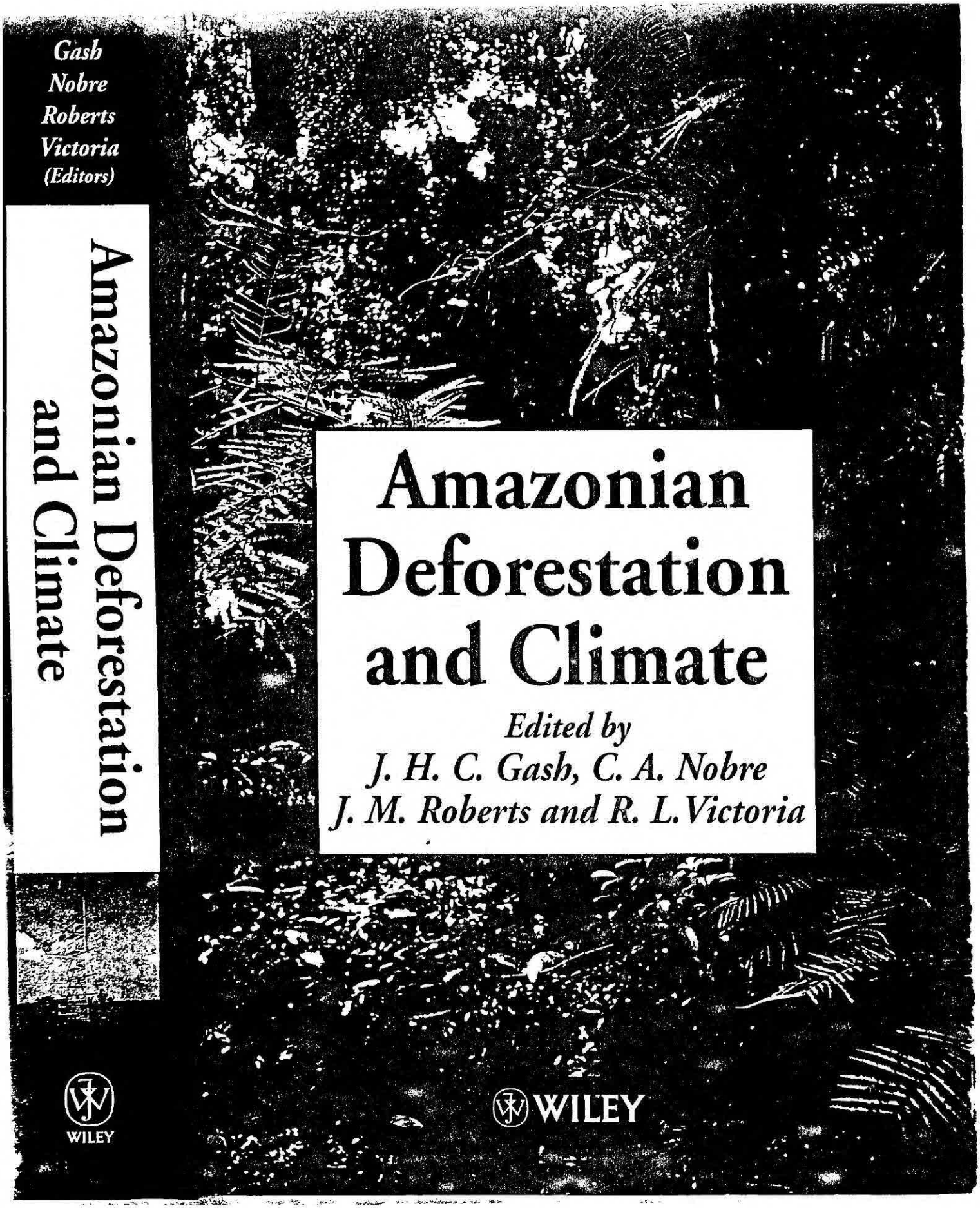


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Amazonian Deforestation and Climate

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# 31 The simulated impact of Amazonian deforestation on climate using measured ABRACOS vegetation characteristics

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## INTRODUCTION

In recent years a number of general circulation model (GCM) experiments have been conducted to assess the impact of complete removal of the South American tropical rainforest on climate. A summary of the most recent experiments is presented in Table 1 (an updated version from Pitman *et al.*, 1993). Differences in the specification of two important vegetation characteristics, albedo and roughness are given; the imposed increases in albedo ranges from 5% to 8% and the decreases in roughness from 0.76 to 2.57 m. Results vary widely between experiments: increases in surface temperature range from 0.1 to 2.3°C, decreases in precipitation from 15 to 640 mm $year^{-1}$ and decreases in evaporation from 25 to 500 mm $year^{-1}$. This study will address four key issues raised by an assessment of these experiments.

**The prescription of the land surface parameters in the forested and deforested scenarios** — the wide disparity in results may be partially explained by the large differences in the specification of vegetation and soil characteristics between experiments. The availability of extensive measurements taken during the ABRACOS field campaigns for paired sites of forest and cleared areas provides a major opportunity to introduce some consensus across the breadth of experiments. In this study measured ABRACOS values of vegetation characteristics are used where possible, to provide a more representative and accurate description of the forest and pasture within Amazonia in our model.

**The response to particular aspects of the deforestation scenario** — previous experiments have indicated that changes in albedo and roughness are important in determining the final deforested climate (Lean and Warrilow, 1989). Two companion experiments that include separate changes to albedo and roughness, from the forest to pasture values, allow clearer identification of the mechanisms involved in the

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response to complete removal of the forest.

**Sensitivity to the change in maximum infiltration capacity of the soil** — previous experiments have made changes in the maximum infiltration rate to represent the observed compaction of soil and consequent reduction in infiltration following deforestation (Wright *et al.*, 1996). This quantity has not been clearly defined from measurements and so an experiment in which all vegetation characteristics except the maximum infiltration capacity are changed from the forest to the pasture values is used to assess the impact of this change on the total deforested climate.

**Response to partial removal of the forest** - most previous Amazonian deforestation experiments have evaluated the response to total removal of the forest, a further experiment in which deforestation is confined to a more realistic reduced area is presented here.

## MODEL DESCRIPTION

The Hadley Centre model, the climate version of the Meteorological Office Unified Forecast/Climate GCM, used in these experiments, has been described in some detail by Jones *et al.* (1995). The atmospheric model has 19 layers, spaced unevenly in the vertical, to give optimum resolution in terms of pressure in the upper troposphere and stratosphere and in the boundary layer, in which there are five layers below 750 h Pa. The horizontal mesh is 2.5° latitude by 3.75° longitude, the same as used by Lean and Rowntree (1993) (called LR in this paper) in an earlier deforestation experiment.

The dynamics use a two-step Heun scheme for horizontal advection with fourth order accuracy, formulated in terms of total water (vapour plus liquid and frozen cloud water) and liquid water temperature (temperature adjusted to allow for the latent heat of cloud water and ice).

The physics of the model is similar to that of the model used by LR. The main differences may be summarised as:

- A four-layer soil hydrology scheme based on Richards's equation is used, with the same vertical layer depths as used by Warrilow *et al.* (1986) for thermal processes.
- Over the South American tropical forest region, stomatal resistance is computed as a function of atmospheric variables (solar radiation, vapour pressure deficit below saturation and temperature) and soil moisture as described by Dolman *et al.* (1991) for forest and Wright *et al.* (1995) for pasture.
- Cloud optical properties are computed as a function of the liquid and ice cloud water contents, with cloud assumed to be liquid for temperatures above 0°C, and ice below -15°C with mixed phase cloud in between.
- The convection scheme has been extended to include representation of a downdraught (Gregory and Allen, 1991).

**Table 1** Comparison of some recent GCM Amazonian deforestation experiments adapted from Pitman *et al.* (1993)

| | Dickinson and Kennedy (1992) | Henderson-Sellers *et al.*(1993) | Lean and Rowntree (1993) | Nobre *et al.* (1991) | Polcher and Laval (1994a) | Polcher and Laval (1994b) | Manzi (1993) | This expt. |
|---|---|---|---|---|---|---|---|---|
| Resolution<br>Surface | CCM1<br>4.5°x7.5°<br>BATS | CCM1-0Z<br>4.5°x7.5°<br>BATS | UKMO<br>2.5°x3.75°<br>Warrilow (1986) | NMC<br>1.8°x2.8°<br>SIB | LMD<br>2.0°x5.6°<br>SECHIBA | LMD<br>2.0°x5.6°<br>SECHIBA | EMERAUDE<br>2.8°x2.8°<br>ISBA | UKMO<br>2.5°x3.75°<br>Warrilow (1986) + interactive resistance + multilayer hydrology |
| Ocean | mixed layer model | mixed layer model | climatological SSTs | perpetual December SST | observed SSTs 1978-1988 | climatological SSTs | climatological SSTs | climatological SSTs |
| Length roughness length (m) | 3 years<br>2.0 / 0.05 | 6 years<br>2.0 / 0.2 | 3 years<br>0.8 / 0.04 | 1 year<br>2.65 / 0.08 | 11 years<br>2.3 / 0.06 | 1.1 years<br>no change | 4.2 years<br>2.0 / 0.06 | 10 years<br>2.1 /0.026 |
| albedo | 0.12 / 0.19 | 0.12 / 0.19 | 0.14 / 0.19 | 0.13 / 0.20 | 0.14 / 0.22 | 0.1 / 0.18 | 0.13 / 0.20 | 0.13 /0.18 |
| ΔT (°C) | +0.6 | +0.6 | +2.1 | +2.0 | +0.1 | +3.8 | +1.3 | +2.3 |
| ΔP (mm) | -511.0 | -588.0 | -295.7 | -640.0 | -186.2 | +394.0 | -15.0 | -157.0 |
| ΔE (mm) | -25.5 | -232.0 | -198.0 | -500.0 - | 127.8 | -985.0 | -113.0 | -295.7 |
| Change in moisture convergence | decreased | decreased | decreased | decreased | decreased | increased | increased | increased |

- The atmospheric boundary layer occupies up to five layers (about 2.5 km), depending on the position of the lowest statically stable layer. In unstable conditions, the increased vertical extent of turbulent eddies is accounted for by allowing non-local mixing (Smith, 1993).

## EXPERIMENT DESIGN

The following set of experiments was designed to give a more realistic portrayal of Amazonian deforestation and to provide a clearer indication of the mechanisms involved.

(1) FOREST - the control experiment - a ten-year, three-month experiment with vegetation parameter values for all points in South America defined as tropical rainforest in the model (see Figure 1) taken mostly from ABRACOS measurements of tropical rainforest.

(2) PASTURE - the deforested experiment - a ten-year, three-month experiment with vegetation parameter values for all points in South America to be deforested (see Figure 1) taken mostly from ABRACOS measurements of pasture.

(3) REDRGH - a five-year, three-month experiment as FOREST, except with roughness reduced from the FOREST value to the PASTURE value and all other vegetation characteristics unchanged.

(4) INCALB - a five-year, three-month experiment as FOREST, except with surface albedo increased from the FOREST value to the PASTURE value and all other vegetation characteristics unchanged.

(5) FIXINF - a five-year, three-month experiment as PASTURE, except the maximum infiltration capacity which was held constant at the value given for FOREST.

(6) HALF - a 10 year three month experiment as PASTURE except that only approximately half of the points were assumed to be deforested

Figure 1 shows the points on the 2.5° x 3.75° grid over South America that were defined as tropical forest. These points are based on the interpolation of the 1° x 1° grid of vegetation types as defined in the SiB model (Sellers *et al.*, 1986) with some alterations based on more recent observations. Those points that were deforested in the HALF experiment are shown. The reduced deforested area was selected on the basis of (i) the assessment of Brazilian deforestation by Skole and Tucker (1993) and (ii) Myers' (1991) national estimates of deforestation fractions for other South American countries. The resulting area includes most of the forests of Colombia, Ecuador and northern Peru in the northwest, and, in the south and east, those of southeastern Peru, northern Bolivia, and southern and eastern parts of the Brazilian Amazonia. Of the total of 66 forested points, 34, just over half, were assumed to be deforested. Figure 1 also shows the two regions that were chosen for analysis. Region 1 essentially encompasses the southern Amazon basin and corresponds most closely with the area used for analysis in LR. Region 2 represents northern Amazonia covering all points north of 1.25°N. Experiments were started at the beginning of

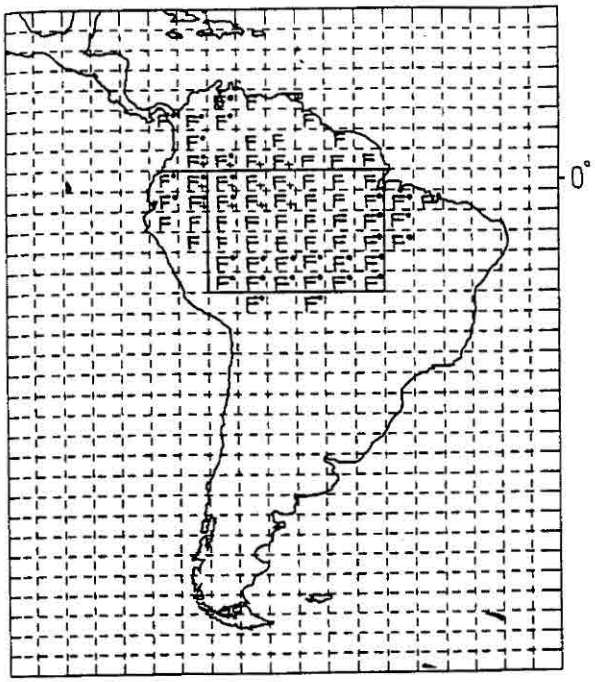



**Figure 1** Model grid for South America showing those points that are defined as forest (F) and replaced by pasture in the deforested scenario. Points marked with a solid circle are forest points that are replaced by pasture in the HALF deforestation experiment. Those points marked with a + are defined as having a constant albedo value all year. The box encompassed by solid black lines shows the southern area (Region 1) and all points north of 1.25°N the northern area (Region 2).

December from initial fields generated by a data assimilation scheme for that time of year. All results presented are averaged over the ten years of the experiment excluding the first three months.

Table 2 shows the vegetation and soil parameters for the FOREST and PASTURE simulations. The measured values of monthly-varying albedo as summarised by Culf *et al.* (1995) were used for those points that have their dry season (and highest albedos) in southern winter or spring and the seasonal cycle was reversed for points where the observed rainfall cycle is approximately opposite, namely most points north of the equator. An area of western Amazonia centred near the equator which effectively has no dry season (a dry season was arbitrarily defined as having less than 300 mm per three month season) was located, using the seasonal rainfall maps of Figueroa and Nobre (1990). For this region the lowest values of albedo (0.12 for FOREST and 0.17 for PASTURE) were assigned throughout the year. All vegetation parameters are for the forest and pasture site at Manaus except values for albedo which are averages over the forest and pasture sites at Ji-Paraná, Marabá and Manaus. Although field measurements have shown that root extraction occurs at depths greater than 3.5 m at all ABRACOS sites (Hodnett *et al.*, 1995), the rooting depth was limited to the maximum depth of soil (about 2.3 m) in the model.

At present only a few point measurements of soil parameters are available from the ABRACOS field campaigns and as variations in soil are apparent on much smaller scales than even vegetation characteristics it was decided that it was inappropriate to assume that these measurements could be taken as representative of the whole Amazon basin. Soil parameters were therefore taken from values given in our

standard model; these parameters vary across the basin with average values as given in Table 2. Most soil parameters were kept constant between the FOREST and PASTURE experiments except the ratio of saturated hydraulic conductivity at the surface relative to the subsurface soil. This was altered to correspond with observations of reduced infiltration due to compaction of the soil following deforestation (Wright *et al.* 1996).

**Table 2** Vegetation and soil characteristics used in the FOREST and PASTURE experiments

| Parameter | FOREST | | | PASTURE | | |
|---|---|---|---|---|---|---|
| | Month (south of equator) | | Month (north of equator) | Month (south of equator) | | Month (north of equator) |
| Albedo | Jan | 12.6 | Jul | Jan | 17.5 | Jul |
| | Feb | 12.3 | Aug | Feb | 17.1 | Aug |
| | Mar | 12.1 | Sep | Mar | 18.1 | Sep |
| | Apr | 12.4 | Oct | Apr | 18.4 | Oct |
| | May | 13.2 | Nov | May | 18.7 | Nov |
| | Jun | 13.9 | Dec | Jun | 18.6 | Dec |
| | Jul | 14.1 | Jan | Jul | 19.2 | Jan |
| | Aug | 14.4 | Feb | Aug | 18.7 | Feb |
| | Sep | 14.2 | Mar | Sep | 17.1 | Mar |
| | Oct | 14.3 | Apr | Oct | 17.1 | Apr |
| | Nov | 14.1 | May | Nov | 17.8 | May |
| | Dec | 13.4 | Jun | Dec | 18.0 | Jun |
| | Mean | 13.4 | | Mean | 18.0 | |
| Surface resistance (s $m^{-1}$) | Interactive | | | Interactive | | |
| Rooting depth (m) | 2.26 | | | 1.5 | | |
| Roughness (m) | 2.1 | | | 0.026 | | |
| Canopy capacity (mm) | 0.74 | | | 0.5 | | |
| Vegetation fraction (%) | 100 | | | 85 | | |
| Soil moisture conc. at wilting point | 0.047 | | | 0.047 | | |
| Soil moisture conc. at critical point | 0.113 | | | 0.113 | | |
| Soil moisture conc. at saturation point | 0.343 | | | 0.343 | | |
| Saturated hydraulic conductivity ($K_s$) (kg $m^{-2}$ $s^{-1}$) | 0.0026 | | | 0.0026 | | |
| B exponent used in hydraulic conductivity dependence on soil moisture | 3.98 | | | 3.98 | | |
| Heat capacity (J $K^{-1}$ $m^{-3}$) | 2.371 x $10^6$ | | | 2.371 x $10^6$ | | |
| Heat conductivity (W $m^{-1}$ $K^{-1}$) | 0.531 | | | 0.531 | | |
| Soil water suction (m) | 0.50 | | | 0.50 | | |
| Surface $K_s$ / subsurface $K_s$ | 1.5 | | | 0.3 | | |

## MODEL VALIDATION

The following section assesses the performance of the model's simulations of the climates of northern South America associated with both forest and pasture covered locations. Until now it has only been possible to compare with climatological and point measurements for undisturbed tropical rainforest (Shuttleworth, 1988) but if we want to improve the confidence we have in the modelled climate scenarios then it is vital to validate the climate associated with deforested sites as well. Measurements taken during the ABRACOS campaign described by Wright *et al.* (1992) and Bastable *et al.* (1993) provide realistic descriptions of the climate typical of cleared areas within the Amazonian rainforest. All model results are averaged over ten years with the first three months of the experiments excluded.

Figure 2 compares modelled rainfall with extensive climatological observations taken over a number of years (Figueroa and Nobre, 1990) for the southern hemisphere summer (December-February) and winter (June-August). Rainfall coverage and amounts over northern South America are well simulated by the model

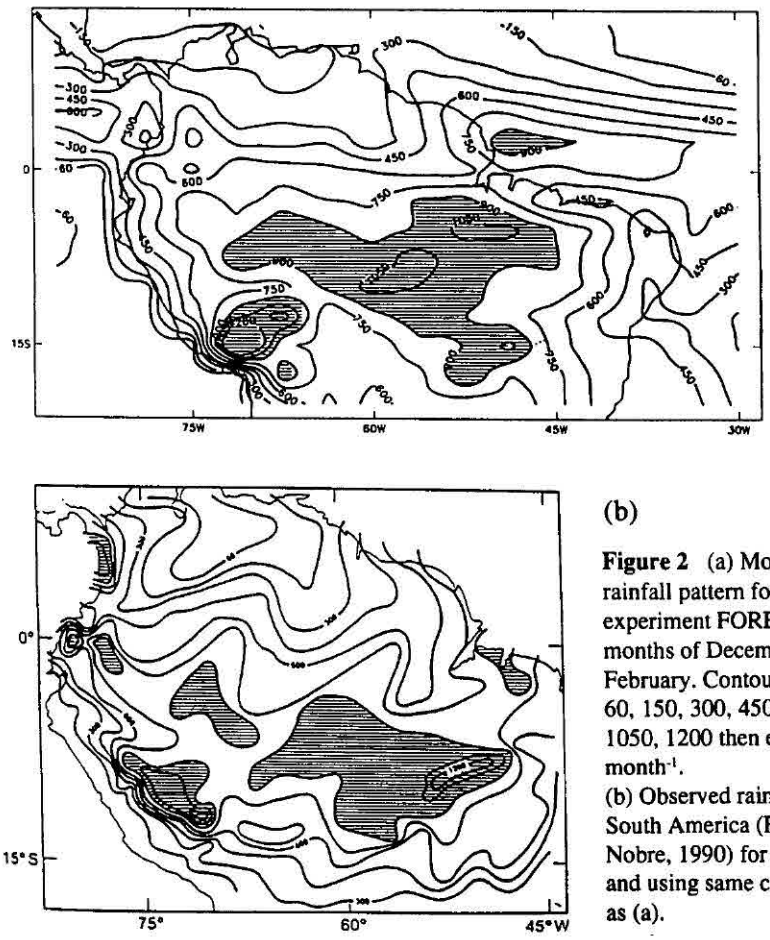
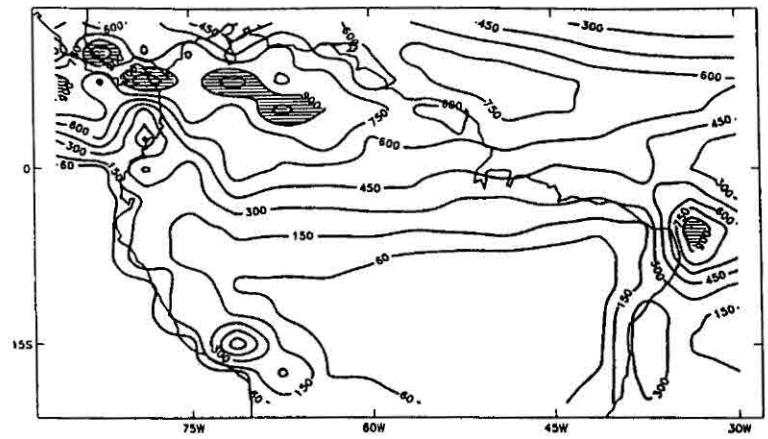



**Figure 2** (a) Modelled mean rainfall pattern for the control experiment FOREST for the months of December, January and February. Contours are at 0, 30, 60, 150, 300, 450, 600, 750, 900, 1050, 1200 then every 300mm month$^{-1}$.
(b) Observed rainfall pattern over South America (Figueroa and Nobre, 1990) for the same period and using same contour interval as (a).



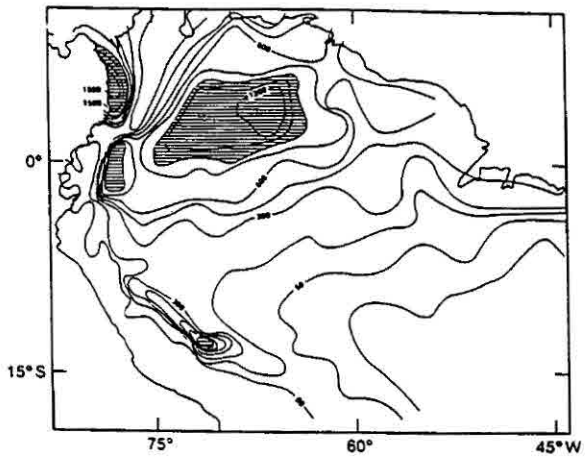




**Figure 2 contd.**
(c) As (a) but for June, July, August.
(d) As (b) but for June, July, August.

in both these seasons. The most notable deficiencies are that the model fails to emulate some of the high rainfall totals recorded in the more mountainous regions of Colombia, Ecuador and Peru. The simulations for the other two seasons (not shown) are equally realistic.

Modelled net radiation at the surface is overestimated by about 25%, in common with a number of other GCMs (Lean and Rowntree, 1993). As a result of this deficiency evaporation rates are overestimated and so to compare with observations it is more useful to normalise the evaporation rates by available net radiation at the surface. Figure 3 compares normalised evaporation, for both FOREST and the control experiment used by LR, with observations for Manaus. The new control shows a marked improvement in modelling evaporation in all months but especially so from July to October when the model previously suffered from an excessive limitation for dry periods. This more realistic simulation can be attributed to a combination of the new formulation of stomatal resistance and the increased rooting depth (previously a rooting depth of 1.27 m was used for forest) together with the

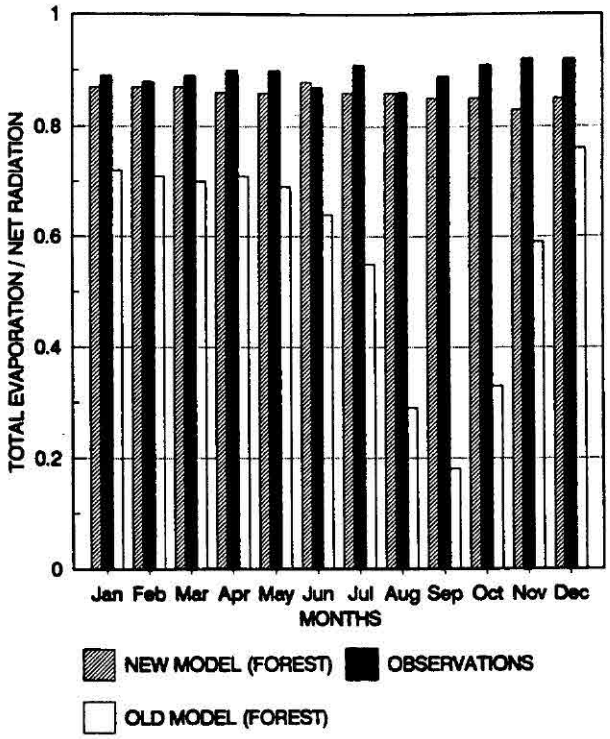



**Figure 3** Modelled monthly mean evaporation as a fraction of net radiation for a single gridpoint centred at 2.5°N 60°W, close to Manaus, for the current model and averaged over four gridpoints centred near Manaus for the old version of the model used by Lean and Rowntree (1993) compared with observations for Manaus (Shuttleworth, 1988).

implementation of the new multilayer hydrology scheme. Modelled interception accounts for 30% of the total evaporation over the year which agrees reasonably well with the value of 25% quoted by Shuttleworth (1988).

Wright *et al.* (1992) reported that during periods when there was negligible soil moisture limitation the observed evaporation rate for a pasture area was more comparable with the transpiration rate from the forest, but during dry periods evaporation rates were much lower. The model is able to reproduce this behaviour. The average reduction in evaporation from 4.0 to 2.8 mm $day^{-1}$ during the relatively dry months of July through to September agrees well with the magnitude of the change reported by Wright *et al.* from 3.8 to 2.1 mm $day^{-1}$ during the 1990 dry season.

Bastable *et al.*(1993) showed the much greater daily variation in climatic variables over clearings compared with those observed over forest. Figure 4 shows the daily cycle in modelled surface temperature for the gridpoint representative of the Manaus site, both with forest and with pasture cover. These values can be compared with measurements of screen height temperature to judge performance although strictly

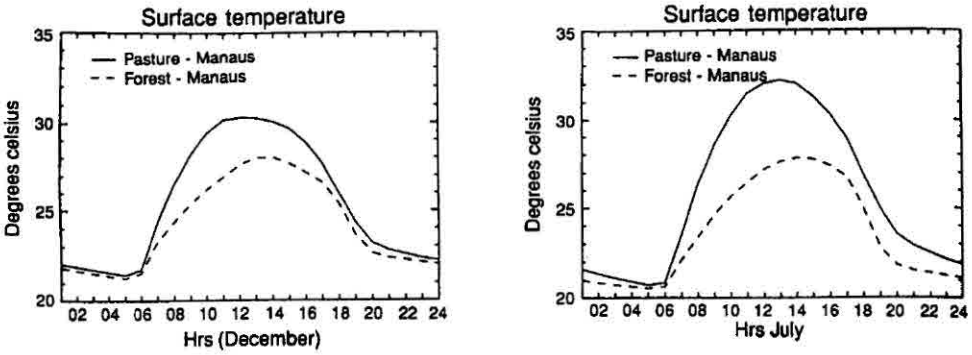



**Figure 4** Modelled hourly surface temperature over forest and pasture for December (left) and July (right).

these variables are not the same. Two months are illustrated: the first for December, typical of a wet month (Figure 4 - left), shows a difference in the diurnal range of 9.1°C for PASTURE and 6.9°C for FOREST which may be compared with the measured values for screen height temperature of 7.1°C and 5.3°C. In contrast, during the relatively dry month of July (Figure 4 - right) there is a much larger difference in diurnal range, 11.4°C for PASTURE and 7.3°C for FOREST compared with the measured values for screen height temperature of 12.7°C and 6.5°C. However, Bastable *et al.* showed that there was an increase in temperature during the day but a decrease in temperature at night over the clearing relative to the forest, whereas the model shows an increase during the day and night.

Bastable *et al.* also present an analysis of the surface radiation balance for the forest and cleared sites. Table 3 shows the modelled surface radiation components averaged over Region 1 for PASTURE and FOREST experiments.

**Table 3** Average daily radiation components at the surface for the FOREST and PASTURE experiments and the difference (PASTURE–FOREST) averaged over Region 1.

| Radiation component | FOREST ($W\ m^{-2}$) | PASTURE ($W\ m^{-2}$) | PASTURE–FOREST ($W\ m^{-2}$) |
|---|---|---|---|
| Solar downward | 223.9 | 233.7 | +9.8 |
| Solar upward | 29.6 | 41.8 | +12.2 |
| Net solar | 194.3 | 191.9 | -2.4 |
| Longwave downward | 404.2 | 407.5 | +3.3 |
| Longwave upward | 441.5 | 456.3 | +14.8 |
| Net longwave | -37.3 | -48.7 | -11.4 |
| Net surface | 157.0 | 143.2 | -13.8 |

In line with the results presented by Bastable *et al.* the difference in the longwave radiation balance makes a large contribution to the difference in the surface net radiation. The longwave radiation balance is influenced by changes in surface temperature and cloudiness. Higher surface temperatures dominate the change in the longwave balance leading to increased longwave cooling from the surface. Increased albedo results in a large increase in the amount of solar radiation that is reflected at the surface. This is largely offset in the model by increased incoming solar radiation as a result of reduced cloudiness; this cloudiness change would not be expected in the observations from the paired sites described by Bastable *et al.*, 1993. because of the very different scale of the forest clearance at their site.

We have shown that the model is able to reproduce the important features of the climate of Amazonia associated with both forested and cleared sites for time scales which range from diurnal to the seasonal.

## RESULTS

This presents the results from ten-year averages of the FOREST, PASTURE and HALF experiments and five-year averages of INCALB, REDRGH and FIXINF which exclude the first three months when the initial conditions are likely to be influencing results. These relatively long simulations (see Table 1) allow a more confident assessment of the statistical significance of the results. The null hypothesis that is put forward is that there has been no change in, for example, rainfall due to deforestation. Student's t statistics for the difference between the annual mean rainfalls for the PASTURE and FOREST experiments are then calculated, using the rainfall data averaged over each year from each experiment. For the ten-year (five-year) experiments the number of degrees of freedom is 18 (8) and hence for a 95% confidence level requiring 2.5 % in each tail, a test for t less than -2.101 (-2.306) or greater than +2.101 (+2.306) is performed. If this criterion is met then the null hypothesis is rejected and it can be concluded that deforestation is responsible for the change in rainfall at the 95% level of confidence. Regional maps are shown with changes significant at the 95% and 99% level of confidence delineated.

### TOTAL DEFORESTATION EXPERIMENT

Table 4 summarises the main changes to the climate of Region 1 brought about by clearance of the forest.

In broad terms results are similar to previous experiments reported by LR with reductions in evaporation and rainfall and an increase in surface temperature. The most notable difference is that the reduction in evaporation of 0.81 mm $day^{-1}$ is partially compensated by increased moisture convergence, resulting in a smaller reduction in rainfall of 0.43 mm $day^{-1}$. This is contrary to results from most previous deforestation experiments but agrees with Polcher and Laval (1994b) and Manzi (1993) — see Table 1.

**Table 4** Comparison of Climate Variables for the FOREST and PASTURE experiments and the difference (PASTURE–FOREST) averaged over Region 1 for this experiment and from Lean and Rowntree (1993) (LRPAS–LRFOR).

| Variable | FOREST | PASTURE | PASTURE–FOREST | LRPAS–LRFOR |
|---|---|---|---|---|
| Total evaporation (mm day$^{-1}$) | 4.32 | 3.51 | -0.81 (-19%) | -0.55 (-24%) |
| Interception (mm day$^{-1}$) | 1.56 | 1.07 | -0.49 (-31%) | -0.08 (-10%) |
| Rainfall (mm day$^{-1}$) | 6.56 | 6.13 | -0.43 (-7%) | -0.81 (-14%) |
| Moisture convergence (mm day$^{-1}$) | 2.24 | 2.62 | +0.38 (+17%) | -0.26 (-8%) |
| Soil moisture (mm) | 346.0 | 150.4 | -195.60 (-57%) | -87.9 (-65%) |
| Total runoff (mm day$^{-1}$) | 2.21 | 2.60 | +0.39 (+18%) | -0.2 (-6%) |
| Surface runoff (mm day$^{-1}$) | 0.52 | 2.22 | +1.70 (+327%) | +0.47 (+27%) |
| Net radiation (W m$^{-2}$) | 157.0 | 143.2 | -13.80 (-9%) | -18.5 (-13%) |
| Sensible heat (W m$^{-2}$) | 31.9 | 41.6 | +9.70 (+30%) | -2.9 (-4%) |
| Latent heat (W m$^{-2}$) | 125.0 | 101.6 | -23.40 (-19%) | -15.8 (-24%) |
| Velocity at level 1 (ms$^{-1}$) | 1.03 | 2.28 | +1.25 (+120%) | +1.03 (+44%) |
| Surface temperature (°C) | 23.8 | 26.1 | +2.3 | +2.3 |

Figure 5 shows monthly means for FOREST and PASTURE for southern Amazonia, Region 1 and northern Amazonia, Region 2 (see Figure 1). Evaporation shows substantial decreases throughout the year with the largest shortfalls occurring when soil moisture restricts evaporation. This is apparent from the large reduction in combined evapotranspiration and soil evaporation (shown as evapotranspiration on graph) at these times of year. Interception is reduced in all months. For southern Amazonia rainfall has decreased for all months but for northern Amazonia rainfall shows small increases as well as decreases; these are associated with regional variations which are discussed later. Increases in surface temperature are due partly to reduced evaporative cooling and partly to reduced surface roughness. Surface runoff is much higher in all months as a result of the imposed reduction in maximum infiltration rate at the surface. The largest increases coincide with times when rainfall is at a maximum and so the reduction in maximum infiltration rate can have the greatest impact. Subsurface runoff (defined as drainage from the bottom of the root zone) is less in all months because of the drier soil resulting from the increased surface

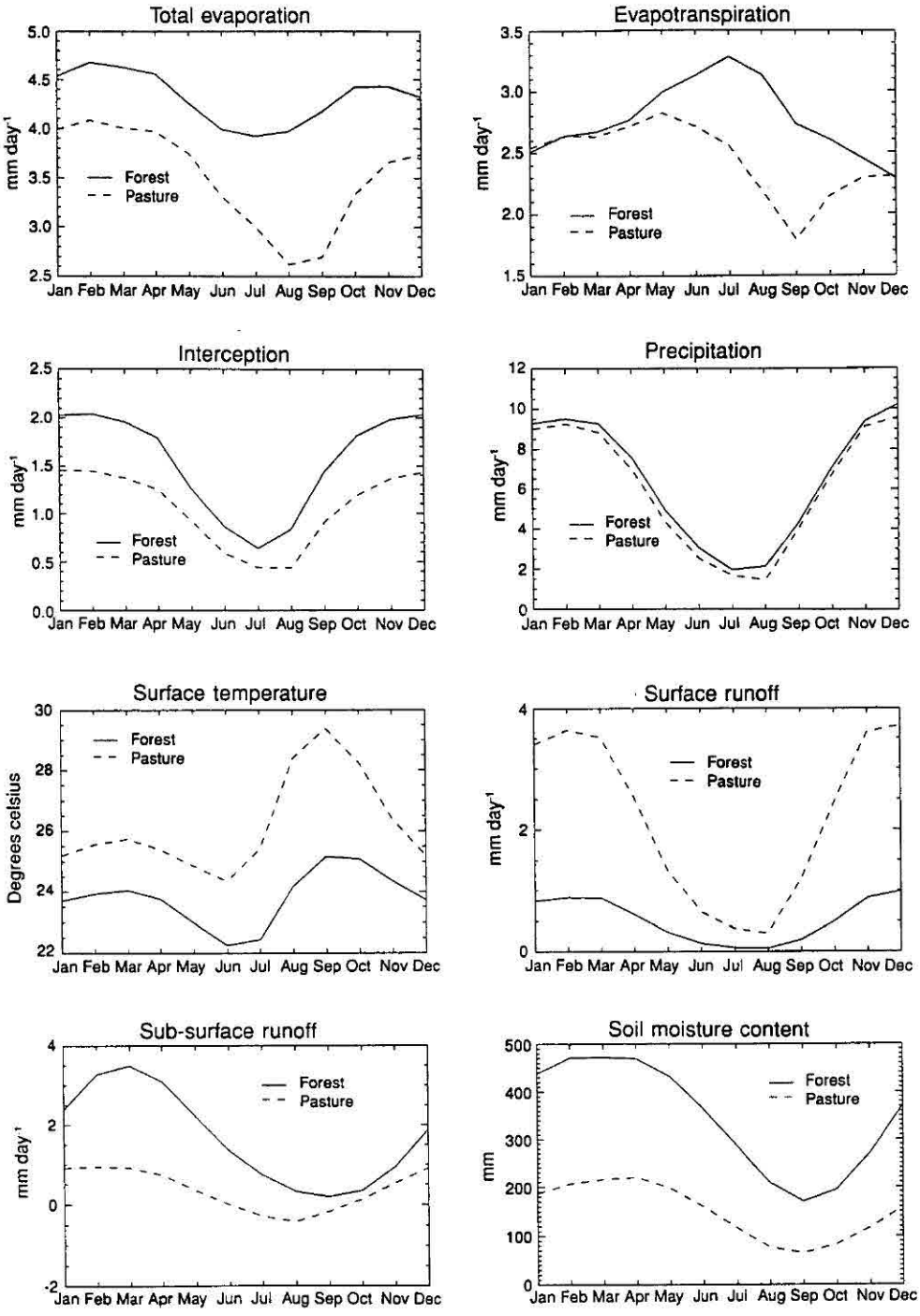



**Figure 5** Modelled monthly mean climate variables for southern Amazonia (Region 1) and for northern Amazonia (Region 2) (overleaf).

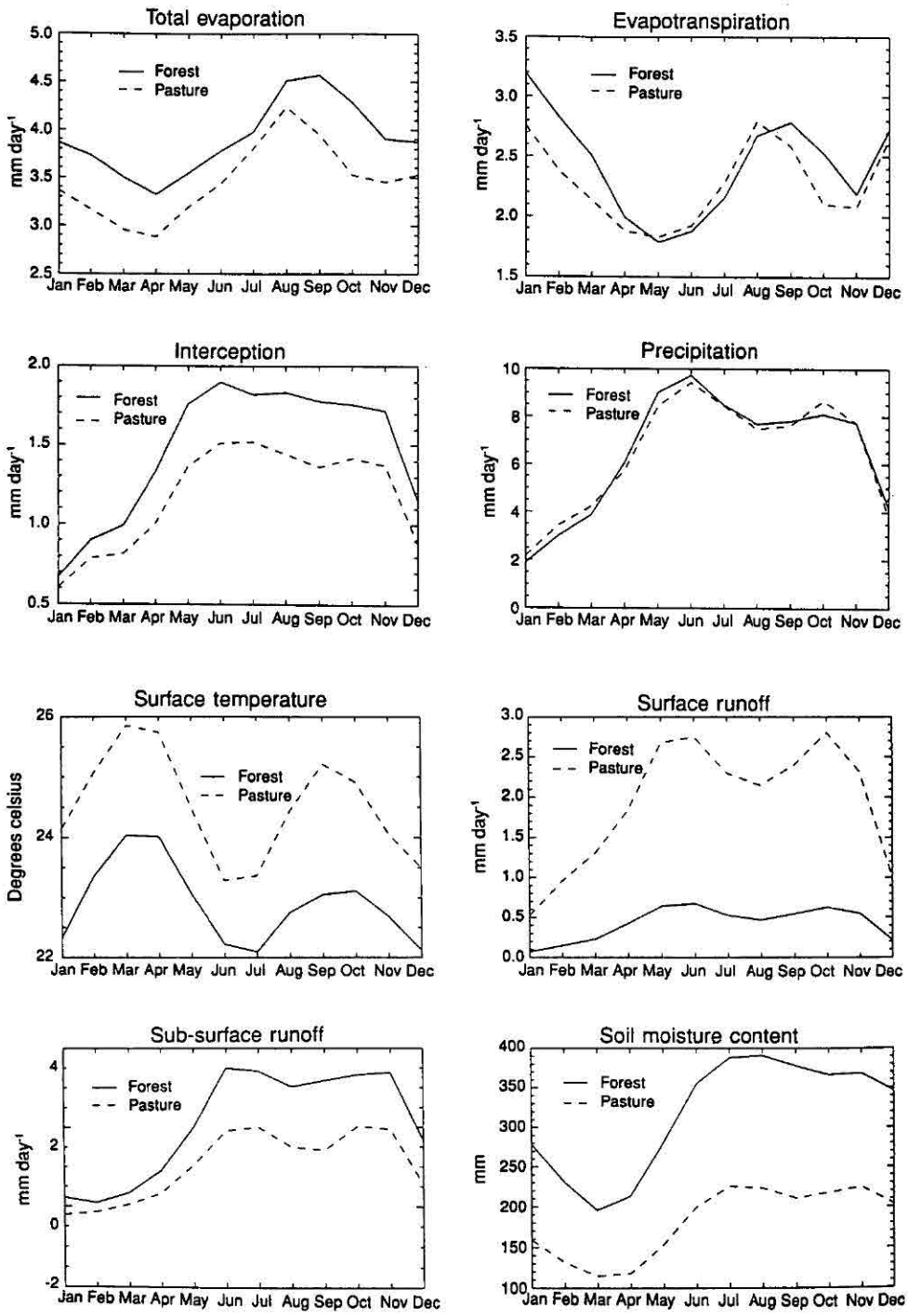



**Figure 5** (contd.)

runoff. During dry months soil moisture is drawn up from below the root zone as low rainfall and evapotranspiration at these times deplete the soil moisture within the root zone.

Figure 6 shows the annual spatial distribution of changes in rainfall, evaporation

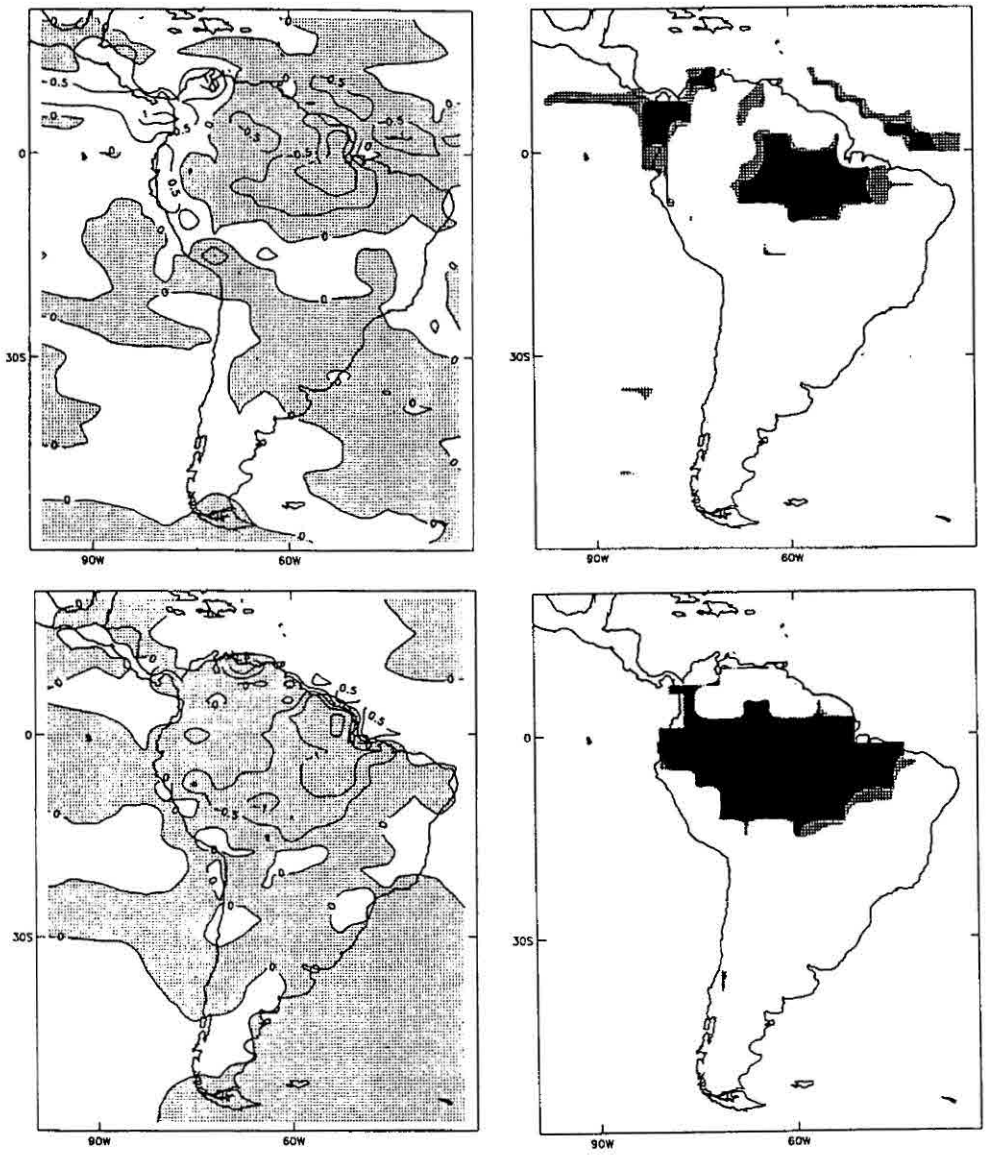



**Figure 6** (a) Modelled annual mean difference (PASTURE–FOREST) in rainfall. Contours are at 0.0, ±0.5, 1.0 and then every 1.0 mm day$^{-1}$ with areas of decrease shaded. (b) Student's t fields showing changes in rainfall that are locally significant at the 95% (cross-hatched shaded areas) and 99% (solid shaded areas) confidence levels. (c) As for (a) except for evaporation. Contours are at 0.0, ±0.5, 1.0 and then every 1.0 mm day$^{-1}$ with areas of decrease shaded.
(d) As for (b) except for evaporation.

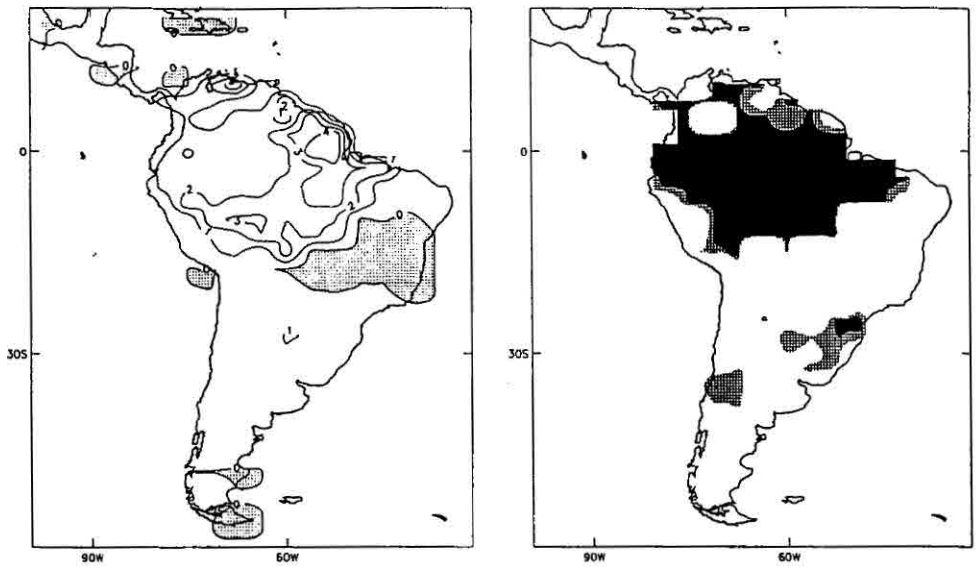



**Figure 6** (contd.) (e) As for (a) except for surface temperature. Contours are at 0.0, ±0.5, 1.0 then every 1°C with areas of decrease shaded. (f) As for (b) except for surface temperature.

and surface temperature together with the statistical significance. Decreases in rainfall cover most of the deforested area. Maximum decreases of over 1 mm day$^{-1}$ or up to about 20% of the FOREST rainfall are located near the mouth of the Amazon and show a high level of significance. This is in contrast to results shown by LR where the maximum decreases coincided with the areas of maximum rainfall. There are significant increases over the coastal regions of northwestern South America including some deforested gridboxes. Decreases in evaporation cover most of northern South America with statistically significant decreases over most of the deforested area. Reductions reach 1 mm day$^{-1}$ in the southern part of the basin which is most strongly influenced by the low rainfall in June, July and August allowing the soil to dry and so restrict evapotranspiration. Statistically significant increases in surface temperature cover almost the whole of the deforested area with maximum increases of over 3°C. These maxima broadly coincide with the maximum reductions in evaporation.

As already stated, the notable difference from most previous deforestation scenarios is the overall increase in annual moisture convergence so this merits closer examination. Figure 7 shows the average monthly mean differences (PASTURE–FOREST) in rainfall, evaporation and the moisture convergence (represented as rainfall minus evaporation) for Region 1. This shows that moisture convergence increases through most of the year with the largest increases taking place from July through to November. This indicates that moisture is flowing into the basin in response to the increased drying during this period. The associated changes in the horizontal velocity potential and divergent wind field at about 200 m above the

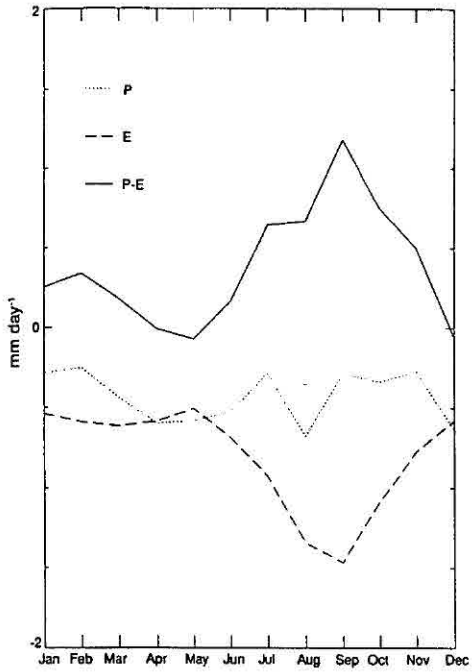



**Figure 7** Modelled monthly mean difference (PASTURE–FOREST) in rainfall (P), evaporation (E) and moisture convergence (P–E).

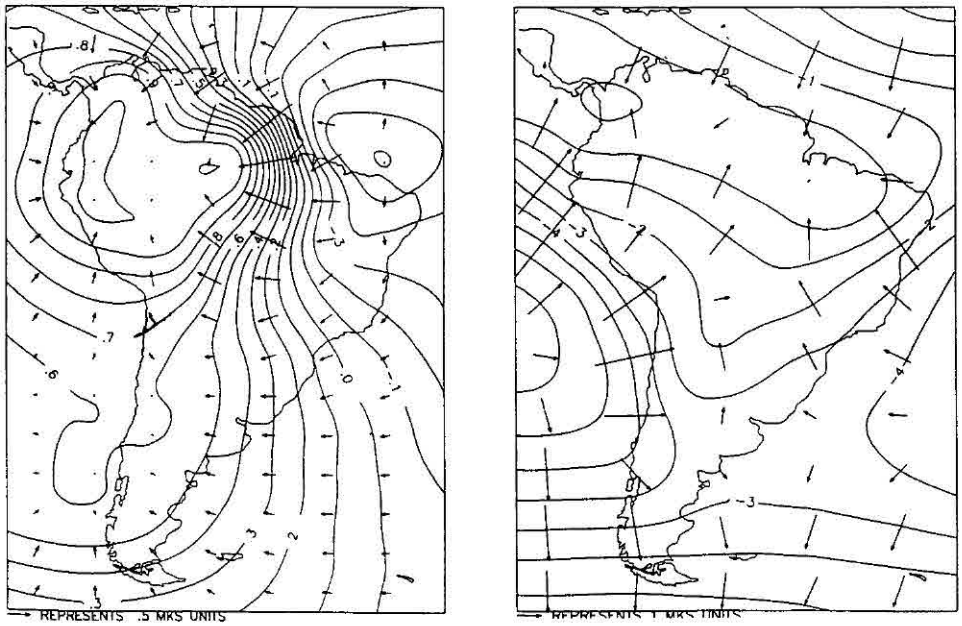


**Figure 8** (a) Modelled annual mean difference (PASTURE–FOREST) in velocity potential and divergent wind field at about 200 m (model level 2) over South America. Contours are every $0.1\times10^6\,m^2\,s^{-1}$. (b) Modelled annual mean FOREST velocity potential and divergent wind field at about 200 m (model level 2) over South America. Contours are every $1.0\times10^6\,m^2\,s^{-1}$.

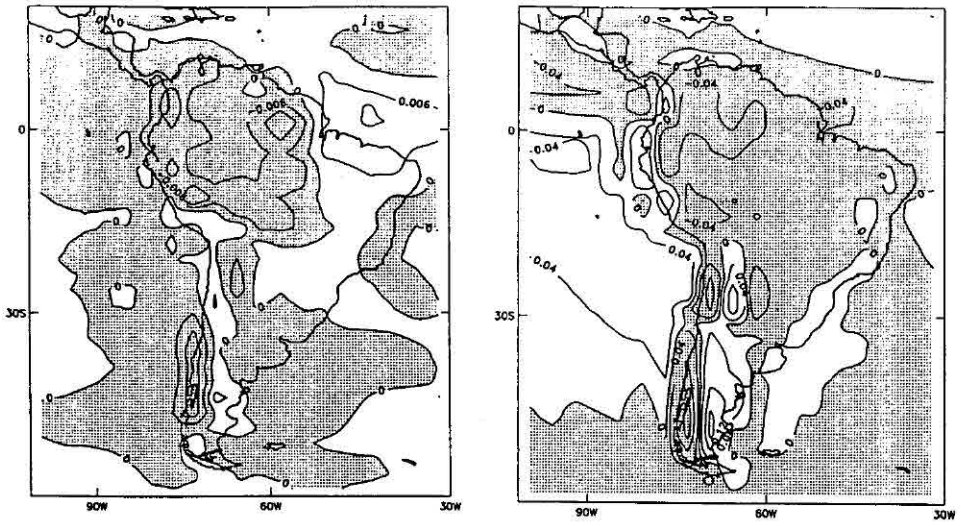



**Figure 9** (a) Modelled annual mean difference (PASTURE - FOREST) in vertical velocity at 700 hPa. Contours every 0.006 hPa $s^{-1}$. Negative areas are shaded and indicate increased ascent. (b) Modelled annual mean FOREST vertical velocity at 700mb. Contours at 0.0, ± 0.04, 0.12 and then every 0.08 hPa $s^{-1}$. Negative areas are shaded and indicate areas with ascent.

surface are shown in Figure 8. This clearly shows an increase in the convergence over western and central Amazonia, which extends up through the boundary layer (not shown). Figure 9 demonstrates that there is a corresponding increase in vertical velocity at 700 h Pa, well above the boundary layer. The impact on moisture convergence, velocity potential and vertical velocity is in agreement with the results shown by Polcher and Laval (1994b).

## COMPANION EXPERIMENTS

In this section results are presented from the set of companion experiments. Area means are averages over all deforested points to give a representative picture of the total changes within both northern and southern Amazonia.

## INCREASED ALBEDO EXPERIMENT

The increased albedo experiment INCALB has retained all the vegetation parameters as defined for FOREST except the surface albedo which has been increased to that of the PASTURE experiment - the average change over the year is +0.046. Table 5 compares some climate variables for the difference between INCALB and FOREST.

Comparing the difference (INCALB - FOREST) with the difference (PASTURE - FOREST), evaporation has decreased but by a much smaller amount. The change

**Table 5** Comparison of some climate variables for the FOREST experiment and the differences (PASTURE–FOREST), (INCALB–FOREST), (REDRGH–FOREST) and (FIXINF–FOREST) averaged over all deforested points.

| Variable | FOREST | PASTURE –FOREST | INCALB –FOREST | REDRGH –FOREST | FIXINF –FOREST |
|---|---|---|---|---|---|
| Total evaporation (mm day$^{-1}$) | 4.12 | -0.76 (-18%) | -0.14 (-3%) | -0.11 (-3%) | -0.3 (-7%) |
| Evapotranspiration (mm day$^{-1}$) | 2.61 | -0.31 (-12%) | -0.09 (-3%) | +0.02 (+1%) | +0.13 (+5%) |
| Interception (mm day$^{-1}$) | 1.51 | -0.45 (-30%) | -0.05 (-3%) | -0.14 (-9%) | -0.43 (-28%) |
| Rainfall (mm day$^{-1}$) | 6.40 | -0.27 (-4%) | -0.46 (-7%) | +0.46 (+7%) | -0.3 (-5%) |
| Moisture convergence (mm day$^{-1}$) | 2.28 | +0.49 (+22%) | -0.32 (-14%) | +0.57 (+25%) | 0.0 |
| Soil moisture (mm) | 351.4 | -186.4 (-53%) | -21.9 (-6%) | +23.6 (+7%) | -103.5(-29%) |
| Total runoff (mm day$^{-1}$) | 2.24 | +0.51 (+23%) | -0.44 (-20%) | +0.45 (+20%) | +0.0 3(+1%) |
| Subsurface runoff (mm day$^{-1}$) | 1.76-1.17 (-66.5%) | | -0.38 (-22%) | +0.48 (+27%) | +0.15 (+9%) |
| Surface runoff (mm day$^{-1}$) | 0.48 | +1.68 (+350%) | -0.06 (-13%) | -0.03 (-6%) | -0.13 (-27%) |
| Net radiation (W m$^{-2}$) | 153.0 | -12.7 (-8%) | -5.35 (-4%) | -3.91 (-3%) | -10.2 (-7%) |
| Sensible heat (W m$^{-2}$) | 33.77 | +9.31 (+28%) | -1.42 (-4%) | -0.70 (+2%) | -1.51(+5%) |
| Latent heat (W m$^{-2}$) | 119.21 | -22.0 (-18%) | -3.87 (-3%) | -3.20 (-3%) | -8.68 (-8%) |
| Horizontal velocity at level 1(m s$^{-1}$) | 1.17 | +1.23 (+105%) | +0.01(+1%)+1.14 (+97%) | | +1.17 (+100%) |
| Surface temperature (°K) | 296.29 | +2.27 | -0.09 | +1.30 | +1.38 |

in evaporation is driven by the decrease in available energy at the surface. This decrease is much reduced compared with the total deforestation experiment as there is little change in surface temperature, and in the longwave energy balance. The reductions in rainfall and moisture convergence are substantial. There is a small mean decrease in surface temperature.

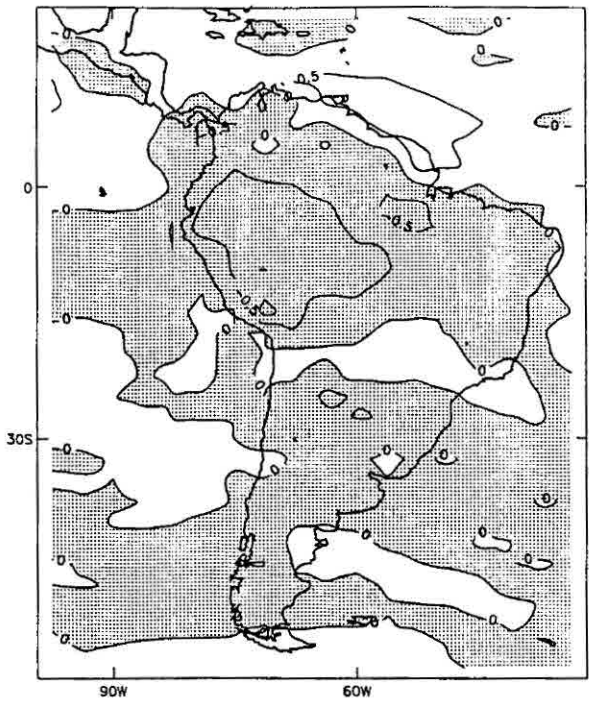



**Figure 10** Modelled annual mean difference (INCALB–FOREST) in rainfall. Contours are at 0.0, ±0.5, 1.0 and then every 1.0 mm day$^{-1}$ with areas of decrease shaded.

Figure 10 shows the annual mean change in rainfall and is to be compared with changes in the total deforestation experiment (Figure 6). Decreases are more widespread than in the total deforestation experiment although maximum reductions are less. Areas of maximum reduction tend to coincide with the location of rainfall maxima. Figure 11 shows the reduction in convergence at about 200 m above the surface. This reduction extends well up through the atmospheric column.

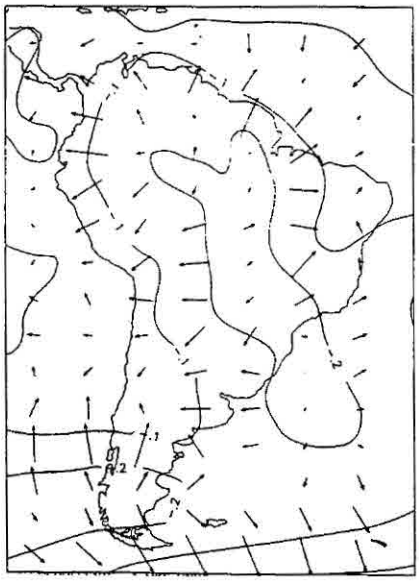


**Figure 11** Modelled annual mean difference (INCALB–FOREST) in velocity potential and divergent wind field at about 200 m (model level 2) over South America. Contours every $0.1\times10^6$ m$^2$ s$^{-1}$. See Figure 8(b) for control.

## REDUCED ROUGHNESS EXPERIMENT

The reduced roughness experiment REDRGH has retained all the vegetation parameters as defined for FOREST except the roughness length which has been reduced from the FOREST value of 2.1 m to the PASTURE value of 0.026 m. Table 5 compares some climate variables for the difference between REDRGH and FOREST.

Comparing the difference (REDRGH - FOREST) with the difference (PASTURE - FOREST), evaporation is reduced much less. Rainfall has increased, in contrast to the decrease in the total deforestation experiment and there is an even larger increase in moisture convergence. Surface temperature has risen but by a smaller amount; these increases are a result of the higher surface temperatures required to maintain the surface fluxes due to the reduced efficiency of the turbulent exchange of energy at the surface.

Figure 12(a) shows the annual change in rainfall and is to be compared with changes in the total deforestation experiment (Figure 6). There is a broad band of increase through central southern and western Amazonia with increases that are as large as the decreases in the total deforestation experiment. This NW-SE band of increase extends well outside the deforested area into southeastern Brazil. Both these increases and decreases to the north east of eastern Brazil are statistically significant (Figure 12(b)). The increased convergence at about 200m is shown in Figure 13. The increased moisture convergence resulting in increased rainfall can partially be explained by the stronger boundary layer winds with weaker frictional stress. Figure 14 shows that there is an increase of about 40% in wind speeds.

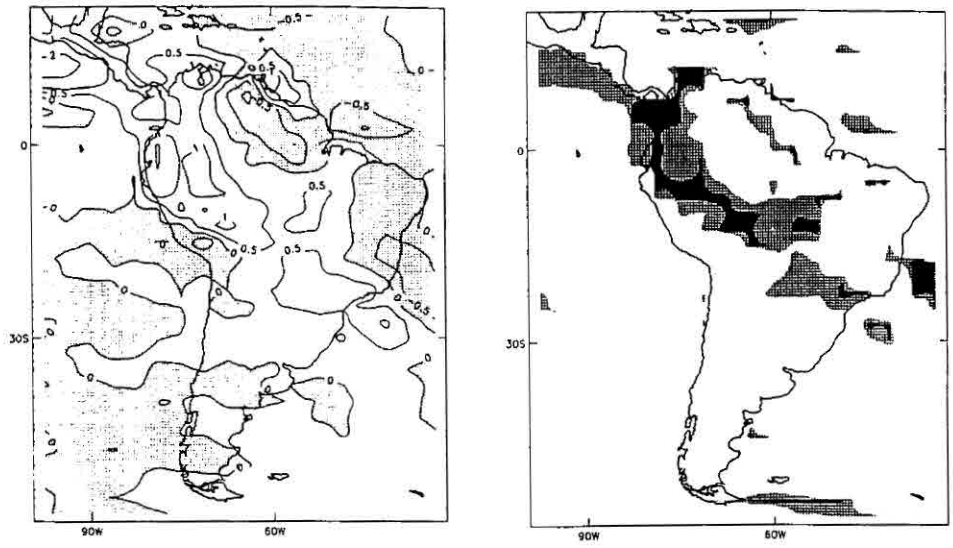



**Figure 12** (a) Modelled annual mean difference (REDRGH–FOREST) in rainfall. Contours are at 0.0, ±0.5, 1.0 and then every 1.0 mm day$^{-1}$ with areas of decrease shaded. (b) Student's t fields showing changes in rainfall that are locally significant at the 95% (cross hatched shaded areas) and 99% (solid shaded areas) confidence levels.

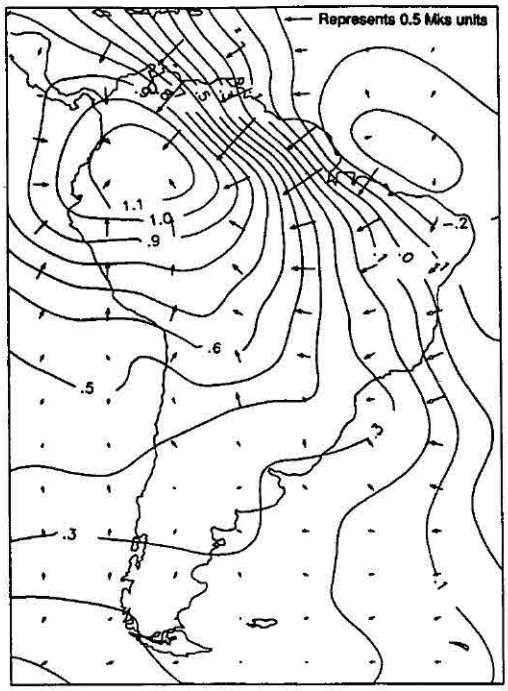



**Figure 13** Modelled annual mean difference (REDRGH–FOREST) in velocity potential and divergent wind field at about 200 m (model level 2) over South America. Contours every $0.1\times10^6$ m$^2$ s$^{-1}$. See Figure 8(b) for control.

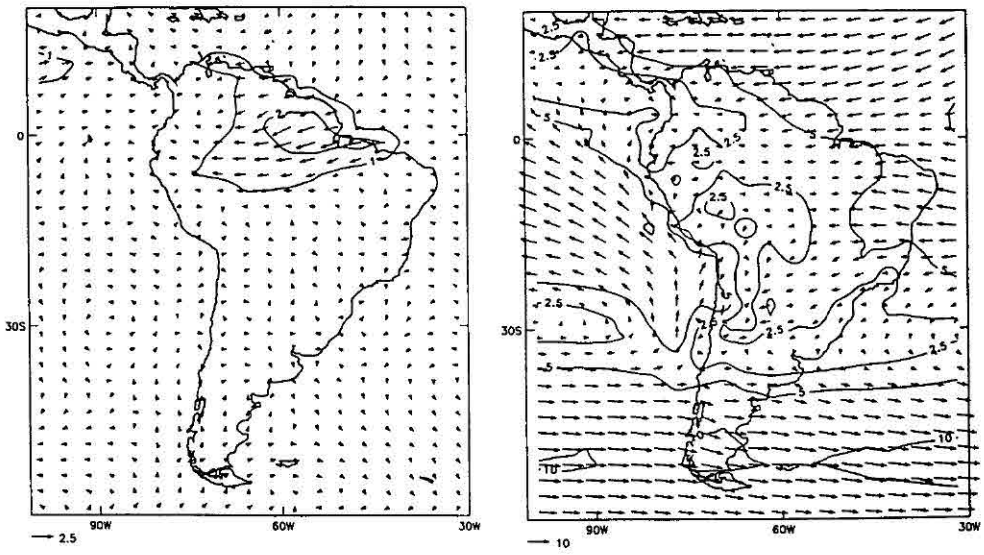



**Figure 14** (a) Modelled annual mean difference (REDRGH–FOREST) in winds at about 200 m (model level 2). Contours every 1 m s$^{-1}$. (b) Modelled annual mean FOREST wind at about 200 m. Contours at 0, 2.5, 5.0, 10 m s$^{-1}$.

## FIXED INFILTRATION RATE EXPERIMENT

The fixed maximum infiltration rate experiment FIXINF has all surface parameters modified to the PASTURE values except the ratio of saturated hydraulic conductivity at the surface relative to the subsurface soil which has retained the FOREST value of 1.5. Table 5 shows differences between FIXINF and FOREST.

Comparing the difference (FIXINF - FOREST) with the difference (PASTURE - FOREST), allowing more water to infiltrate into the soil results in a decrease in surface runoff compared with the very large increase in surface runoff in the total deforestation experiment. As more water infiltrates into the soil the reduction in soil moisture total is much less than in the total deforestation experiment (approximately half). Drainage is increased relative to FOREST as a result of the reduced rooting depth. The increases in total runoff and hence the loss of water from the system are less than in (PASTURE - FOREST). The most significant impact of this smaller reduction in moisture within the system is shown by the increase in evapotranspiration. Interception is reduced by similar amounts to those in the total deforestation experiment. Overall the reduction in total evaporation is less than half that in the total deforestation experiment. Surface temperature has increased but by a smaller amount, consistent with the smaller reduction in evaporation. Changes in rainfall are more closely related to changes in evaporation with no compensating increase in moisture convergence as in the total deforestation experiment. The increase in moisture convergence in the total deforestation experiment was largest during the dry seasons in response to the large reductions in soil moisture at these times. There is still a small increase in moisture convergence during these seasons in (FIXINF - FOREST) associated with the relative drying of the soil (not shown).

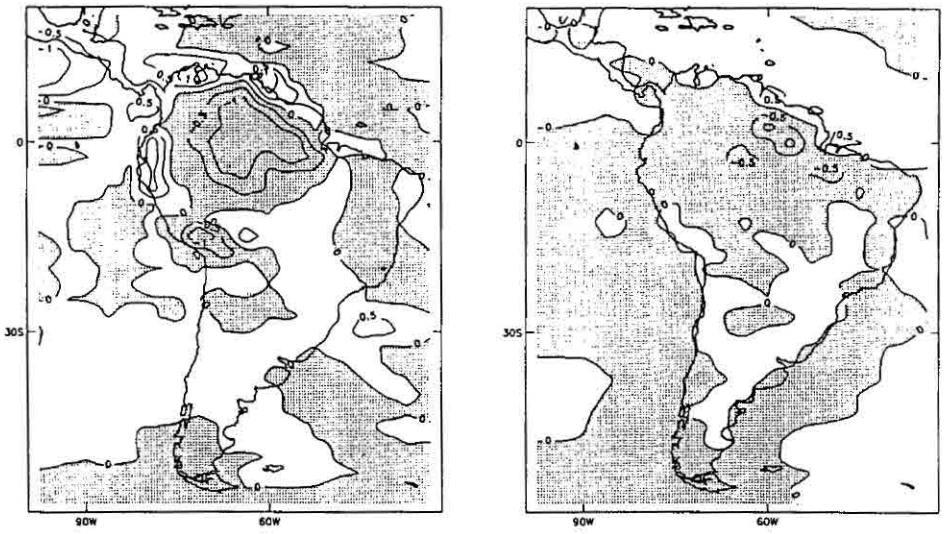



**Figure 15** (a) Modelled annual mean difference (FIXINF–FOREST) in rainfall. Contours are at 0.0, ±0.5, 1.0 and then every 1.0 mm day$^{-1}$ with areas of decrease shaded. (b) As for (a) except for evaporation.

Figure 15 shows the annual mean changes in rainfall and evaporation and is to be compared with changes in the total deforestation experiment (Figure 6). The area of maximum decrease in rainfall of more than 1 mm day$^{-1}$ is shifted towards the west and covers a much larger area. Reductions in evaporation cover most of northern South America but the large decreases in the southern part of the deforested area present in the total deforestation experiment are absent due to the retention of higher soil moisture levels during the winter months.

## HALF DEFORESTATION EXPERIMENT

In this experiment, the full set of deforestation changes including the reduction in maximum infiltration rate was applied to a reduced deforested area.

Figure 16 shows that the annual mean rainfall changes are similar in some respects to those from the total deforestation experiment. There are increases over western and southern regions of the original forested region, and decreases over most of the rest of northern South America. However, the largest decreases are not over the deforested region but over part of the remnant forest of central Amazonia. Further analysis will explain these patterns, one obvious feature is that the model's response is on a larger scale than in the relatively small deforested regions. It is interesting that the region of increases over Colombia and Ecuador coincides with that of statistically significant increases in observed rainfall deduced from trends in outgoing longwave radiance for 1974-90 by Chu *et al.* (1994). The evaporation changes (not shown) were much as expected on the basis of the total deforestation experiment, with widespread reductions in parts of the deforested region where there is a pronounced dry season.

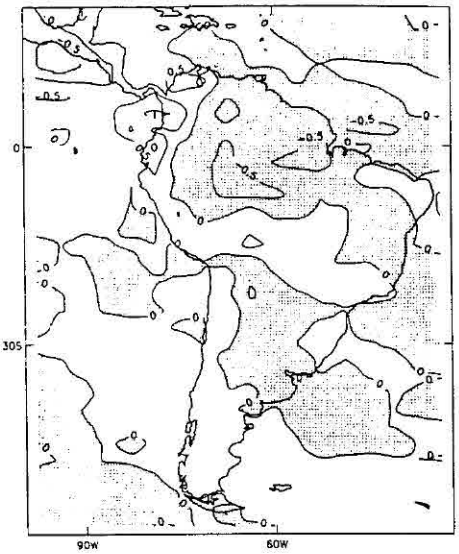



**Figure 16** Modelled annual mean difference (HALF–FOREST) in rainfall. Contours are at 0.0, ±0.5, 1.0 and then every 1.0 mm day$^{-1}$ with areas of decrease shaded.

## DISCUSSION AND CONCLUSIONS

The aim of these experiments was to find the climatic response to a more realistic portrayal of Amazonian deforestation by using the most up-to-date measurements of vegetation characteristics for forest and replacement pasture locations. These relatively long ten-year simulations have allowed more confidence to be placed in the results because of their higher statistical significance. The series of single component change experiments have provided a clearer understanding of the mechanisms involved in the response to total deforestation.

The effect of increased albedo broadly agreed with the Charney (1975) hypothesis that increased albedo reduces the energy available to the column and so forces descent in order to maintain a temperature similar to the adjacent regions. In the Amazon basin this will tend to suppress ascent and rainfall and, by implication, the moisture convergence into the region. Results from the experiment in which albedo alone was increased from the forest to the pasture value shows that rainfall was reduced in a rather uniform manner across northern South America with decreases of 0.5 to 1.0 mm $day^{-1}$ or about 10% in the annual mean. Results from the experiment in which roughness was reduced from the forest to the pasture value show a marked increase in moisture convergence leading to increased rainfall; there is broad band of increase in rainfall through central southern and western Amazonia with maximum increases of over 1 mm $day^{-1}$. One explanation of this response is that the boundary layer winds are much stronger with weaker frictional stresses. These results can be compared with a similar but shorter eight-month experiment carried out by Lean and Warrilow (1989). They showed a reduction in moisture convergence and reduced rainfall. It is difficult to attribute the difference in response to any one cause although a number of differences existed between the models and the experiments. Two of the most likely reasons to explain the differences are the prescribed change in roughness (in this experiment a change of 2.1 m was imposed compared with the 0.8 m reduction in Lean and Warrilow) and the deficiencies in the earlier climate simulation, notably the overestimation of interception and the re-evaporation of rainfall by the canopy. Sud *et al.* (1988) obtained decreased convergence and rainfall over northern South America in July with reduced roughness. This disparity in results may be explained by the lower Andes barrier in their model (typically about half the height used in our model); a mountain barrier such as the Andes tends to force convergence to be contained within the deforested area, whereas in the absence of this barrier all extra downwind convergence would occur outside of this region. The response to changes in roughness is therefore rather complex and dependent on a number of factors including the model and its climate simulation, the magnitude of the change in roughness and the height of the mountain barrier to the west.

The experiment in which all vegetation parameters were modified except the maximum infiltration rate was originally designed because of the notably large impact that the reduction in infiltration and reduced evaporation were having together with the uncertainty in defining the magnitude of the change in this

parameter. Results from this experiment were the most unexpected. The reduction in average annual evaporation of 0.35mm day$^{-1}$ (8%) was substantially less than the 0.81mm day$^{-1}$ (19%) decrease in the total deforestation experiment. This could be attributed mainly to the retention of more soil moisture during the dry season. Changes in rainfall were more closely related to changes in evaporation with no compensating increase in moisture convergence as in the total deforestation experiment.

If it is assumed that the changes in roughness and albedo dominate the response in the total deforestation experiment to the exclusion of changes in all other vegetation parameters, then by adding the changes together from these two individual experiments one might expect to get some way towards the experiment in which all parameters have been modified except the reduced maximum infiltration rate. However there are substantial discrepancies in rainfall and evaporation shown by the difference patterns in Figure 17 - this is formed by the difference in fixed maximum infiltration rate experiment from the sum of the changes due to albedo and roughness. Although there are only small differences in evaporation which can probably be attributed to the stomatal resistance and rooting depth changes, discrepancies in rainfall are substantial. Over eastern Amazonia, there are no differences above 0.5 mm day$^{-1}$ but within western Amazonia there are discrepancies of over 1 mm day$^{-1}$. This implies that there are a number of non-linear interactions taking place.

Results have been shown to be highly sensitive to the specification of a number of key parameters - the most surprising result was the response to fixing maximum infiltration rate at the surface which reduced the area-averaged evaporation decrease from 0.81mmday$^{-1}$ (19%) to 0.35 mmday$^{-1}$ (8%). If GCMs are to produce credible

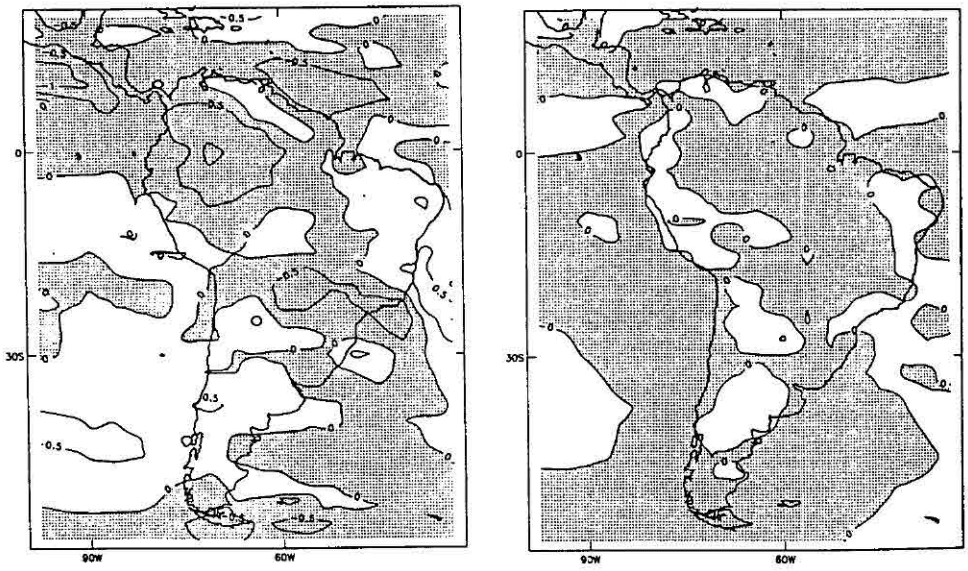



**Figure 17** (a) Modelled annual mean difference (FIXINF–FOREST) – { (INCALB–FOREST) + (REDRGH–FOREST) } in rainfall. Contours are at 0.0, ±0.5, 1.0 and then every 1.0 mm day$^{-1}$ with areas of decrease shaded. (b) As (a) except for evaporation.

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## RESUMO

Experimentos de desmatamento da Amazônia foram conduzidos utilizando-se o MCG do Hadley Centre. As caracterísitcas da floresta e pastagem foram obtidas a partir dos dados do Projeto ABRACOS. A completa retirada da floresta Amazônica produziu as seguintes modificações médias (para toda Amazônia): redução na evaporação em 0,81 mm $d^{-1}$ (19%) e na precipitação em 0,43 mm $d^{-1}$ (7%), e aumento na temperatura da superfície em 2,3°C. Estes resultados assemelham-se aos obtidos em experimentos anteriores. Entretanto, as diferenças relativas em magnitude indicam que o aumento na convergência de umidade compensa, parcialmente, a redução de evaporação, em contraste com a maioria dos experimentos anteriores. Os resultados também mostram grandes diferenças regionais na variação da precipitação média anual sobre a América do Sul, com redução sobre a maior parte da área desmatada e aumento próximo aos Andes. Um experimento de desmatamento, confinado a uma área reduzida mais realista, mostrou que as maiores reduções de precipitação se localizaram sobre a floresta remanescente na Amazônia Central, ao invés de sobre a área desmatada. Em outra série de experimentos, variando-se separadamente a rugosidade, albedo e infiltração máxima do solo, foi examinada a resposta do clima em face a essas modificações. Estes experimentos indicaram que o clima final, gerado pelo modelo, é muito dependente dessas variações discretas nos parâmetros e é fortemente influenciado pela interação não linear destas variações.

predictions of regional changes due to deforestation it is necessary to use realistic and accurate specification of these parameters. Use of ABRACOS measurements of vegetation and soil characteristics in future Amazonian GCM deforestation experiments will signify an important evolution in adding more realism to such simulations.

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