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Amazon Deforestation in CFS

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1. Introduction

Many simulations of the potential effects of tropical deforestation on climate have been made using atmospheric general circulation models (AGCMs) coupled to land models and forced by *specified* SST (*e.g.* Dickinson and Henderson-Sellers, 1988; Nobre *et al.*, 1991). Recently, CGCM (coupled general circulation models, which include dynamical oceans) simulations of tropics-wide (Voldoire and Royer 2005, referred to as VR05) and Amazon (Schneider *et al.* 2006, referred to as S06) deforestation have been made. We extend these CGCM results by examining the effects of Amazon deforestation on the coupled ocean-atmosphere-land climate system using the NCEP CFS. A primary advantage of CFS is that it has a much more realistic simulation of current Amazon climate than the CGCMs used in the earlier studies.

Century length control and deforestation simulations are carried out with CFS. The results suggest that the impact of Amazon deforestation would be a warmer and drier Amazon, as well as a warmer tropical Pacific and tropical North Atlantic. However, these changes are small. ENSO is not noticeably affected. Sensitivities to changes in the land surface processes are diagnosed using uncoupled AGCM simulations, using GFS, the atmospheric model component of CFS. The GFS simulations suggest that albedo changes are the controlling influence for the Amazon deforestation effects found in CFS, due to the mechanism outlined by Charney (1975).

An unexpected warming occurs in the northern North Atlantic region in the deforestation simulation. We examine the Meridional Overturning Circulation and other quantities in the simulations in an attempt to understand the origins of this change, which appears to be related to the physically inconsistent treatment of sea ice.

2. Models and data

Two 100 year simulations were carried out with CFS, a current climate control simulation (CONTROL) and a deforestation simulation (DEFOREST) in which tropical rainforest in the Amazon region (vegetation type 1) was replaced with perennial ground cover (vegetation type 7). In the deforested region, the albedo and surface roughness were also changed to values appropriate for areas of vegetation type 7 found near the Amazon. The vegetation change reduces the resistance to surface evaporation. The main effects of the deforestation on the specified surface properties were an increase in the shortwave beam albedo to about 30% from about 23% and a decrease in the roughness length to 0.1 m from values larger than 2 m. The simulations were started from analysis with identical Jan. 1, 1985 initial and boundary conditions.

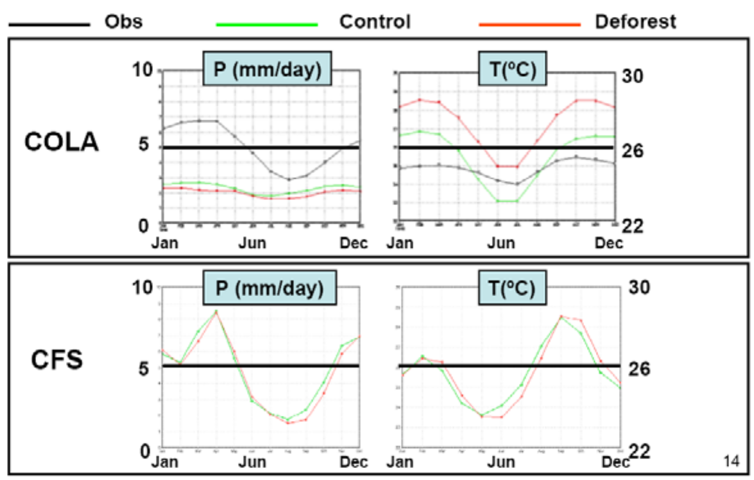

Fig. 1 Annual cycle of monthly means of precipitation (left) and surface temperature (right) averaged over land in the box from 80°W to 40°W and 15°S to 8°N for the COLA CGCM (top) and CFS (bottom). Observations/analysis are the black curves, the CONTROL simulations are green, and the DEFOREST simulations are red.

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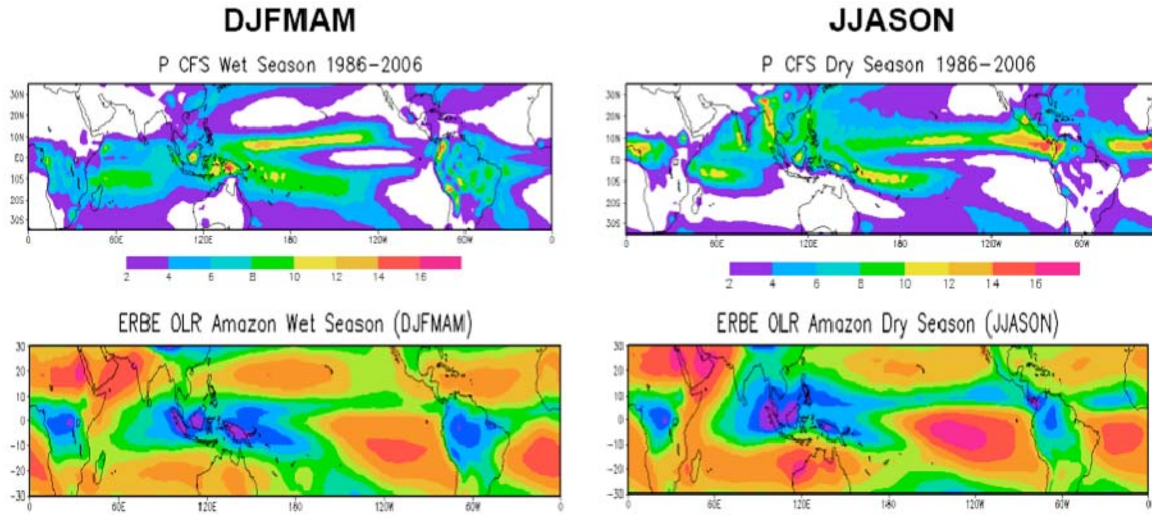

Fig. 2 Precipitation for CONTROL (top, mm/day) and ERBE OLR (bottom, contour interval 10 W/m^2; cool/warm colors in OLR correspond to high/low precipitation) for the Amazonian wet (December through March, left) and dry (June through November) seasons.

A caveat concerning these simulations is that CFS is not designed for long climate change simulations. For one thing, the CO_2 concentration is constant in time. Additionally, the domain for ocean-atmosphere interaction is non-polar, and the sea ice distribution is specified. Therefore, the freezing and melting of sea ice are not directly tied to the ocean temperature, which can lead to energetic and physical inconsistencies.

3. Results

a. Simulation of current climate in Amazonian region

Figure 1 shows the climatology of the area averaged Amazon precipitation and surface temperature for observations/analysis, CFS, and the S06 COLA CGCM (consisting of the COLA V2 AGCM, SSiB land, and MOM3 OGCM with anomaly coupling). The model climatologies are taken over the 100 simulated years. The observed annual mean precipitation is about 5 mm day^{-1}, which is also the value simulated by CFS CONTROL. However, the COLA CGCM control simulation produces an annual mean precipitation of about 2 mm day^{-1}, only about 40% of the observed value, and much too small to support a rain forest. Similarly, the control simulation from the CGCM of VR05 (consisting of the ARPEGE-climate AGCM, ISBA land model, and LODYC OGCM) produces a very dry Amazon, with an annual mean rainfall of 3.5 mm day^{-1}. The more realistic performance in the simulating the climatological precipitation was the main motivation for us to adopt CFS for the experiments.

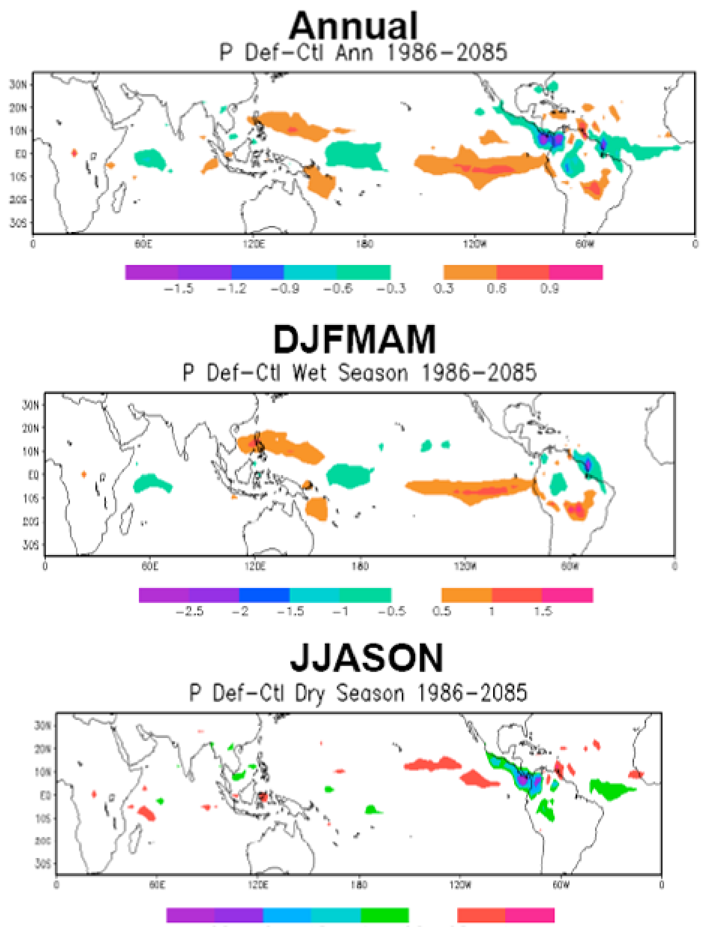

Fig. 3 Precipitation difference (mm/day) DEFOREST minus CONTROL, averaged from 1986 to 2085.

There are, however, biases in CFS that are obvious from Fig. 1. The amplitude of the annual cycle of precipitation is too large, as is the amplitude of the annual cycle of surface temperature. Additionally, the CFS surface temperature is about 1°C too high, and the COLA control simulation is closer to observations in this quantity. However, CFS has a drift in the surface temperature (see Fig. 6). When averaged over the first 10 years of the simulations, CFS annual mean land surface temperature in the region of Fig. 1 is 25.2°C, which is cooler than the 100 year mean by about 1°C and close to the analysis, while precipitation is not changed much.

Figure 2 compares the wet and dry season 1986-2005 climatological precipitation for CONTROL with the climatology of ERBE OLR (OLR is a commonly used a proxy for precipitation from deep convection). The precipitation distribution over the Amazon region in CONTROL is reasonably smoothly spatially distributed, although not as smooth as the OLR. There are some orographically-tied features that appear to be associated with the Andes and which are not seen in the OLR. The CONTROL Amazon precipitation distribution appears to have a much more realistic spatial distribution than that found in S06 for the COLA AGCM. The rainfall deficit bias in the dry season shown in Fig. 1 appears to be due to a severely deficient rainfall to the south of the equator in South America.

b. Topical and subtropical changes due to Amazon deforestation

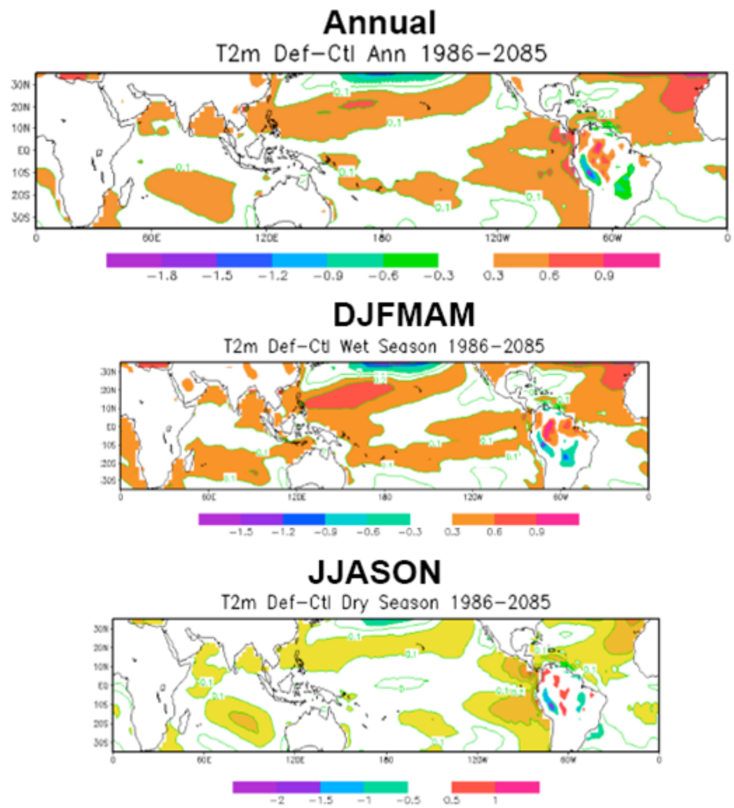

Fig. 4 Air temperature at 2 m difference (K), DEFOREST minus CONTROL, averaged from 1986 to 2085. Temperatures over ocean and land have different scales. Color bar is for temperature over land.

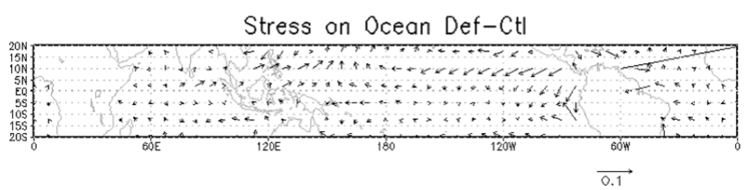

Fig. 5 Annual mean surface wind stress on ocean (dynes/cm^2) DEFOREST minus CONTROL.

The changes in precipitation and surface temperature due to the Amazon deforestation, DEFOREST minus CONTROL, are shown in Figs. 3 (precipitation) and 4 (temperature). Deforestation locally leads to a decrease in precipitation and warming of surface air temperature in the core of the deforested region for both the wet and dry seasons as well as the annual mean. However, there is a compensating increase in rainfall and associated cooling on the southeast flank of the Amazon region.

We have conducted two sets of experiments with the GFS AGCM to separate the influences of the physical processes involved in our deforestation simulation. One set examines the changes in vegetation type, and the other the combined effects of changes in surface albedo and surface roughness. The change in vegetation reduces the resistance to evaporation, which leads by itself to enhanced rainfall and surface cooling. The increased albedo by itself would be expected to lead to decreased rainfall and surface cooling by the enhanced subsidence mechanism of Charney (1975); however, reduced cloudiness associated with the reduced rainfall acts to mitigate the surface cooling. The role of reduced roughness is less easy to anticipate, and we have not isolated the sensitivity to this process. When the changes are compared, the albedo/roughness effect turns out to be dominant.

The remote effects of the deforestation include warming of the SST in the eastern tropical Pacific and tropical North Atlantic, and increased precipitation in the eastern equatorial Pacific, as well as widespread warming of SST in the northern hemisphere and southern Indian Ocean. Precipitation decreases in the near-equatorial Atlantic during the dry season, and the western tropical Pacific.

The changes in the Atlantic and Pacific can perhaps be connected to the atmospheric dynamical response to the local response over the Amazon. As shown above, the local response is: 1) reduction in magnitude and changes in distribution of the latent heat release, and 2) warmer surface temperature. Figure 5 shows that the Amazon deforestation is associated with easterly surface wind anomalies in the tropical Atlantic, with northerly/easterly anomalies north of the equator and westerlies at 5°S in the tropical Pacific east of the dateline. The precipitation and surface wind anomalies in the tropical Atlantic and eastern Pacific, and the Pacific SST are similar to those found by S06. However, the Atlantic response in S06 was a cooling to the south of the equator. The SST changes in S06 were tentatively explained there as originating from a Gill-type response (Gill 1980) to the decreased Amazon atmospheric heating competing with the response to the increased land surface temperatures. The response to surface temperature anomalies can also be viewed as a Gill-type response (Neelin 1989), but with a smaller effective depth, although this argument is not commonly applied to land surface temperatures. According to the simple model, the reduction in heating would produce surface wind directions opposite to those seen in DEFOREST minus CONTROL in the equatorial Pacific and Atlantic near South America, while the response to the warmer surface temperature would produce wind directions in agreement with those found in CGCMs. To explain the results, the land surface temperature forcing would have to be more important in producing the surface wind over the oceans near the deforested region. The response to the deep heating anomaly would be expected to be the dominant far field response. The precipitation and Pacific SST changes in the corresponding regions in VR05 also appear to be similar. In contrast to CFS, VR05 also found cooling in the tropical Atlantic.

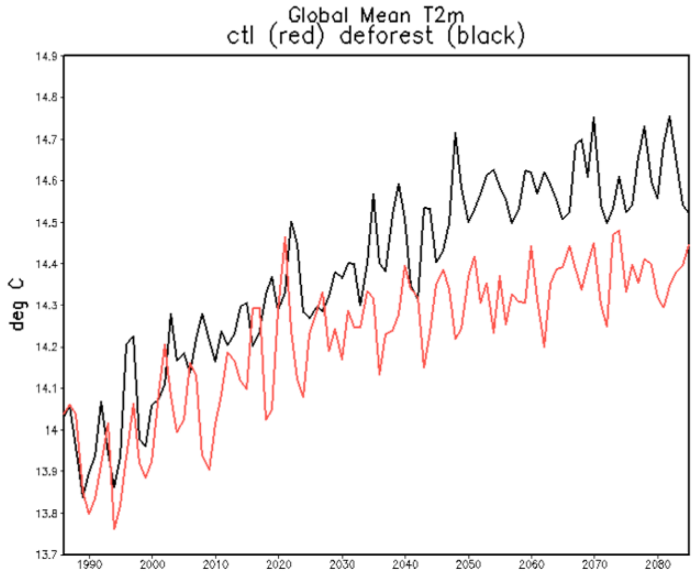

Fig. 6 Global and annual mean 2 m air temperature for CONTROL (red) and DEFOREST (black).

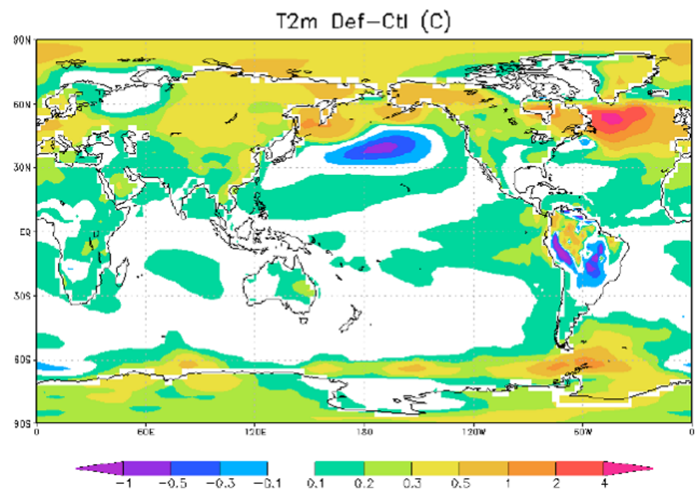

Fig. 7 Annual mean air temperature at 2 m difference (K), DEFOREST minus CONTROL, averaged from 1986 to 2085. Temperatures over ocean and land have different scales. Color bar is for temperature over ocean.

c. Global scale changes associated with Amazon deforestation

Figure 6 shows the global mean temperature evolution for CONTROL and DEFOREST. Both simulations show evidence of a significant drift or "warming commitment," with global mean temperatures initially warming rapidly and then leveling off after about 60 years. This is the expected behavior if there is a net surface flux into the ocean (or downward top of the atmosphere heat flux) when the atmosphere is in equilibrium with the ocean in the current climate configuration. A warming commitment is not an indication of biases in the model, and in fact may indicate that the model is behaving realistically, so long as the initial state is realistic (Schneider 1996). The drift is about a 0.5°C warming for CONTROL and substantially more, 0.8°C, for DEFOREST. The mechanism connecting deforestation to the larger warming is not clear; therefore we made a substantial effort to try to understand this result.

The spatial distribution of the DEFOREST minus CONTROL surface air temperature change in the global domain is shown in Fig. 7 (same data as Fig. 4 in lower latitudes). The warming in DEFOREST is greatest in high latitudes, and there is a very large warmer region in the North Atlantic. There is no obvious dynamical link between these high latitude regions and the Amazon.

The large SST anomaly in the North Atlantic suggests the possibility of involvement of the Atlantic Meridional Overturning Circulation (AMOC). The change in the AMOC is shown in Fig. 8. The surface flow in the North Atlantic shows an increase, which is of the right sign to lead to warmer SST in the North Atlantic, but the 1 Sv magnitude of the change is too weak to explain the changes shown in Fig. 7.

Further analysis shows that there may be a problem with the model physics in the vicinity of the large SST increase in Fig. 7. Figure 9 shows SST and heat flux from the ocean model output. The SST increases by order 20°C in Hudson Bay and the northern North Atlantic, while the heat flux is into the ocean in the regions of the largest SST increase and does not respond strongly to the warmer SST. Also, this strange behavior is found in a region where the specified sea ice is non-zero. If the sea ice was physically consistent with the SST, the warming SST would melt the ice. Instead, the insulating effect of the ice appears to be leading to enhanced warming of the SST. The positive heat flux into the ocean in the northern part of Hudson Bay and to the east in the North Atlantic does not seem to be physically defensible, especially in DEFOREST given the warm SST. There is also a jump in the heat flux across a line of constant latitude to the south of this region that is suspicious. It is clear that there is something amiss in the model, at least in DEFOREST,

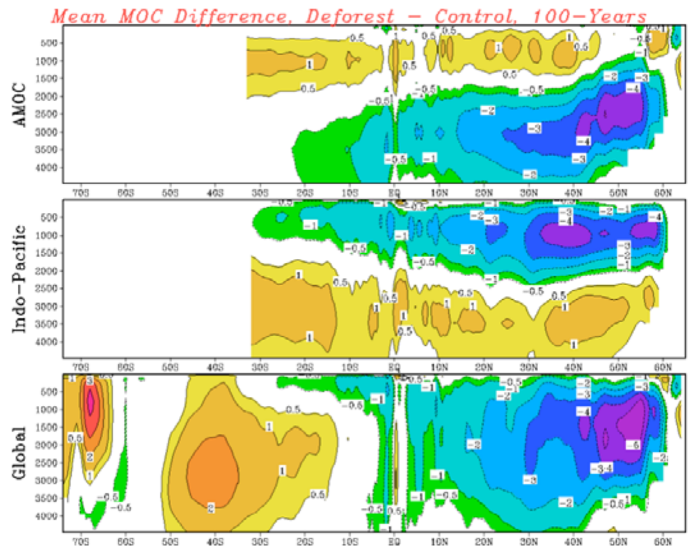

Fig. 8 Change in meridional overturning mass flux (Sv), DEFOREST minus CONTROL. Top: Atlantic; middle: Indo-Pacific; bottom: global. Positive values indicate clockwise circulation.

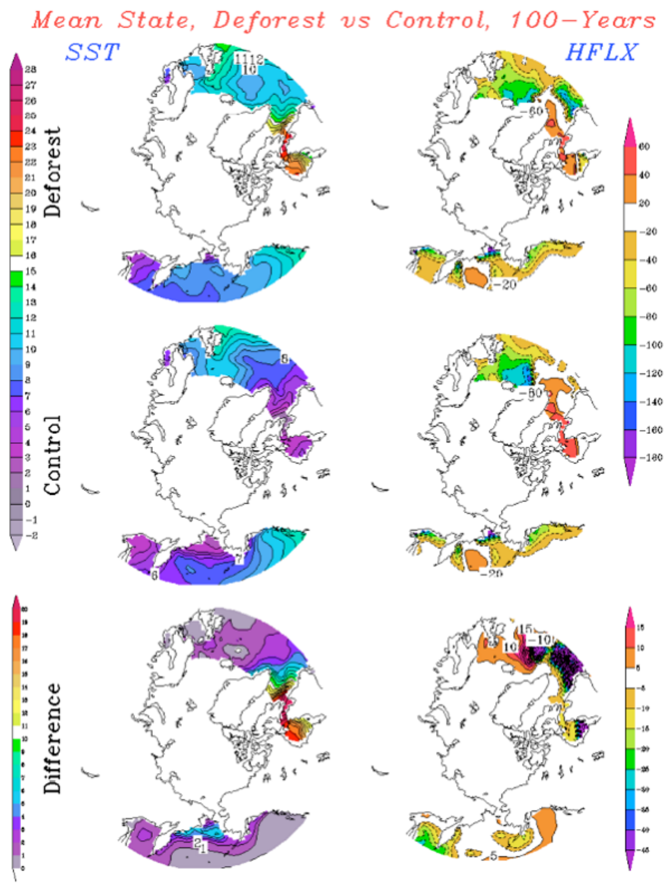

Fig. 9 SST (left) and net downward surface heat flux (right, W/m^2) for DEFOREST (top), CONTROL (middle), and DEFOREST minus CONTROL (bottom).

which needs to be diagnosed, understood, and corrected before going further with this investigation. The obvious candidate processes are the sea ice and high latitude oceanic sponge layers.

4. Conclusions

We investigated the response of the coupled atmosphere-ocean-land system to a hypothetical complete Amazon deforestation. The purpose of the investigation was to identify the sensitivity of the climate system to changes in the land surface properties. The local changes were a general warming and drying in the Amazon region, primarily caused by to the changes in the surface albedo and roughness. The remote effects included warming of the eastern tropical Pacific and tropical Atlantic, increased precipitation in the eastern equatorial Pacific, and reduced precipitation in the equatorial Atlantic. The precipitation and Pacific SST changes are in agreement with other similar studies, indicating that these changes may be robust. However, the SST changes in the tropical Atlantic are opposite in sign to those in the other studies. The SST changes are apparently due to the influence on the ocean of the dynamical response of the atmosphere to the warmer Amazon surface temperatures, since the reduction in latent heat release would be expected to lead to the opposite effects on surface winds and hence tropical SST.

There was little effect on ENSO SST variability in CFS. S06 found an increase in ENSO amplitude from Amazon deforestation and attributed this to changes in the basic state (*i.e.* the changes in the ocean thermal structure climatology). However, the ENSO variability in CFS appears to be associated with stronger coupled instability and a more regular oscillation than in the COLA CGCM. Possible reasons for the lack of sensitivity of ENSO in CFS compared to the COLA CGCM then may be either the stronger coupled instability, the smaller warming in the land surface temperature and consequently smaller changes in the ocean thermal structure, or the secular warming in CFS.

The long simulations showed that CFS has a warming climate commitment of order 0.5°C for current initial states and the constant modern climate CFS CO_2 concentration. Amazon deforestation apparently enhances the global mean warming, but this effect appears to have been due to a problem in the model physics that needs to be investigated, and which may be connected to the code modifications we made.

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