GEOPHYSICAL RESEARCH LETTERS, VOL. 19, NO. 19, PAGES 1947-1950, OCTOBER 2, 1992

IMPACTS ON REGIONAL CLIMATE OF AMAZON DEFORESTATION

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Abstract. A simulation of the climate response to Amazon deforestation has been carried out. Precipitation is decreased on the average by 25% or 1.4 mm/day, with ET and runoff both decreasing by 0.7 mm/day. Modifications of surface energy balance through change of albedo and roughness are complicated by cloud feedbacks. The initial decrease of the absorption of solar radiation by higher surface albedos is largely cancelled by a reduction in cloud cover, but consequent reduction in downward longwave has a substantial impact on surface energy balance. Smoke aerosols might have an effect comparable to deforestation during burning season.

Introduction

The continuing conversion of tropical forests to other uses suggests an urgent need to better understand the effect of this conversion on climate. Recent development of more realistic treatments of the role of vegetation for surface evapotranspiration (ET) and energy balance now allows quantitative modeling of impacts of changing land cover in simulations with General Circulation Models (GCMs) [*Dickinson and Henderson-Sellers*, 1988, hereinafter referred to as DHS; *Lean and Warrilow,* 1989, referred to as LW; *Nobre et al.*, 1991, referred to as NSS].

The DHS study used an early version of the Biosphere Atmosphere Transfer Scheme (BATS) [as described by *Dickinson et al.*, 1986] along with an early version of the National Center for Atmospheric Research (NCAR) Community Climate Model. BATS uses geographically distributed ecosystems as input to determine values for various biogeophysical parameters it requires. Tropical forest prescribed over the Amazon basin was assumed by DHS to be entirely converted to a degraded grassland.

Both the LW and the NSS studies made essentially the same assumption. All the studies correspondingly assumed an increase of surface albedo, a decrease of surface roughness, and changing soil properties, such as decreased rooting depths and decreased infiltration rates. LW used a relatively simple parameterization for vegetation, and NSS assumed prescribed cloudiness and a fixed sea-surface temperature.

All these recent studies found that deforestation would increase surface temperatures in the range 1-4°C, opposite to that expected from albedo change alone, as a consequence of the reduced surface roughness. They all inferred a reduction in ET (*e.g.*, from 150 mm/yr in DHS to about 500 mm/yr in NSS). The studies differed strikingly in precipitation changes. The DHS study found very little change in precipitation overall. LW and NSS found substantial decreases in precipitation, even larger than the decreases in ET, so that runoff also decreased.

The three studies addressed the same question but differed in quite a few details of their treatments. The DHS study used a relatively coarse resolution spectral model (R-15 = 4.5° lat. by 7.5° long.), whereas the LW and NSS studies used about double that resolution. DHS and NSS looked at a single year, whereas LW examined a 3-year simulation. Assumed changes in various parameters differed, *e.g.*, the increase in albedo with deforestation was as little as 0.05 in

TABLE 1. Value of albedo and roughness assumed to represent forest and deforested conditions

	DHS (this paper)	LW	NSS
albedo forest	0.12	0.14	0.12
albedo deforested	0.19	0.19	0.21
roughness forest (m)	2.00	0.80	2.70
roughness deforested(m)	0.05	0.04	0.08

TABLE 2. Model fields averaged over the simulation and over the Amazon forest

Field	Control	Deforested	Change
Daily Max. Temp. (K)	304.1	306.7	2.6
Daily Min. Temp. (K)	294.8	294.6	-0.2
Mean Surf. Soil Temp. (K)	298.8	299.4	0.6
Precipitation (mm/day)	5.5	4.1	-1.4
Runoff (mm/day)	2.0	1.3	-0.7
Evapotranspir. (mm/day)	3.5	2.8	-0.7
Interception (mm/day)	1.3	0.8	-0.5
Sensible Flux (W/m^2)	54.0	56.0	2.0
Absorbed Solar Rad.(W/m^2)	215.0	212.0	-3.0
Net Longwave Rad. (W/m^2)	59.0	74.0	15.0
Fractional Cloud Cover	0.53	0.46	-0.07
Relative Soil Moisture	0.7	0.4	-0.3

Paper number 92GL01905
0094-8534/92/92GL-01905$03.00

TABLE 3. Changes in the initial radiative forcing, feedback, and system response

Radiative Forcing	Energy Reduction (W/m^2)
Albedo	16
Roughness	18
Total initial forcing	34
Cloud feedback, solar radiation	-13
Feedback, downward longwave	7
Surface longwave feedback	-10
Final radiative forcing	18
Response	
ET	20
Sensible	- 2
Net response	18

LW and as large as 0.09 in NSS. The overlying atmospheric GCMs in the three studies were all quite different. With relatively short simulations, it is possible to make inaccurate estimations of regional climate change if there is significant interannual variability. It seems important to clarify the sources of the discrepancy or to establish whether the lack of change in precipitation is reproducible. The DHS study involved modeling components that are no longer available, so further analysis and repetition of that study are not possible.

Therefore, the Amazon deforestation simulation was redone with current modeling components, *i.e.*, a version of the later NCAR model (CCM1) along with the current version of the BATS parameterization (BATS1e). The results of this study are in agreement with the LW and NSS studies and so add additional support to the hypothesis that large decreases in regional precipitation occur with large-scale deforestation.

Modeling Framework

Atmospheric climate is simulated in this study with the NCAR CCM1 [*Williamson et al.*, 1987]. We have extensively modified this code in conjunction with adding the detailed BATS land package. One major change was the inclusion of a diurnal cycle, which is necessary for adequate simulation of land properties. For this cycle, solar heating at the land surface is evaluated every time step (half-hour for the R-15 model resolution). A consequence of adding a diurnal cycle of solar heating to the standard version of the model (with fixed ocean temperatures and hence not forced to conserve energy) was a substantial energy imbalance at the top of the atmosphere, with excess absorption of solar energy by about 10 W/m^2. This is in contrast to the standard CCM1 which, over an annual cycle, is nearly in energy balance. Previously, an excess of solar radiation [*Dickinson*, 1989; *Shuttleworth and Dickinson*, 1989] was noted in CCM1 surface fluxes relative to those measured in the first Anglo-Brazilian field program [*e.g., Shuttleworth*, 1988]. This seemed partially to account for the excess ET and interception noted in DHS. Thus, we introduced the cloud radiation scheme of *Slingo* [1989], as developed for the CCM1, and tuned parameters for cloud liquid water to increase reflected solar radiation. In doing so, global radiation balance was achieved.

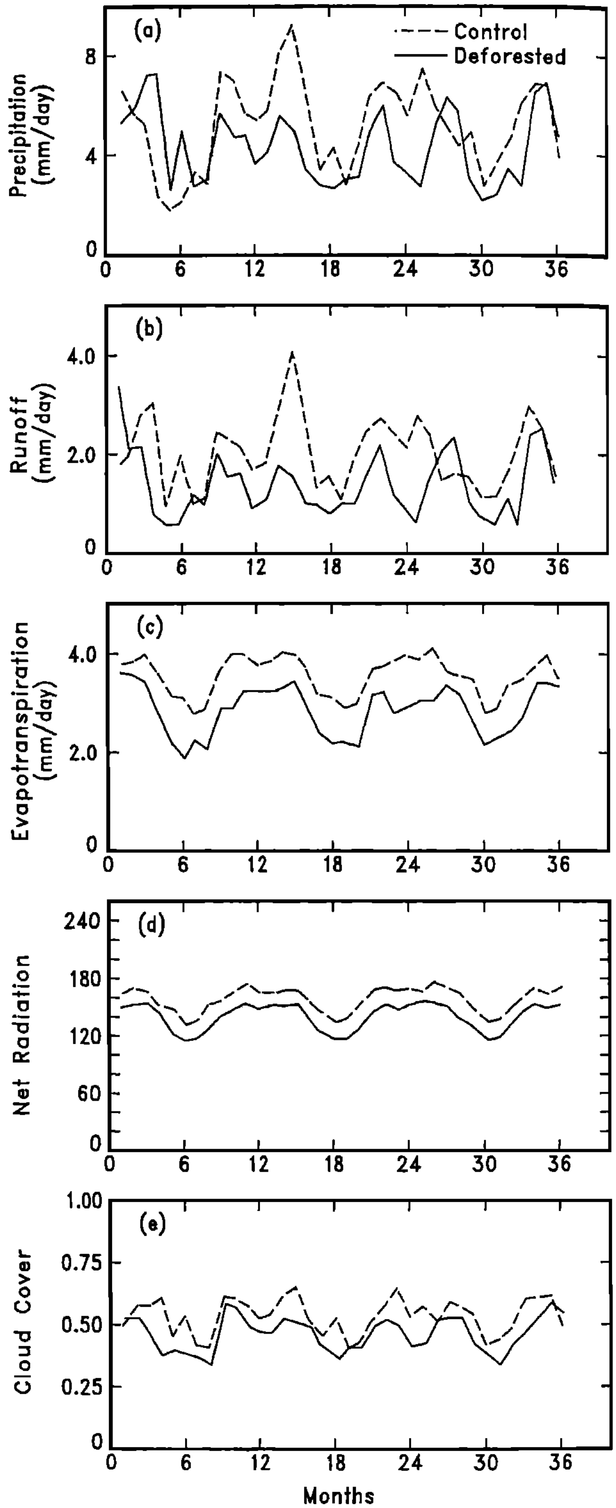

Fig. 1. Time series of monthly means over the Amazon basin for the indicated fields.

Another major, otherwise undocumented change was the introduction of a flux-corrected interactive ocean calculation.

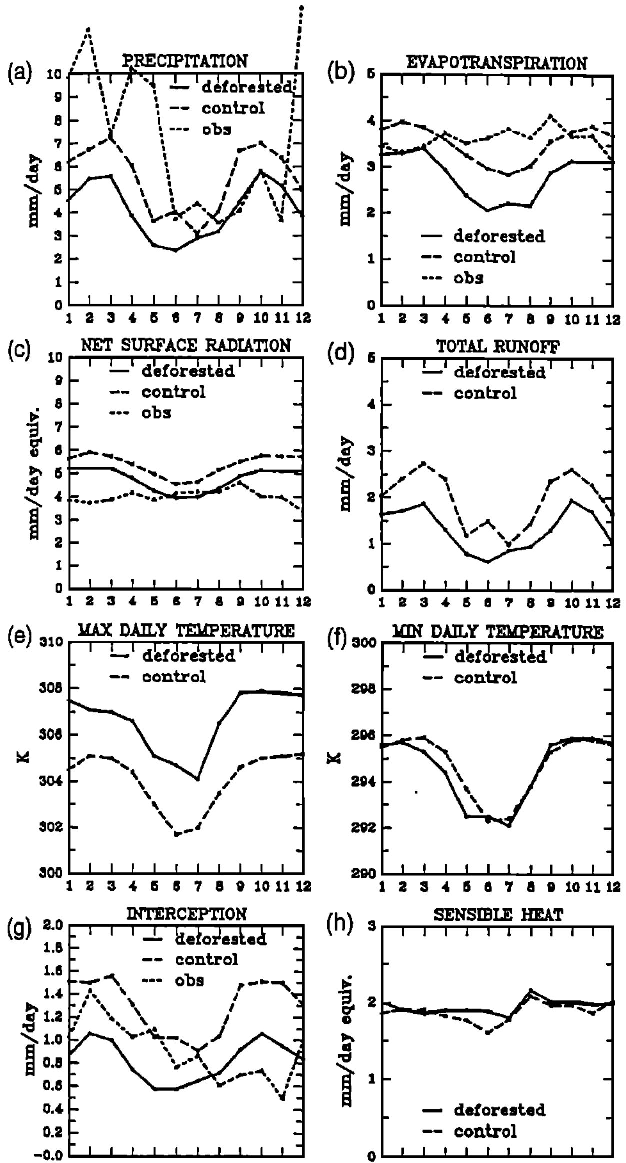

Fig. 2. Seasonal cycle for indicated fields from monthly means averaged over the 3-year integration and over the Amazon basin. Where indicated, fields reported by Shuttleworth (1988) for 2°S, 60°W are given as "obs".

Because of initial tuning to global radiation balance and because of energy balance integrated over the ocean and annual cycle, drifts in ocean temperature were small after the first year of simulation. The control was integrated for 10 years, at which point it became clear that the treatment of sea ice needed improvements before proceeding further. Since this was not expected to affect tropical simulations, we restarted at year 7 and proceeded three years with the Amazon deforestation scenario.

Several improvements have been introduced into the BATS code since its use for the study by DHS. Of these, the most significant physical changes were adjustments to various aspects of stomatal resistance parameterization to better model the data of *Shuttleworth* [1988]. These were: a) reduction of the maximum storage of intercepted water by the canopy from 0.2 mm to 0.1 mm per unit leaf plus stem area index; b) reduction of the minimum stomatal resistance from 250 s/m to 150 s/m for tropical forests and to 200 s/m for the degraded pasture, and a ×2 increase, for all vegetation types, of the parameter that determines the flux of visible radiation at which stomatal resistance is double its minimum value; and c) assumption that the stomatal conductance decreases linearly with "vapor pressure deficit," until stomatal resistance is increased by a factor of 10 at a deficit of 36 mb.

The changes made in the model to represent deforestation were largely the same as in DHS and so are very briefly summarized: roughness length was reduced from 2.0 to 0.05 m, albedo increased by 0.07, fraction of vegetation cover decreased from 0.9 to 0.8, rooting depth reduced from 1.5 m to 1.0 m, the stomatal resistance parameterization modified to correspond to that of grass, the soil texture class increased by 2, the soil color class decreased by 2 [*cf.* Table 3 in *Dickinson et al.*, 1986], and the roots distributed uniformly within the rooting zone. The changes in albedo and roughness (compared with other recent studies in Table 1) are believed to be the most important.

Results

The deforestation simulation described here is likely too brief to generate stable spatial patterns of change. Hence, we examine principal surface hydrological fields, averaged over the model tropical forest points, the area approximately from 13°S to 5°N and 50°W to 80°W, consisting of a 3×4 grid of points south of the equator and 4 grid points 2.4° north of the equator and excluding one forest point further north.

Monthly averages of the 3-year simulation of deforested conditions are compared in Figure 1 with the control. Only the first month of the deforested simulation appears to be drastically out of equilibrium, but the presence of the deep soil water reservoir implies many additional years of simulation would be required for soil moisture to be close to equilibrium. Frame (a) shows that precipitation has sufficient interannual variability that monthly differences between control and deforested can vary widely from year to year and even change sign. Runoff in frame (b) shows the same degree of variability. However, ET [frame (c)] and, even more so, net radiation [frame (d)] have stable year-to-year repeatability.

Averages over the 36-month period of comparison are given in Table 2. With the 7% decrease in fractional cloud cover, more solar radiation is absorbed at the surface, compensating for the increase in albedo. Hence, reduction of net surface energy is dominated by an increase in net longwave, a consequence of increasing surface temperature and decreasing cloudiness. Surface temperatures increase only in daytime and by a relatively small amount, so the cloudiness decrease dominates the change in net longwave.

Reduction in ET by 0.7 mm/day (mostly from a net reduction in interception of 0.5 mm/day) is equivalent to a reduced surface energy flux of 20 W/m^2. This flux is close to the change in net radiation of 18 W/m^2, as indeed required by surface energy balance, since sensible fluxes increase by 2 W/m^2. Relative soil moisture, that is, soil moisture in rooting zone normalized by the difference between field capacity and wilting point, decreases with deforestation. The reduction in precipitation, on average, is double the reduction in ET, and hence, as expected, runoff is reduced about as much as ET.

Monthly average fields, averaged over the three years of deforestation simulation are shown in Figure 2. For comparison, we also plot observational data from Ducke Reserve near

Manaus [*Shuttleworth*, 1988] for precipitation, ET, and interception. There is no reason to expect exact correspondence between point measurements at 2°S, 60°W and model output over the whole Amazon, centered at 4°S, 65°W. However, any extreme disagreement would be notable.

The model average appears to follow the seasonal cycle of precipitation at Ducke, but is somewhat drier. The control ET is similar to that observed, but is somewhat less during the dry season. Net surface radiation exceeds that observed, on the average, by about 20%. The model interception exceeds that observed, except in the middle of the dry season. Overall, the agreement between model and observed surface radiation fluxes and ET terms is much better than that reported in DHS, evidently primarily from changes in cloud radiation parameterization. The changes resulting from deforestation seen in Figure 2 have already been commented on, except for the surface air temperature change. Temperatures increase substantially during the day with deforestation, but hardly change at all at night.

Table 3 gives a description in terms of initial radiative forcing, feedback, and system response. The effect of changing cloud cover on absorbed solar radiation is inferred from the change in incident solar radiation. The effect of albedo change is obtained as the total change in absorbed solar (3 W/m^2) minus that from changing cloud cover. The term "surface longwave feedback" is simply the change in upward longwave required to balance the change in absorbed solar plus downward longwave. The "roughness" term is the increase in upward longwave (8 W/m^2) minus that required to balance the above net downward fluxes. The total initial "forcing" plus "feedback" terms are summed to give the final radiative forcing. The decrease in downward longwave from less cloudiness of 7 W/m^2 is twice as large as the reduction in total absorbed solar.

Changes in surface energy balance terms of 10–20 W/m^2 are not very large, indeed at the limits of what might be detectable from surface observations or remote sensing. Such differences could readily arise from variations in atmospheric properties, either small changes in cloud cover properties or modest ones in aerosol cover, *e.g.*, a cloud cover change of 5–10% or aerosol optical depth of 0.20, assuming 30% of scattered radiation in clear sky regions is reflected upward. Biomass burning during the dry season commonly covers the Amazon basin by at least that much aerosol.

Conclusions

A simulation of Amazon deforestation has been carried out with the NCAR CCM1 and BATS surface model. ET reductions comparable to those of DHS are found. In contrast to DHS, mean rainfall decreases of about 500 mm/year are calculated, comparable to those obtained by LW and NSS. The ratio of this change to change in ET is substantially larger than that of the other studies.

Surface energy balance is initially perturbed by modification of albedo and surface roughness. However, with cloud feedback, reduction of solar radiation absorbed at the surface (3 W/m^2) is small compared to the increase of net longwave loss (15 W/m^2). The latter consists of 8 W/m^2 resulting from warmer surface temperature and 7 W/m^2 from less downward flux with the reduction in cloudiness. To the extent that the climate response to tropical deforestation depends on cloud feedbacks that are poorly parameterized and validated and on energy balance changes that might occur from other causes, we cannot regard it as well understood.

Other possible causes of comparable changes in surface energy balance could be changes in cloud properties or cover or the smoke from biomass burning during the dry season. This smoke would need a scattering optical depth as little as 0.2 to perturb surface energy balance by amounts comparable to those from the modeled deforestation.

Acknowledgments. The authors thank Dr. A. Henderson-Sellers for discussions and comment on this manuscript and M. Sanderson-Rae and K. Skemp for text improvements. Work at the University of Arizona has been supported by a National Science Foundation grant, No. ATM-9113163.

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(Received May 11, 1992;
accepted August 6, 1992.)