas and one of the two North American areas.

[15] Because the remote areas examined were selected according to the magnitude of the precipitation response, it is still possible that we are seeing random variations, some of which are large and happen to form a contiguous area. Can we get the same effect by comparing runs with no Amazon vegetation differences between them? *Carpenter et al.* [1989] described the use of randomized intervention analysis to determine if an ecosystem manipulation applied to a set of lakes had a significant effect compared with a set of unmanipulated control lakes. Chemical observations were taken from both sets of lakes, and the authors point out that "the null model states that all possible permutations of the data have an equal probability of being observed." The test statistic was taken as the mean difference between the experimental and control lake chlorophyll concentrations, and this was compared with the differences obtained

Table 1. Student's t Test Statistic and Percentage With Which We Can Reject the Null Hypothesis (Ho), Assuming 94 ($2n$-2) Degrees of Freedom

Area	Month	t	Reject Ho, %
Amazon	January	16.251	99.9
Central America	August	4.266	99.9
Gulf of Mexico	August	4.686	99.9
West Pacific	February	2.103	97.5
West Pacific	August	1.333	75
Indian Ocean	October	2.347	97.5
Dakotas	July	2.442	99
Midwest Triangle	July	2.091	97.5

when the control and experimental data values were combined randomly into "control" and "experimental" categories and the mean difference taken. The actual experimental-control difference was in the top 5% of values from the "false" experimental-control differences, and the authors concluded that the manipulation had a significant effect.

[16] With our six control and six deforested runs, we created 400 false ensembles in which each "control" consists of tree control and three deforested runs, and the "deforested" comprises the remaining three control and three deforested runs. As in the work of *Carpenter et al.*, [1989] by comparing the differences between the false controls and false deforested with those of the legitimate ensemble, we can determine if those of the latter are significant with respect to the former.

[17] Each false ensemble (as well as the "true" ensemble, with deforested runs compared with control runs) is evaluated by obtaining the difference in precipitation for each simulation mean month at each grid point. We hypothesized that a true signal would be coherent in space and time, while random noise would be scattered in space and short-lived. A boxcar smoother is therefore applied to the data to erase small, short-term differences in precipitation:

$$p_{\mathrm{sm}}(i,j,t) = \frac{1}{27}\sum_{t'=t-1}^{t+1}\sum_{j'=j-1}^{j+1}\sum_{i'=i-1}^{i+1} p(i',j',t'), \qquad (1)$$

where $p(i, j, t)$ is unsmoothed precipitation (in millimeters per day), $p_{\mathrm{sm}}(i, j, t)$ is smoothed precipitation (in millimeters per day), and t is time (in months).

[18] All areas outside of the deforested region in which precipitation deficit exceeded 0.5 mm/d were identified, and the global precipitation deficit was summed over these areas. The results are shown in Figure 3. We see that the true ensemble yields a seasonally varying signal with a summertime maximum that exceeds any signal in the false ensemble. Taking the summer (June through September) sum of precipitation deficit, we see that the true ensemble precipitation deficit lies in the top 3% of those of the false ensembles. The smoothed precipitation field comprises the deficit area over Central America and the West Pacific, the rest having been smoothed away. When we repeat the analysis with a lower threshold (0.3 mm/d) (Figure 4), we again see the true ensemble dominating the mean of the false ensembles throughout the summer. The precipitation field now includes both tropical areas, the West Pacific and Indian Ocean regions, and the summertime total precipitation deficit lies in the top 7% of the false ensembles. These results suggest that the global differences between the true deforested and control runs are generally larger than those obtained by comparing runs with no net vegetation differences and that the deforestation of the Amazon generates a significant propagating signal.

5. Correlation

[19] It is still unclear what the exact mechanism is that can transmit a signal generated by Amazon deforestation to another area of the world. We have done correlational analyses for three of the affected areas (Central America, the Gulf of Mexico, and the Indian Ocean) to see if changes in the Amazon due to deforestation (the "signal") can be related to changes in the remote areas (the "response"). What we find is that at least two mechanisms exist for transmitting signals.

[20] We see that in August, an increase in easterly zonal wind (in the deforested run over the control run) at 787 mbar leaving the Amazon results in a precipitation decrease in the Central American region (correlation of -0.51, Table 2). The Amazon wind aloft correlates well with the pressure-weighted wind shear over Central America (0.65), and this shear in turn correlates negatively with the precipitation (-0.79). Since the mean Amazon zonal wind at 787 mbar is increased in the deforested runs, we may expect a net reduction in precipitation in the Central American region. This is a mechanism similar to that which suppresses Atlantic hurricanes during El Niño years, when the altered circulation features strong westerlies over the equatorial Atlantic [*Vitart and Anderson*, 2001].

[21] We also correlate changes in Amazon geopotential with the changes over the Gulf of Mexico and Indian Ocean areas during their respective months (August for the gulf and October for the Indian Ocean). We see that Amazon geopotential changes correlate with geopotential changes in both remote areas, and these in turn correlate with precipitation. Both relationships result in statistically significant (99%) correlations between Amazon geopotential changes and precipitation changes in the remote areas. The exact mechanism is less certain, but these geopotential-communicated effects suggest that a Rossby wave process is involved.

6. Conclusions

[22] We have simulated the deforestation of the Amazon with the GISS GCM and found several remote areas where this local change to the surface had a noticeable response. The modeled Amazonian climate responds strongly to Amazon deforestation, seeing a strong reduction of rainy season hydrology. The remote response of an Amazon deforestation is statistically weaker but still noticeable and significant. The remote effect tends to be strongest in the areas closest to the Amazon and decreases "downstream" as one passes over the Pacific.

[23] The remote areas that showed a response saw a decrease in precipitation that lasted throughout much of the year, with a single month experiencing the largest, most significant reduction (usually during the rainy season). The

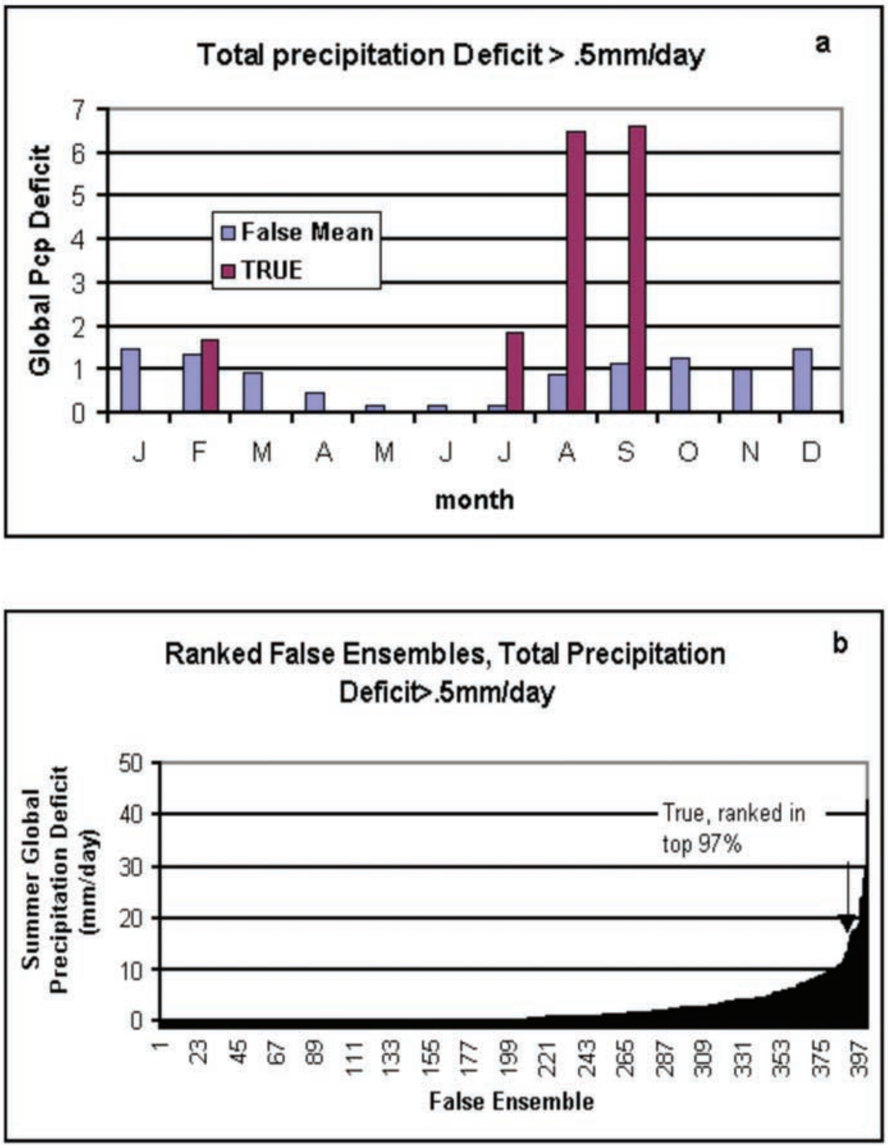

Figure 3. (a) Comparison of total precipitation deficit exceeding 0.5 mm/d by month for the true ensemble and the mean of false ensembles. (b) Total summer (June through September) precipitation deficit exceeding 0.5 mm/d for the true and all false ensembles.

global precipitation reduction due to the deforestation was seen to be larger than that obtained when controls and deforested runs were combined randomly, and correlational links were observed between the Amazon and three of the remote areas.

[24] Earlier modeling studies of Amazon deforestation tended to agree in general (most called for reduced Amazon precipitation, for example) but disagreed in the specifics (the magnitude of the modeled change differed among the models). Our study purports changes in a deforested Amazon climate similar to those studies, strengthening the probability that deforestation will affect the local climate. The strength of the changes (−296 mm/yr for precipitation, −214 mm/yr for evaporation) falls within the range of values given earlier, although the precipitation change is close to the low end.

[25] From a practical point of view, a reduction of precipitation in the Dakotas and Midwest Triangle implies an impact on water resources in these regions and, more specifically, on agriculture productivity. We hypothesize that these teleconnections between the Amazon and the remote areas are due to the fact that the changes in the Amazon serve as a wave source. For example, we have observed varying temperature reductions at high levels (i.e., in the westerlies) over the Amazon in response to the deforestation (likely due to reduced latent heat release). It is also possible that the changes over the Amazon alter the Hadley circulation in the region or affect moisture transport into the Northern Hemisphere tropics.

[26] Ultimately, the goal of our study was to highlight the sensitivity of the climate system to changes in land cover

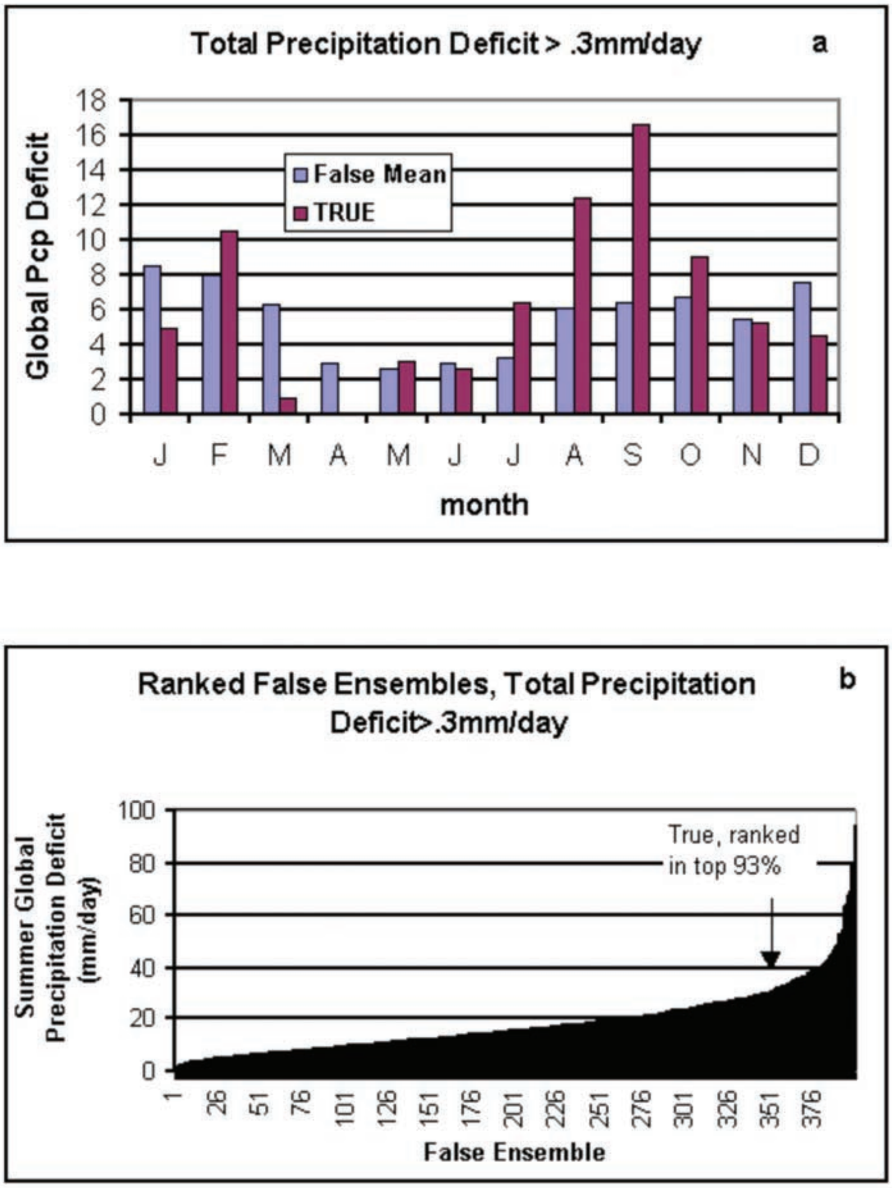

Figure 4. Same as Figure 3 but for a precipitation deficit exceeding 0.3 mm/d.

and land use. In the future, it will be valuable to perform long simulations with an interacting ocean, allowing for the effects of El Niño–Southern Oscillation. Additionally, a higher model resolution and a better parameterization of convection generated by landscape heterogeneity could increase the effect found here. By no means is this study complete, and further research on this topic is very much needed.

Table 2. Correlation of Amazon Variables With Remote Variables[a]

Variables	Month	Correlation
Easterly 787-mbar winds through left edge of Amazon (UAmz) versus Central American shear (CAM shear)	August	0.65
CAM shear versus Central American precipitation (CAM pcp)	August	−0.79
UAmz 787 mbar versus CAM pcp	August	−0.51
Amazon 635-mbar geopotential (PhiAmz) versus Gulf 635 mbar geopotential (GulfPhi)	August	0.73
GulfPhi versus Gulf precipitation (Gulf pcp)	August	−0.73
PhiAmz versus Gulf pcp	August	−0.49
Amazon 125-mbar geopotential (PhiAmz) versus Indian Ocean 125-mbar geopotential (PhiIndOcn)	October	0.77
PhiIndOcn versus Indian Ocean precipitation (IndOcn pcp)	October	−0.6
PhiAmz versus IndOcn pcp	October	−0.55

[a] All variables are deforest-control.

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