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Implications of Tropical Deforestation for Climate: A Comparison of Model and Observational Descriptions of Surface Energy and Hydrological Balance [and Discussion]

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Implications of tropical deforestation for climate: a comparison of model and observational descriptions of surface energy and hydrological balance

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Quantitative estimates of the impacts of tropical deforestation on climate can only be considered through use of models of climate that contain adequate treatments of both the land and atmospheric components. Recent global climate model (GCM) calculations by Dickinson & Henderson-Sellers of the effect of removing the Amazon forest attempted to include a detailed canopy model of the forest and the assumed grass replacement. An important role for the structure of the forest canopy was suggested by this study. However, data of Shuttleworth on the seasonal variation of Amazon evapotranspiration show much lower values during the wet season than were obtained in the GCM study and, consequently, much less seasonal variation. The reason for this discrepancy is examined by using results both from the GCM used in the deforestation study and a three-year simulation with a more recent version. The major source of the discrepancy is found to be a large excess of net surface radiation in the GCM simulations, and an excess rainfall interception loss, which is a consequence of this excess radiation. The modelled transpiration appears to agree with the observations.

1. Introduction

Speculation as to the role of forests in the climate dates back at least to Christopher Columbus. How deforestation might deleteriously affect climate in the U.S.A. was of considerable concern in the 19th century (Thompson 1980). We are currently faced with relatively rapid removal of forests in many areas of the tropics. Yet our understanding of how this deforestation might affect regional and global climate is still rather limited.

The Amazon Basin, as the world's largest tropical forest, serves as an important example of this question. I do not enter here the debate as to what secondary vegetation would regenerate in a deforested area. What regrowth will occur is a difficult ecological question that depends, among other things, on the spatial extent of the forest removal, the competition between secondary species, and changes in the frequency of sporadic destructive events such as fires. Reports on this question range from secondary forests that match closely enough the primary forest structure to make no difference for climate to lateritic wastelands of little water-holding capacity.

For the sake of a specific modelling focus, it is convenient to assume conversion to a degraded grassland, a reasonable possibility, especially when forests are converted to pasture land. Studies of the regional hydrological balance of the Amazon (see, for example, Salati 1987) have established that at least half of the incident rainfall is evaporated or transpired back into the atmosphere providing water vapour for further rainfall. To the extent that this evapotranspiration depends on the forest canopy, one might anticipate reductions in evapotranspiration and increases in runoff with forest removal. However, this question can only be considered quantitatively through use of a three-dimensional global climate model (GCM) that models the land surface with sufficient realism to represent the roles of both forested and of deforested land. Such a study (Dickinson & Henderson-Sellers 1988) has indicated an important role for canopy aerodynamic roughness in determining evapotranspiration, runoff and surface temperature. However, analysis of a multi-year series of data from a micrometeorological tower near Manaus (Shuttleworth 1988*a*) indicates difficulties with the model of Dickinson & Henderson-Sellers and suggests a radically different perspective, that evapotranspiration over the tropical forest is controlled primarily by energy balance at this mid-continental site (see also Shuttleworth, this symposium) and that perhaps evapotranspiration would be modified only by changes in albedo. The intent of this paper is to use a comparison of data of monthly averages from our GCM simulations over the seasonal cycle with the observations of Shuttleworth to highlight aspects of the GCM that appear to need improvement, and by combining the results of the GCM with the observations to help clarify current understanding of possible climatic consequences of tropical deforestation.

2. Summary of past modelling studies

Many past GCM modelling studies have indicated a considerable sensitivity of regional climate to surface processes controlling net radiation and the fluxes of moisture, heat and momentum (e.g. as reviewed by Mintz (1984)). However, the specific role of forests or the effects of their removal is still inadequately known; relatively little attention has been given to this question, and our understanding as to what processes are important in answering it has been limited.

Two past studies have specifically addressed the impact of removing the Amazon forest. Henderson-Sellers & Gornitz (1984) did such a study with the Goddard Institute for Space Studies GCM. Their model had no specific parameterization for vegetation, but represented its role simply through prescription of albedo, surface-roughness and the water-holding capacity of a two-bucket soil-water model. The model rainfall patterns were fairly unrealistic and no attempt was made to analyse details of the model annual cycle over the Amazon. Their study found a decrease in rainfall by 15–20 mm per month and also decreases in evaporation and total cloud cover but little change in surface temperature.

Dickinson & Henderson-Sellers (1988) considered essentially the same question with the community climate model (CCM) of the National Center for Atmospheric Research (NCAR). They argued for the importance in such a study of including separate parameterizations of the foliage energy budget, the intercepted precipitation, and soil hydrology. Consequently, they used a detailed land process model, the 'Biosphere–atmosphere transfer scheme (BATS)' coupled to the CCM for their study of the impact of Amazon deforestation. Their CCM simulation showed changes over the deforested region in both surface temperature and hydrology. Surface temperature increased by several degrees, evapotranspiration decreased, and runoff increased.

To interpret better the results of the global model simulation, they also analysed stand-alone calculations with the BATS model, using prescribed atmospheric conditions. With these, they established that the BATS model gave more realistic water vapour fluxes than the GISS bucket model, both in diurnal means for drying out from a saturated soil or over the diurnal cycle of a dry day with the model run to steady state with periodically occurring rainy days.

Validation of models of the climatic impacts of tropical deforestation requires: (*a*) an adequately realistic simulation of atmospheric processes, especially those determining precipitation, solar and longwave radiation incident at the surface, and coupling between the surface and overlying column with regard to winds, temperature and humidity; and (*b*) an adequately realistic simulation of the role of surface processes, both with and without the forest, in terms of energy and water balance, especially with regard to albedo, surface roughness, and canopy and soil controls of evapotranspiration.

Traditionally, GCMS have been validated in terms of temperatures and winds away from the surface, radiative fluxes at the top of the atmosphere, and broad annual average patterns of precipitation. Surface conditions, except for sea level pressure patterns, have largely been ignored in validation of model outputs for two reasons, (*a*) lack of data and (*b*) concern for subgrid-scale biases in the data. However, as stated above, validation against observed surface conditions and processes is crucial for studying the climatic role of tropical forests. Thus a multiple parameter data set over an annual cycle, such as that of Shuttleworth (1988*a*), is extremely valuable for this purpose and should be carefully compared with corresponding model simulations.

3. COMPARISON OF MODELLED VERSUS OBSERVED ANNUAL CYCLE OF RAINFALL, NET RADIATION, TRANSPIRATION AND INTERCEPTION FOR MANAUS

The measurements of Shuttleworth (1988*a*) were taken near Manaus at 3° S and 60° W. The GCM study of Dickinson & Henderson-Sellers focused on the average from nine model grid points representing the region 0° S to 13.5° S and 50° W to 70° W. For consistency with that study, we continue to examine that region. The Manaus site is located in the North Central grid square of this comparison region. It should be representative of the comparison region during the wet season but during the dry season may perhaps be too wet because at that time there is a gradient of decreasing rainfall south of Manaus. The Dickinson & Henderson-Sellers study obtained a 13 month simulation by using the older version of the CCM (CCM0B), and the BATS model has been further improved since then. A three year control integration using the new CCM1 model and updated BATS is now available, so we compared output from the Manaus tower with both the 13 month simulation with CCM0B and a seasonal average of the three year CCM1 integration.

Figure 1 shows the precipitation from these two models compared with that of Shuttleworth (1988*a*). All the records show the same general pattern of seasonal cycle but the CCM0, in particular, is rainier during the wet season and less rainy during the dry season than indicated by the data. The CCM1 shows somewhat less rainfall during the wet season but somewhat more during the dry months. The differences between the three curves are within the range of interannual variability for rainfall indicated by figure 2 of Shuttleworth (1988*a*). However, the changes between the two models could exceed the natural variability of the model averaged over the region represented by the nine grid squares as indicated by the differences between individual years of the CCM1 simulation.

Figure 2 compares evapotranspiration. Both models show excessive values compared with Shuttleworth's data, with CCM0B showing essentially twice as much as that measured. Does this imply that the surface model is removing more energy than made available by solar radiation? The answer is no. Figure 3 shows net radiation and figure 4 shows the difference between net radiation and evapotranspiration. This comparison identifies a large overestimate by the CCM

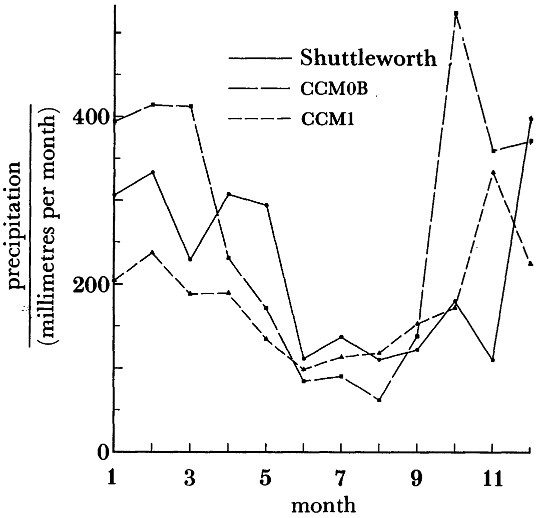

FIGURE 1. Monthly precipitation observed by Shuttleworth (1988*a*) and from older (CCM0B) and newer (CCM1 versions of the NCAR community climate models (CCM1 both with the BATS surface package). Shuttleworth's data go from September 1983 to the end of September 1985, CCM0B spans 13 months with two January series, and CCM1 includes three years of model output. All months with multiple data were averaged.

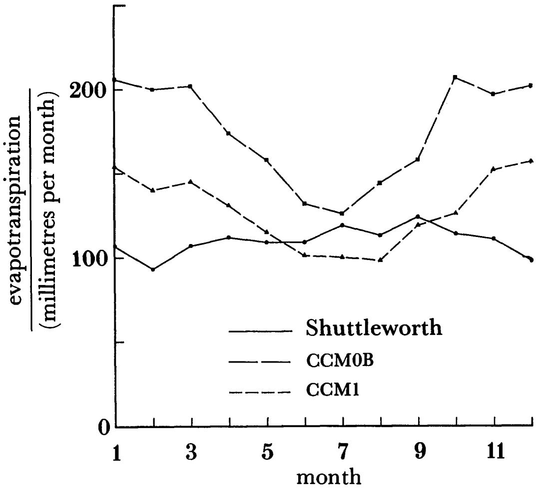

FIGURE 2. As in figure 1 but for evapotranspiration.

of net downward radiation as the primary reason for the discrepancy. This excess net radiation is largely the result of too much incident solar radiation; model albedos and net longwave fluxes are apparently not unreasonable. It is remarkable that with a separation of four years of active model development, both versions of the CCM give such similar seasonal cycles of net radiation. Indeed, in considering figure 4, it can be seen that the evapotranspiration is not out of line with the net radiation: during the very wettest months of CCM0B, there is a slight excess of evapotranspiration over net radiation, but the CCM0B over an annual average is not far from the observed difference. Perhaps more worrisome is the larger difference from observations shown in the CCM1 simulation. However, this discrepancy, in part, must be a consequence of the relatively low rainfall of the CCM1 wet season together with its large excess of net radiation.

There are several features of the BATS canopy model that may significantly exaggerate the

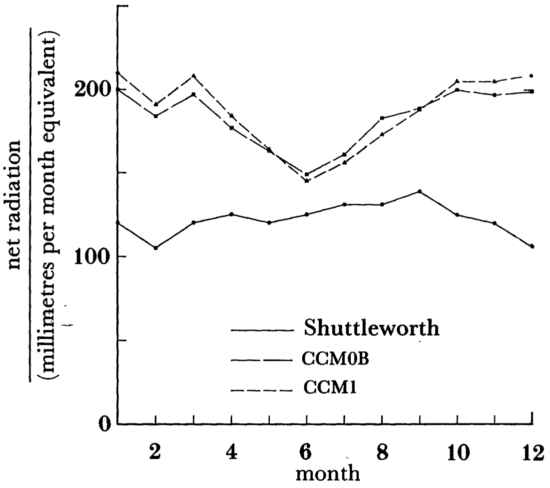

FIGURE 3. As in figure 1 but for net radiation (absorbed solar radiation and downward longwave minus upward longwave), expressed in units of equivalent water flux.

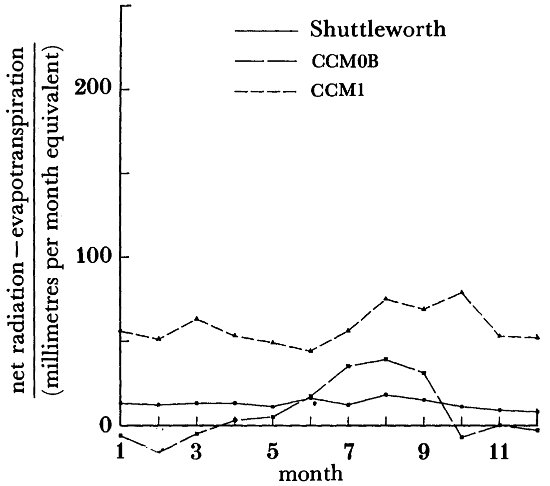

FIGURE 4. The difference between the net radiation of figure 3 and the evapotranspiration of figure 2.

amount of rainfall intercepted. First, the water holding capacity of the foliage must be considered. A capacity of 0.2 mm per leaf area has been assumed. The model tropical forest has a leaf-area index of 6 and assumes 0.9 of a grid square covered by vegetation or 1.08 mm total water capacity compared with the 0.74 mm reported by Shuttleworth (1988*a*) for the Amazon site. A potentially more serious source of model error is the neglect of spatial variability, which effectively greatly reduces the water holding capacity of the foliage over a model grid square (Shuttleworth 1988*b*). Finally, the model formulation for convective rainfall assumes a maximum of 0.30 cloud cover to allow for the spatial variability of convective processes, in so far as they affect clouds. However, this cloud prescription has the undesirable side effect of providing at least 0.70 clear sky (sunny) conditions during tropical rainfall, and hence an exaggerated supply of radiative energy to drive interception. The comparison of modelled and observed interception in figure 5 indeed shows a large model overestimate of interception loss, with the largest values of CCM0B being nearly twice that observed, and those of CCM1 being up

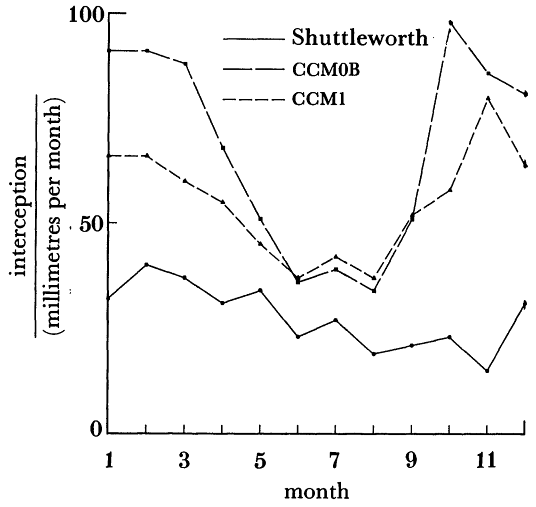

FIGURE 5. Interception defined as the difference between precipitation incident on top of canopy and precipitation reaching the ground. BATS model includes in this term (small and with negative sign) the contribution of dew dripping from the foliage.

to 50% too large. This model bias is not out of line with the model bias towards excess solar radiation, in general, and excess solar radiation during rain events, in particular. Thus the effect of the error in effective water holding capacity of foliage, although probably present, is not clearly distinguishable in this comparison. Finally, figure 6 compares the difference between evapotranspiration and interception loss. This term should largely represent the canopy transpiration. Here, the CCM0B exceeds that observed over most months and by up to 50 mm during the peak wet season. It comes close to Shuttleworth's data during the dry season. By contrast, CCM1 is close to Shuttleworth's data during the wet season but is less by up to 50 mm during the dry season.

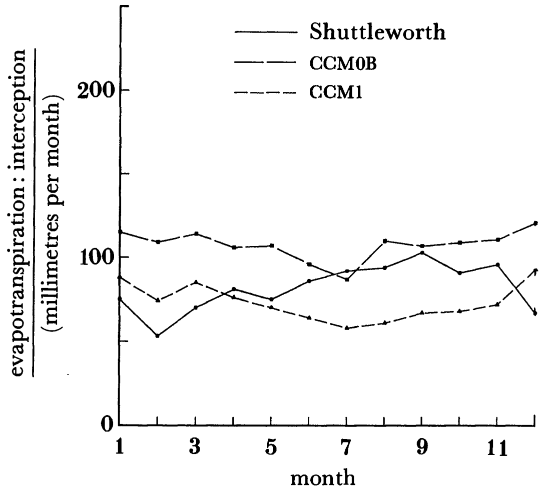

FIGURE 6. The difference between figure 2 and figure 5, representing mostly canopy transpiration but also some soil evaporation. The latter is negligible at the Manaus site because of the dense forest canopy, but in the CCM, 0.1 of the model area is assumed unshaded by vegetation.

In conclusion, the transpirations of the two model simulations differ more from each other than from the data of Shuttleworth. These differences are presumed to result from the large difference in rainfall over the Amazon region in the two simulations. The low CCM1 transpiration suggests the presence of water stress of the vegetation over much of the year. Such stress could be the result of the low rainfall and excess radiation but also may in part result from an inadequate soil model, both in texture, as modified by biological processes, and in the depth to which forest roots can access soil moisture.

4. Discussion and conclusions

In comparing modelled surface fields over the Amazon with the measurements of Shuttleworth, a large excess of net radiation and of interception of precipitation in the model has been noted, especially during the rainy season. The excess radiation depends on atmospheric processes within the model, probably a deficiency of the model clouds and their radiation interaction. The assigned upper limit of 0.30 for cloud cover during convective rainfall may give excessive surface solar radiation over precipitating areas. The excess interception loss appears to follow closely the excess solar radiation, but presumably also results from inadequate treatments of subgrid scale rainfall, both with respect to its correlation with solar radiation and the consequent reduction in effective water holding capacity of the foliage. Except for the difficulties summarized above, the Dickinson & Henderson-Sellers (1988) study appears to have captured the role of the forest canopy with regard to regional evapotranspiration. Hence I still accept the results of that study as at least qualitatively correct. The overestimate of interception probably leads to an overestimate of runoff increases, but the overestimate of net radiation could reduce the runoff sensitivity. Also of concern is the possibility that the excess net radiation, by increasing the rate of evapotranspiration, would tend to amplify rainfall rates during the wet season and increase aridity during the dry season. A relatively low rate of evapotranspiration during the dry season, especially for the CCM1 model, suggests drought-stressed vegetation, in contrast to that observed. This possibility calls into question not only the model's treatment of surface runoff but also its assumed effective water-holding capacity of the soil. The latter depends on rooting depth and soil structure, both of which are poorly known.

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Discussion

P. G. **Jarvis** (*Department of Forestry and Natural Resources, University of Edinburgh, U.K.*). How sensitive is Dr Dickinson's big-leaf Penman–Monteith model to the net radiation, R_n? It seems to me that he needs to decompose the model and show the extent of its sensitivity to R_n, as he has parameterized it, before he can draw the conclusions he has about the discrepancy between his simulations and the data of Shuttleworth (1988*a*, *b*).

R. E. **Dickinson**. I agree that until such sensitivity studies are made, a strong connection between R_n and rainfall interception loss is not established quantitatively. In figure 15 of Dickinson & Henderson-Sellers (1988), we showed, for a prescribed atmosphere, the sensitivity of various surface fields to the parameters that change during deforestation, including that of the evapotranspiration, ET. In particular, a change of albedo from 0.12 to 0.19 decreased ET by about 10 W m^{-2}. Estimating that this increase in albedo is approximately equivalent to an increase in R_n of 20 W m^{-2}, I infer a 50 W m^{-2} over-estimate of evaporation from the 100 W m^{-2} excess in net radiation. This value is at the lower limit of the 50–100 W m^{-2} excess ET shown in figure 1. However, inclusion of atmospheric feedbacks generally increases the sensitivity of ET to solar radiation according to the well-known arguments of Jarvis and McNaughton. I will only know how to include these feedbacks in a satisfactory manner, and better establish sensitivity, with further GCM simulations still to be done.

J. L. **Monteith**, F.R.S. (*International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, India*). Dr Dickinson was fortunate to have Dr Shuttleworth's measurements to test his model against. Has he any feeling for the number of tests of this kind that are likely to be needed before the general circulation modellers can feel reasonably confident that they've got their surface conditions properly specified?

R. E. **Dickinson**. Ideally, such tests should be made over several sites and for a range of climatic conditions over each biome. This argument suggests the need for at least several dozen sites. At some fraction of these sites, questions of spatial variability and scaling up to model grid squares should be addressed quantitatively, as is being done in the HAPEX and FIFE programs.

J. A. **Clark** (*Department of Physiology and Environmental Science, University of Nottingham, U.K.*) Dr Dickinson's model and his experiments have been designed to test the future consequences of the (possible, and probable?) removal of tropical rain forest. Has he reversed the process, and 're-forested' North America and Europe? Some commentators have suggested that the clearance of forests by our ancestors may have caused climate change. His model could, therefore, be tested against estimates of change derived by palaeoclimatologists from pollen sequences: perhaps an unintentional testing experiment has already taken place?

R. E. **Dickinson**. I have not done such studies but I agree that they would be interesting, especially if the change in forest cover and plausible connections to climate response could be quantified. The question of Amazon forest removal has been addressed first because of the large size of the Amazon forest, and because of various arguments suggesting that climate may be more sensitive to change in surface energy fluxes in the tropics than elsewhere. This is evidenced in the importance of oceanic temperature anomalies which give the El Nino – Southern Oscillation phenomena.

T. A. Black (*Department of Soil Science, University of British Colombia, Canada*). What is the boundary condition for water flow at the bottom of the root zone? How important is it to make this realistic?

R. E. Dickinson. The boundary condition at the bottom of the root zone is given by the hydraulic conductivity evaluated for the given soil type and for the mean water density of the root zone.

D. A. Warrilow (*Meterological Office, Bracknell, U.K.*). Why did Dr Dickinson change the value of saturated hydraulic conductivity during deforestation?

R. E. Dickinson. The soil type was changed to make it more clay-like to decrease the saturated hydraulic conductivity. In reality, one would not expect the soil type to change quickly, if at all, but I wanted to simulate the effect of greater compaction, and hence the lower hydraulic conductivity, that results from forest removal and use of the land by grazing animals.