Application of a GCM to Study the Surface Hydrological Budget of Amazonia

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ABSTRACT

Using The Florida State University Global Spectral Model, hydrological budgets are calculated over the Amazon River basin for the boreal summer of 1979 with and without a complex biosphere model (BATS) coupled to the atmospheric model. Substantially increased precipitation and latent heat fluxes over the Amazon are noted for the BATS case, along with better maintenance of low-level flow patterns. Partitioning of the rainfall and latent heat flux into detailed component terms from BATS reveals evidence of ''moisture recycling,'' particularly in relation to the intercepted rainfall. Monthly variations in the component terms for precipitation, latent heat flux, and upper soil moisture are described. A total runoff efficiency of 75% is simulated by the model, while the surface runoff efficiency is about 30%. Model performance in the locality of two intensive field study areas (Pará and Rondônia) of the Large-Scale Biosphere–Atmosphere Experiment in Amazonia has been examined via time series from the two models and observed data. The 850-hPa temperatures and wind speeds are both overestimated by the models. However, use of BATS has reduced the temperature bias by about 30%. Most significantly, the phase of the wind speed variations over Rondônia is maintained in agreement with the observations throughout the seasonal forecast.

1. Introduction

It is well known that the Amazon Basin has a significant influence on the global atmospheric circulation. Grimm and Silva Dias (1995) have shown that upper-level divergence over central Brazil acts as a source of important teleconnection patterns in the Northern Hemisphere winter. Hence, the meteorological fluctuations of Amazonia are most appropriately considered within a global context.

The hydrological budget of Amazonia is of particular importance due to the presence of some of the world's largest river systems, seasonal inundation of land, and the general abundance of moisture. Hence, there is concern that large-scale land use changes may significantly alter the sediment transport, chemistry, and flow regimes of rivers within the region. Such changes could in turn also result in oceanographic changes in the region of the Amazon River plume.

The tropical land and atmosphere form a complex, intricately coupled system. The surface fluxes not only control the inputs of water and energy to the atmosphere but depend on the dynamic and thermodynamic characteristics of the planetary boundary layer (da Rocha et al. 1996). Interactions involving cloudiness, soil water content, evaporation, hydrology, and vegetation cover are all linked together in this highly nonlinear system. Naturally, moist convection is the primary route (Lloyd 1990) by which water, energy, and trace constituents are transported from near the surface into the free atmosphere. As such, it is reasonable to expect a significant impact on the region's climatology and hydrology in the wake of large-scale land cover changes (Dickinson and Henderson-Sellers 1988; Dickinson and Kennedy 1992; Cutrim et al. 1995; Bastable et al. 1993).

It is widely believed that the hydrology of the Amazon Basin is sensitive to large-scale land use changes over the area. Hence, many researchers are interested in examining how the hydrological budget is modified by deforestation within the region and other variations associated with different vegetation types (e.g., Nobre et al. 1991; Lettau et al. 1979; Lean and Rowntree 1993). The consequences of large-scale land use change and climate change on the hydrology of the Amazon can best be explored by means of numerical experiments with a physically based biosphere model coupled to a global atmospheric model (Thomas and Henderson-Sellers 1992).

The synthesis of these issues into an integrated study

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of the roles of land surface and hydrological processes over the Amazonian region is the overarching goal of the Large-Scale Biosphere–Atmosphere Experiment in Amazonia (LBA) (Nobre et al. 1996). Interest in the Amazon has particularly been piqued in recent years because of the large-scale conversion of some parts of the basin from complex rain forest and cerrado ecosystems to generally marginal agricultural land use.

2. Study objectives

In this study, an attempt has been made to examine, in detail, the hydrological budget over Amazonia; that is, all components of the hydrologic cycle that involve processes at the land–ocean surface interface. Such a study holds value not only for describing the relative importance of different terms contributing to the hydrologic budget but also as a benchmark for eventual comparison against modified vegetation scenarios. We aim in particular to illustrate, via numerical experimentation, the following issues relevant to the Amazonian hydrological cycle: 1) the surface and meteorological controls on vertical fluxes of water, 2) variations of such controls in time during Northern Hemisphere summer (the dry season in Amazonia), and 3) comparisons of model performance over Rondônia and Pará, the two probable locations for intensive field study in LBA (as indicated in Nobre et al. 1996). Although these results are properly valid only for 1979, they represent a useful initial application of the experimental techniques.

3. Experimental setup

The Florida State University Global Spectral Model (FSUGSM), at T42 resolution, has been modified to explicitly include atmosphere–biosphere interactions for use in seasonal forecasting and climate sensitivity studies. The biosphere component is based on the Biosphere–Atmosphere Transfer Scheme (BATS) developed by Dickinson et al. (1993). Along with a control version of the FSUGSM, which has no biosphere component, the model is integrated for the period of 11 May–31 August 1979, initialized with the First Global Atmospheric Research Program Global Experiment (FGGE) gridded data. Boreal summer corresponds to the Amazonian dry season and was found by Nobre et al. (1991) to be the season most sensitive to land surface changes. The control model has no prognostic determination of soil moisture and uses a surface energy balance approach.

The BATS model explicitly describes the interaction of vegetation cover with the atmosphere. This includes a very complete parameterization of the surface hydrological cycle. For soil moisture and temperature, up to three nested soil layers are modeled by the ‘‘force–restore’’ approach. Explicit prognostic snow cover allows the local surface albedo to vary dynamically. The initial soil moisture variables were obtained by a ‘‘spinup’’ run of the model for 30 days starting with approximately 90% saturated soil. These values were then used as ‘‘initial’’ as the model was restarted for the actual simulation. The use of a modified BATS scheme (as opposed to other similar schemes) is particularly desirable since the process-oriented architecture of BATS makes itself amenable to such detailed hydrologic budget studies.

For use in this study, BATS has been modified by the use of more vegetation types and various computational refinements. The seasonal variation of vegetation characteristics is described at each grid point by a seasonal climatology of normalized difference vegetation index (NDVI) variations. The hydrologic budget is accumulated over the Amazon River basin with 19 basic terms from BATS (Fig. 1), which can be combined in various ways for ease of interpretation. Through these terms and various combinations of them, modeled surface hydrologic processes can be examined in great detail.

Since such details of the basinwide hydrologic budget cannot be clearly defined by observations, some measure of the surface model’s performance relative to the control is sought by examination of the more general combinations of terms or by nonhydrologic parameters, such as temperature, which are known to be sensitive to surface hydrologic processes.

A more thorough description of the numeric models can be found in L. White and T. Krishnamurti (1998, manuscript submitted to *J. Appl. Meteor.*) and in White (1996).

4. Regional fields

To give some idea of the spatial variation of BATS vegetation characteristics over South America, the mean leaf area index (LAI) for July is shown in Fig. 2. While most of the Amazon Basin is described by a large, nearly constant LAI, there are significant contrasts evidenced over other regions of the continent. The locations of the regions of Pará and Rondônia (the primary research areas of LBA) are shown by ‘‘P’’ and ‘‘R’’ in this and other similar figures, while the approximate boundaries of the Amazon River basin are shown by the stippled area. There is particularly noticeable variation in LAI over the Nordeste region of Brazil. Vegetation density (as indicated by NDVI) falls off rapidly upon approaching the Pacific Ocean. Relatively small values are also found south of 30°S, where vegetation is affected by the Southern Hemisphere winter. Although many of these variations are outside of the Amazonia region, it is felt that proper simulation of land–surface interactions on the rest of the continent is of importance to obtaining a suitable seasonal simulation for the Amazon Basin itself.

a. Winds

Mean flow fields for June and August are shown in Figs. 3 and 4 for the 850-hPa level at 1200 UTC. The

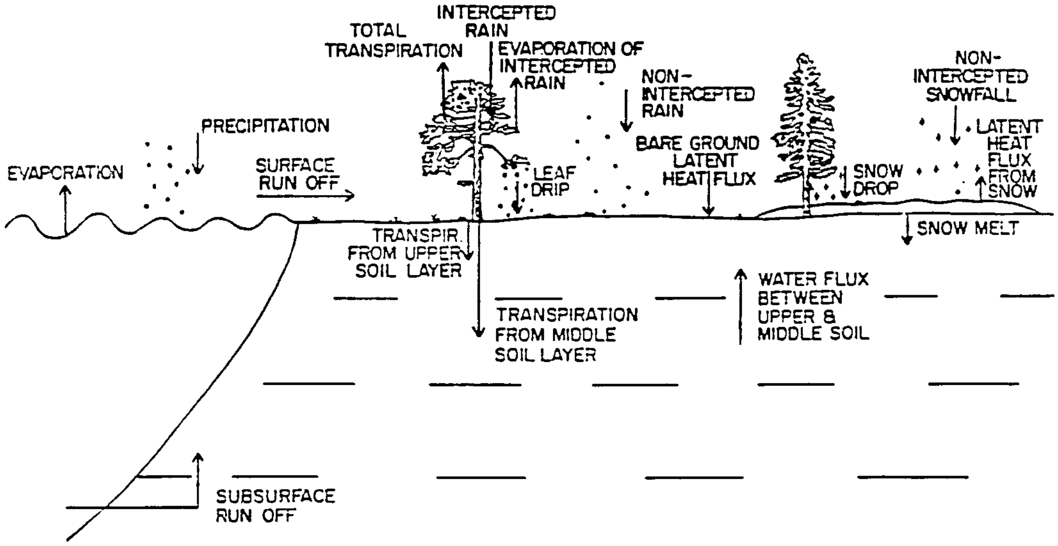

FIG. 1. Basic moisture budget terms that are accumulated from BATS.

choice of this level for model comparisons was driven by the desire to be sufficiently near the surface to see land surface impacts and yet address the concern that lower levels fields might be contaminated excessively by analysis difficulties in the vicinity of terrain. In June the BATS model produces a subtropical anticyclone over southern Brazil that agrees much better with the FGGE observed data than the control does. The cyclonic center associated with the Central American monsoon is also positioned well in the BATS run, over Panama rather than the Caribbean Sea. Flows over the Andes are affected by extrapolation beneath the terrain. Note that the models consistently have difficulty with the flow off the coast of Chile, which is presumably related to interaction with the southern and central Andes.

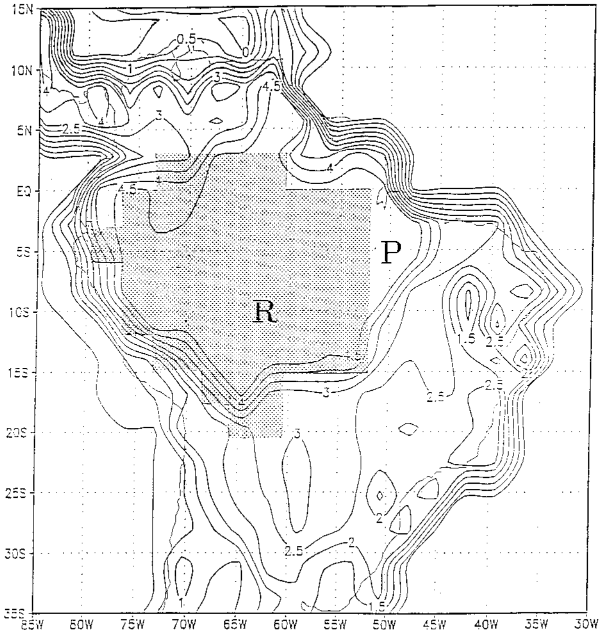

FIG. 2. Mean leaf area index used by BATS for July. The approximate river basin area used for budget studies is indicated by stippling.

The model flow fields for August are similar to June for the southern half of the region. However, there are substantial differences north of the equator. The control is extending the Central American monsoonal flow north of 15° with no indication of a low center (even at 1000 hPa). In contrast, the BATS experiment has some indication of a low center near Panama and easterly flow immediately to the north. This is in relatively good agreement with the observed strong cyclonic center over Panama and associated easterlies over the Caribbean Sea. Another major problem with the control is the development of a zonally oriented trough near 13°N, which results in a large area of westerly winds over the ocean to the northeast of Brazil. Both BATS and the observed data indicate a smooth field of easterlies within the area.

Hence, it appears that the use of BATS has been beneficial to the delicate balancing between Southern and Northern Hemisphere air masses that governs the positioning of the Central American monsoon circulation, the ITCZ, and associated easterlies. The most dramatic difficulties for the control appear to be near the end of the integration due to model drift, indicating the potential role of vegetation forcing in driving the large-scale seasonal flow variations of northern South America and the adjoining oceans.

b. Rainfall

Rainfall accumulations for August are shown in Fig. 5. Gridded observed values are from the archive of the

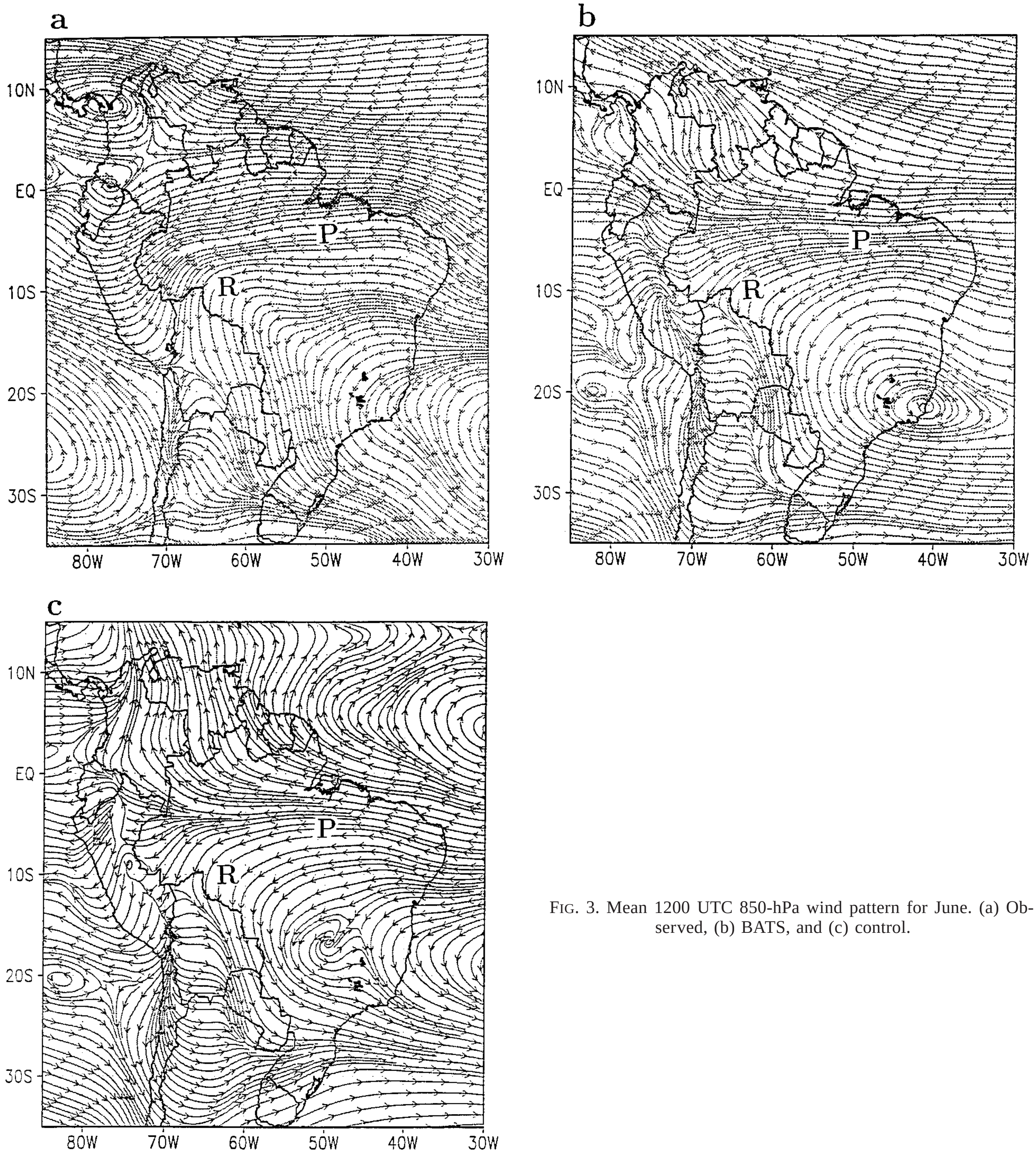

FIG. 3. Mean 1200 UTC 850-hPa wind pattern for June. (a) Observed, (b) BATS, and (c) control.

Goddard Space Flight Center and are derived from an outgoing longwave radiation–based satellite algorithm. Although comparison is difficult, there are a few interesting points. Most notable is that rainfall is somewhat more widespread over Brazil with BATS than in the control, though not quite so much as observed. A minor point of improvement with BATS is the increased rainfall in the vicinity of the Amazon delta and the eastern Brazilian coast. Both models have difficulty over the Andes. Although not within the Amazon Basin, there is a fairly dramatic improvement with BATS in the rainfall over the Rio de la Plata region. This could be associated with how the model's low-level flow is feeding into the frontal systems that typically organize precipitation over the region during the southern winter. The large ''observed'' rainfall over extratropical oceans could be an artifact of satellite rainfall estimation techniques used in the Goddard data. We have not attempted validation of model runoff with observed river discharge.

5. Time series

In the two regions of intensive mesoscale study for the LBA field experiment, time series of the model runs and observed variables have been compared. These two localities were chosen for LBA because of their proximity to areas of widespread deforestation in the eastern and southern portions of Amazonia (Nobre et al. 1996). We have only done validation against gridded data rather than the relevant point data from the Anglo–Brazilian Amazonian Climate Observation Study. Although not centered over the most deforested areas, the points chosen, Pará and Rondônia, are within zones of very strong gradient between fairly undisturbed and heavily modified vegetation covers. The forests of Pará are more of the drought deciduous variety, subject to deforestation (and secondary regrowth) for a relatively long time, and have generally infertile soils. In contrast, Rondônia has relatively fertile soils, has only more recently been subject to agricultural conversion, and is in a position to be more readily affected by Southern Hemisphere weather systems. The model time series presented here are 7-day running averages of the 1200 UTC values, averaged over the four grid points within the respective region. The observed time series are running averages of the 1200 UTC, 1.875° FGGE data at the point nearest the center of the region.

Both the control and BATS models consistently predict higher than observed 850-hPa temperatures for both Pará and Rondônia (Fig. 6). However, the BATS values are about 1 K closer to the observed on average. It appears that much of the model bias appears from a spinup period of about 20 days when the models steadily warm, while the observed temperatures are cooling. It is believed that this difficulty is both related to the crude parameterization of turbulent boundary layer processes and the initialization of the models at a time when the observed temperatures are relatively warm.

Time series of the wind speed at 850 hPa over Pará and Rondônia (Fig. 7) show generally much larger values with the models. However, there is a striking similarity between the phases of wind speed oscillations over Rondônia in the BATS and observed data. Over Pará, all three time series are behaving somewhat differently. Yet the BATS time series is remarkably similar to that over Rondônia. Hence, it seems that the BATS experiment did a surprisingly good job at simulating flow disturbances in the southern Amazon but extended these same disturbances too far northward (to Pará).

Presumably the inability of the atmospheric model to meaningfully deepen the PBL is a factor in the consistent maintenance of excessive winds at low levels. It is possible that difficulties in estimation of the surface roughness length may play some role in the noted discrepancies.

6. Atmospheric budgets

An atmospheric moisture budget provides a useful starting point for the detailed hydrologic budgets. All budgets are calculated for the area indicated in Fig. 2. Over this region, the mass integral of the moisture conservation equation over the tropospheric column provides us with the usual atmospheric budget equation, that is, net change of moisture over Amazonia equals evaporation minus total precipitation plus the net moisture flux convergence (computed as a residual). We have computed these from the results of the control and BATS climate model simulations for each month (Fig. 8).

July is a relatively dry month over this region with the minimum rainfall of the four months. The June drying of -0.30 mm day^{-1} in the BATS run is accounted for by an export of moisture of 2.3 mm day^{-1}, whereas the control run has -0.41 mm day^{-1} for the net change and 2.62 mm day^{-1} for the export. The smaller drying with BATS appears more reasonable than the control.

Among these four months the rainiest month is May. The regional rainfall predicted by BATS (4.0 mm day^{-1}) exceeds that of the control (2.9 mm day^{-1}). It is also interesting to note that the rainfall over Amazonia during this rainy month can be accounted for (using BATS) almost entirely by strong surface evaporation (4.92 mm day^{-1}). Note that, while this is applicable for monthly timescales, the local moisture flux convergence would be expected to play a larger role for specific storm events on a daily timescale. Overall, the use of BATS resulted in more rainfall and more evaporation compared to the control in all cases. The simulation of net drying was excessive for the control and generally associated with enhanced exports.

7. Surface hydrologic budgets

For simplicity of discussion, the basic hydrologic budget terms from BATS are aggregated into the terms listed in Table 1. For the partitioning of land precipitation, terms are represented in bar graphs as percentages of the incident precipitation (before interception). Similarly, terms contributing to the land latent heat flux are shown as percentages of the total latent heat flux over land areas in Fig. 9. Figure 10 shows the monthly rates of precipitation and latent heat flux. Because both positive and negative terms make up the budget of upper soil moisture, each term is normalized by the total precipitation input to the soil surface (rain plus snow melt) (Fig. 11).

a. General characteristics

The hydrologic budgets reveal that the total four-month rainfall over the Amazon River basin increases

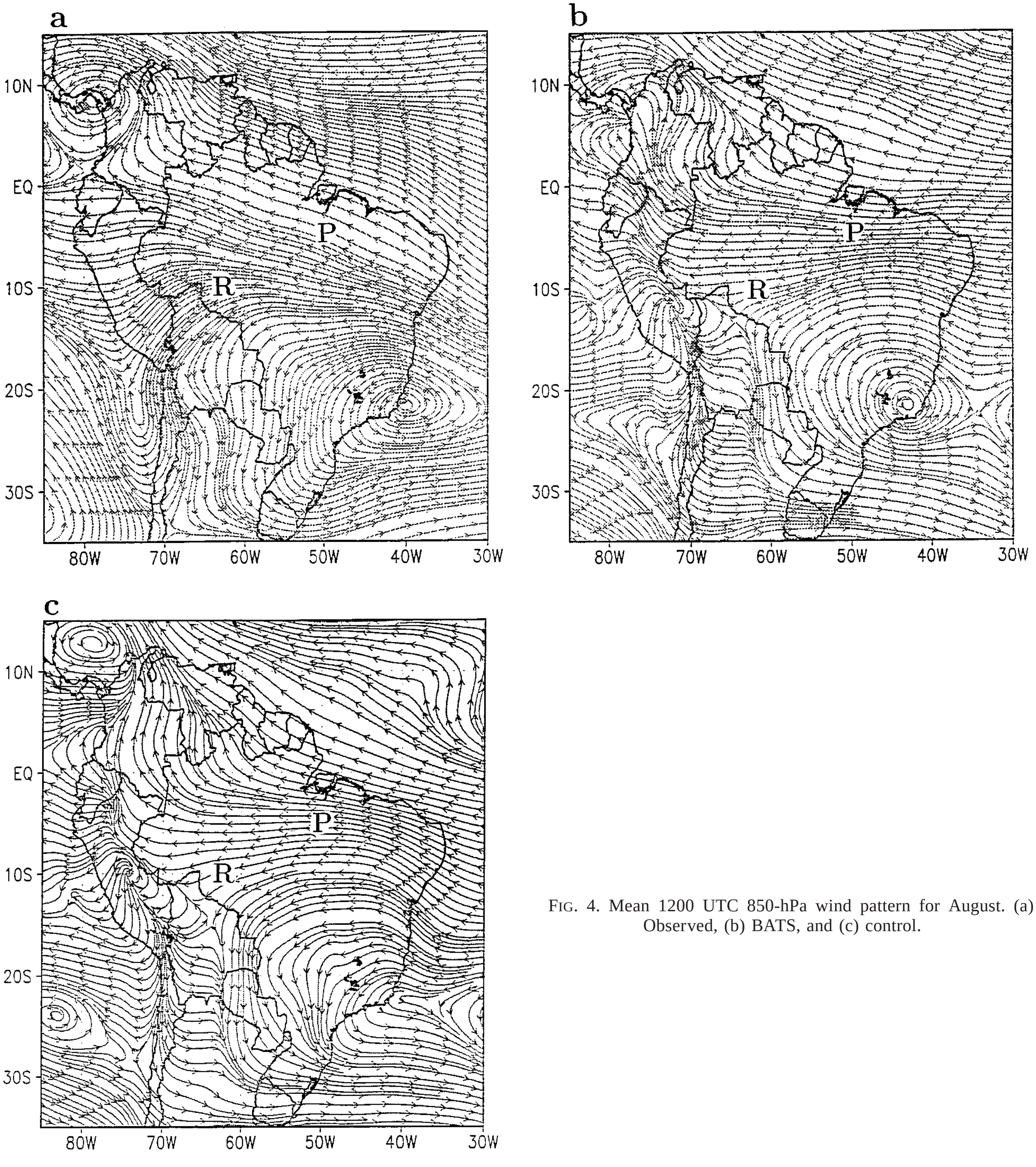

FIG. 4. Mean 1200 UTC 850-hPa wind pattern for August. (a) Observed, (b) BATS, and (c) control.

from about 160 to about 270 mm by using BATS rather than the control. In general, the T42 FSUGSM is known to underpredict rainfall over the Amazonian region. Hence the fact that use of BATS substantially increases the total rainfall appears to represent a major improvement relative to the control. Use of BATS also increases the total latent heat fluxes for the period by over 70 mm. This is indicative both of the ability of BATS to maintain large latent heat fluxes over land areas and of the interrelationship between latent heat fluxes and precipitation when the land surface is appropriately simulated. The latter is important for the conceptual model of ‘‘moisture recycling’’ described by Lettau et al. (1979).

As expected over a heavily forested region, only a very small fraction of the precipitation falls on bare

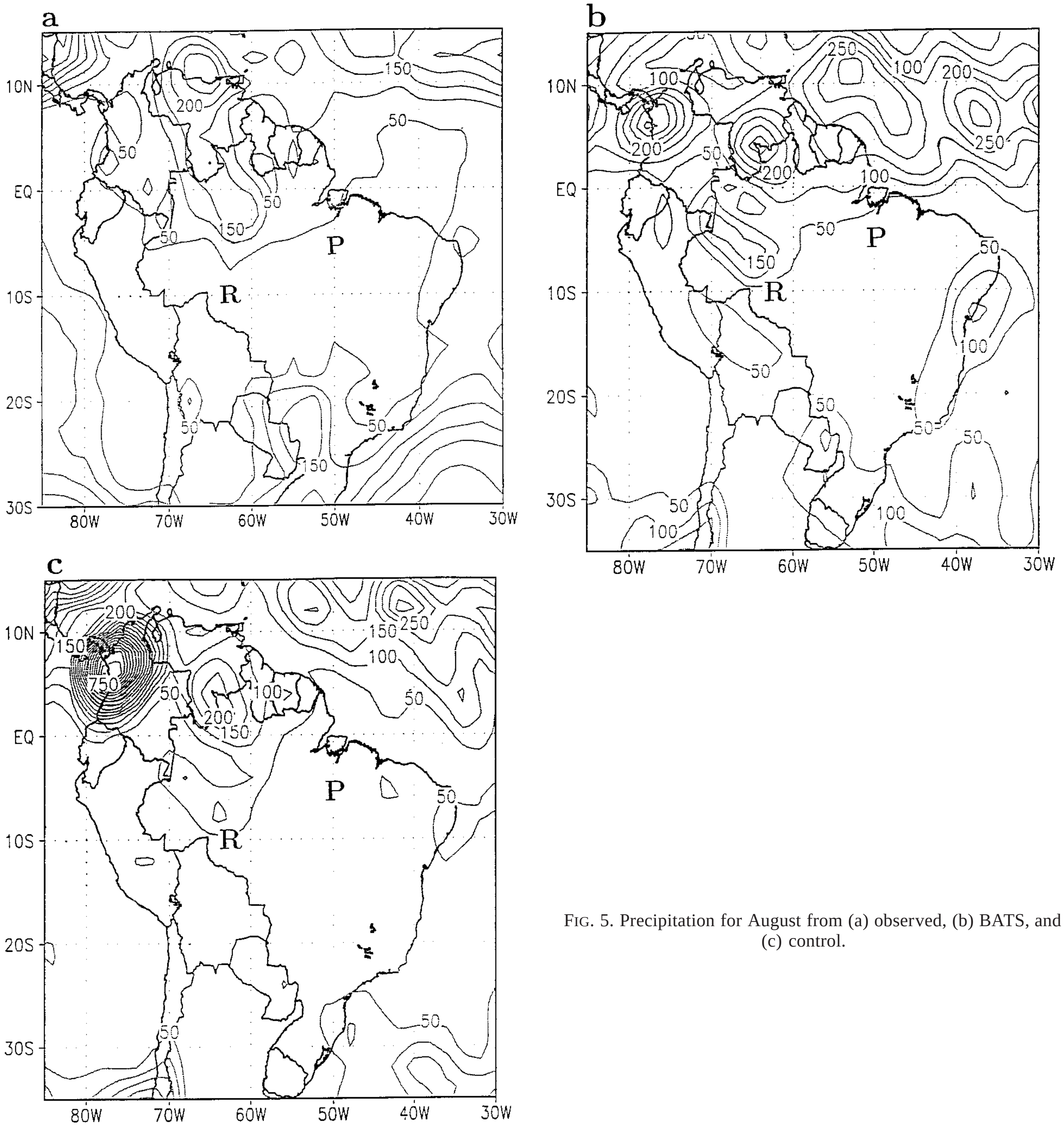

FIG. 5. Precipitation for August from (a) observed, (b) BATS, and (c) control.

ground in BATS (see Fig. 9a). Even though the bare ground evaporation is larger than one might expect, this is nevertheless one of only two budget regions (of 12 regions that we have studied) where transpiration makes up the largest part of the latent heat flux. Although geographic distributions of the terms are not available, it is believed that much of the bare ground evaporation is from the less heavily vegetated areas in the Andes that drain into the Amazon Basin and could be related to problems with the soil moisture initialization. Also, much of the latent heat flux originates as evaporation from the foliage (Fig. 9b). The proportion of latent heat flux from such evaporation of intercepted rainfall agrees favorably with the results of Dolman and Gregory (1992) for a point near Manaus using a one-dimensional model. However, the precipitation partitioning is not in

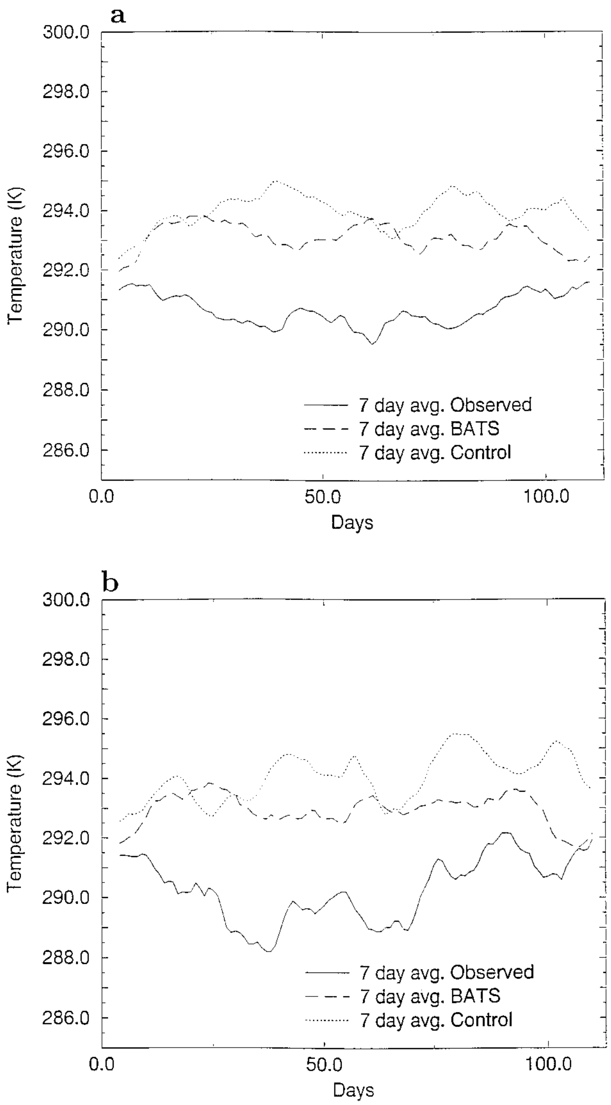

FIG. 6. Smoothed time series of 850-hPa 1200 UTC temperature over (a) Pará and (b) Rondônia.

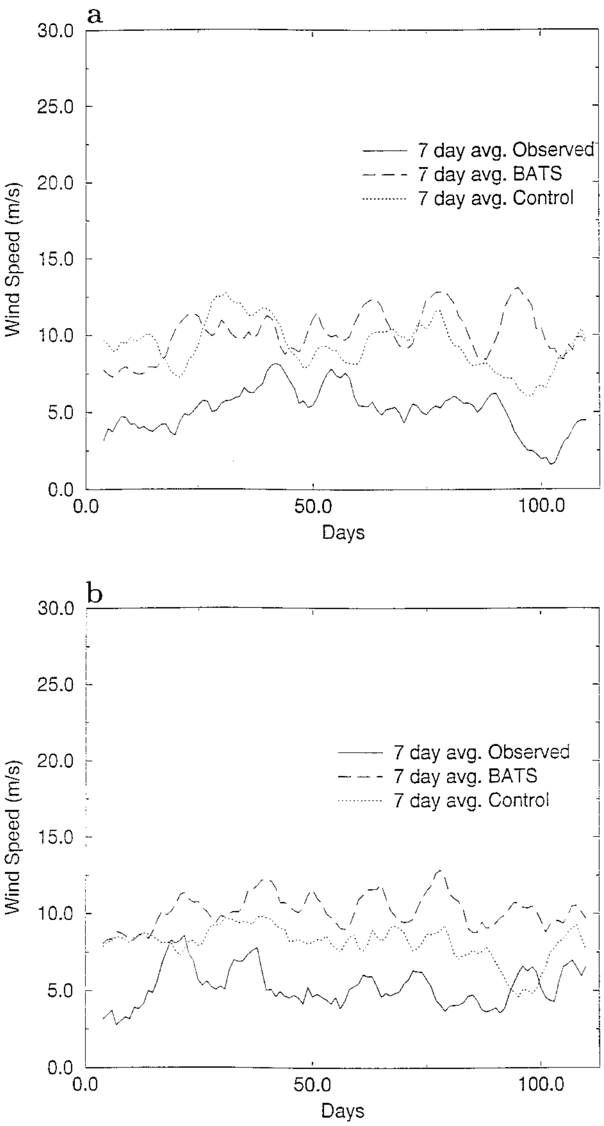

FIG. 7. Smoothed time series of 850-hPa 1200 UTC wind speed over (a) Pará and (b) Rondônia.

agreement with their results due to lower rainfall totals in the current simulation.

b. Monthly variations

In comparing the monthly precipitation over the Amazon from the control and BATS (Fig. 10a), the most obvious feature is that both models simulate the expected seasonal minimum of rainfall in July associated with the displacement of the ITCZ to the northern edge of the basin. However, the BATS rainfall is consistently much larger than that of the control, which appears to be much too dry. Examination of the BATS precipitation partitioning month by month (Fig. 9a) shows that the portion of rainfall that is not intercepted remains at a constant small amount of around 7%. In all months, the majority of rainfall takes the form of leaf drip to the ground surface. But this is clearly modulated by the amount of total precipitation due to the fact that the intercepted (and reevaporated) rainfall amount is limited under wet conditions by the maximum amount of water that can be stored on the leaf surfaces. This relative invariance of the interception results in interception making up a larger fraction of the rainfall budget during the months with less precipitation. To counteract this effect, of course, the fractional contribution of leaf drip decreases during the drier months.

The seasonal evolution of latent heat fluxes (Fig. 10b) is consistent with the precipitation variation in BATS. The control, however, does not have such a consistent pattern and has generally lower values. Note that the latent heat fluxes exceed the precipitation for all four months in both models. Such an imbalance is not un-

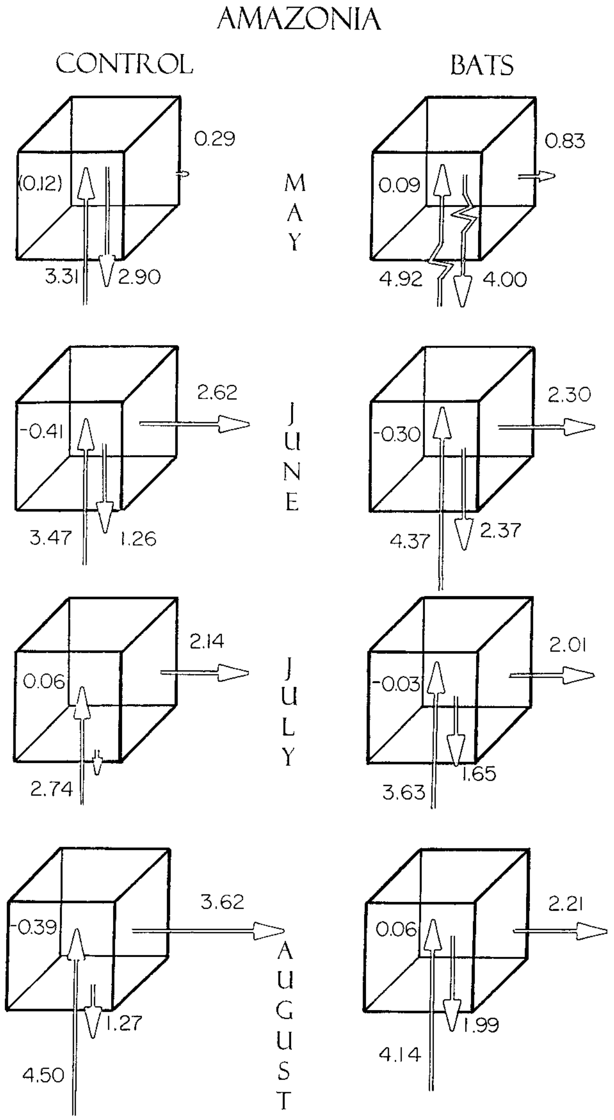

FIG. 8. Atmospheric column moisture budgets over the Amazon Basin from the control and BATS runs (mm day^{-1}).

reasonable since the northern summer is the dry season within the Amazon. The fact that the bare soil evaporation term (Fig. 9b) decreases substantially during the first three months of the simulation may indicate that it is partly associated with difficulty in properly initializing the soil moisture over the Andes. It is suspected that the spinup of soil moisture may not have been long enough for the relatively dry altiplano, resulting in excessively moist initial model conditions over the region. The contribution of transpiration increases during the drier months as the upper soil moisture becomes depleted and the more slowly varying root zone soil moisture becomes a more dominant source of moisture for the atmosphere. In contrast, the evaporation of intercepted water from the foliage remains at a nearly constant relative contribution of under 20%.

TABLE 1. Major moisture budget terms represented in Fig. 11.

Land precipitation	
A	Nonintercepted rainfall
B	Leaf drip
C	Rainfall lost to interception
D	Snowfall
Land latent heat flux	
A	Bare ground evaporation
B	Transpiration
C	Evaporation of intercepted rainfall
D	Latent heat flux from snow surface
Upper-soil moisture budget	
A	Rainfall reaching ground
B	Bare ground evaporation
C	Transpiration from upper-soil layer
D	Surface runoff
E	Moisture flux between soil layers
F	Snow melt

In the upper soil moisture budget (Fig. 11), the rainfall and bare ground evaporation terms are nearly balanced. Hence, the other terms are important for determining the net moisture change, even though they are not so large. Over the integration as a whole, less than 10% of the transpiration comes from the upper soil (~10 cm deep), indicating both the drying of the upper soil during the dry season and the greater depth (~1 m) of the root zone. Therefore, the bare soil evaporation plays a relatively large role in the budget of the upper soil moisture.

BATS simulates a very large surface runoff efficiency during May and June of around 30% of the precipitation. When the total runoff is considered (i.e., including that from subsoil drainage), the efficiency is in the neighborhood of 75%. Even in the surface runoff, the efficiency does not respond immediately to the decreased rainfall in June but appears to lag by about a month. The moisture flux between soil layers is a difficult term to understand the behavior of since it normally acts to minimize vertical soil moisture gradients and therefore tends to behave as a term to balance the residual of all the other terms. It seems that the sudden decrease of rainfall in June causes a drying of the upper soil within that same month, while the root zone soil remains relatively moist. Hence, the upward moisture flux increases somewhat. By July, however, the root zone soil moisture is also becoming depleted by transpiration and the gradient and moisture flux are reduced. It would thus appear that the moisture flux between soil layers is of greatest importance during such transition periods.

8. Concluding remarks

Inclusion of the biosphere model, with its more realistic parameterization of the surface hydrology, within the FSUGSM has clearly resulted in a general improvement of the seasonal simulation over Amazonia during the dry season. Major flow features are better repro-

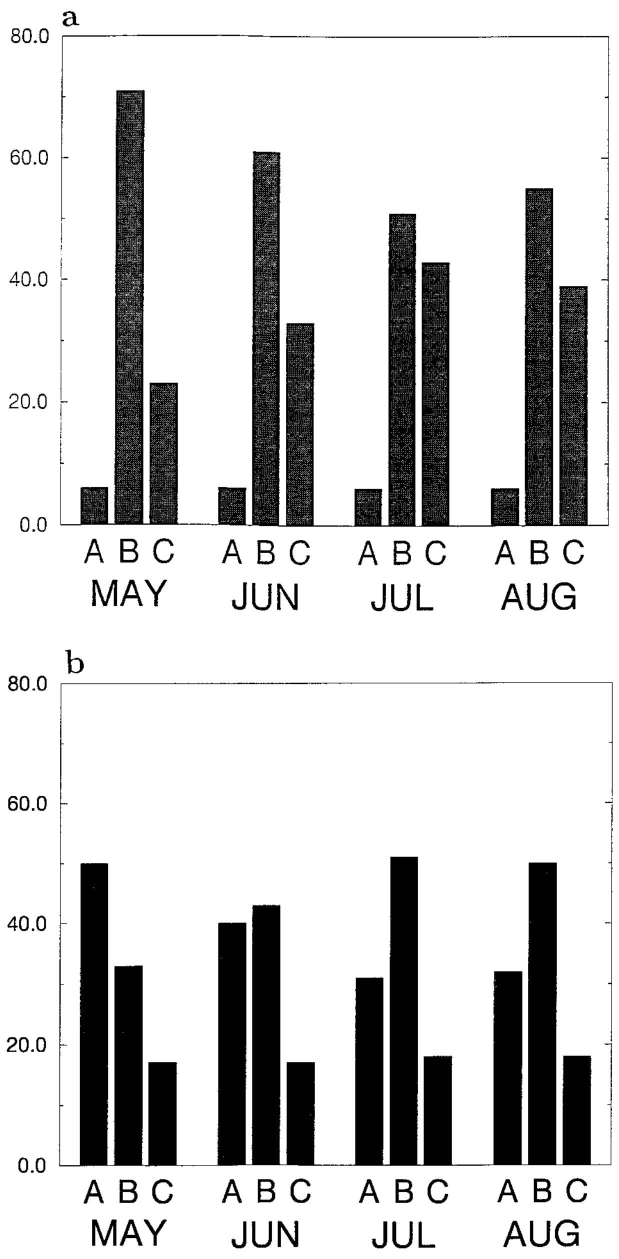

FIG. 9. Monthly BATS partitioning of budget components for (a) precipitation over land and (b) latent heat flux over land.

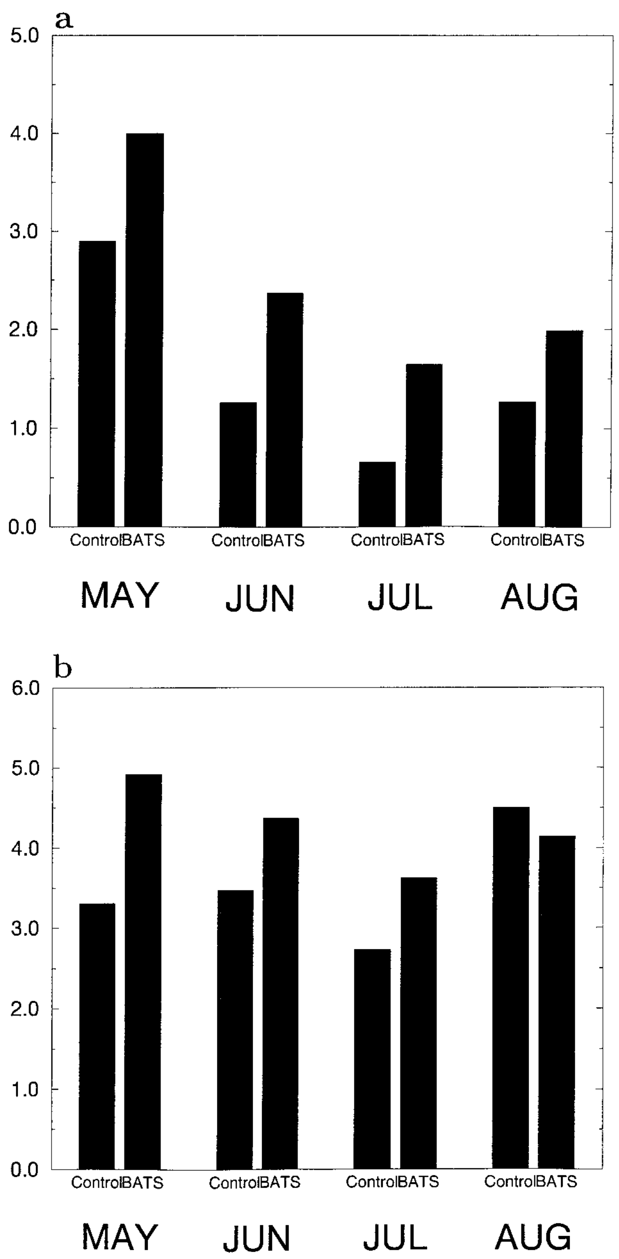

FIG. 10. Control model and BATS monthly mean rates (mm day^{-1}) of (a) precipitation over land and (b) latent heat flux over land.

duced and rainfall totals are substantially increased, which is in better agreement with observations. Time series for Rondônia and Pará indicate that BATS has reduced the bias in 850-hPa temperature and produces wind oscillations over Rondônia that are remarkably similar to observations. For each of the four months considered, it is found that use of BATS has increased the regional rainfall and evaporation relative to the control. Stronger moisture flux divergence in the control seems to be producing excessive atmospheric drying over the Amazon. Detailed examination of the model's hydrologic budgets reveals the varying interactions between surface processes at different points in the seasonal cycle of rainfall. We have also shown the important role of rainfall interception and recycling within the Amazon River basin.

Further analysis of these global simulations will continue for this and other regions. Similar numerical experiments for other seasons and at higher spatial resolution are planned. Efforts are currently under way to utilize the modified BATS model within a regional spectral model that is nested within the FSUGSM.

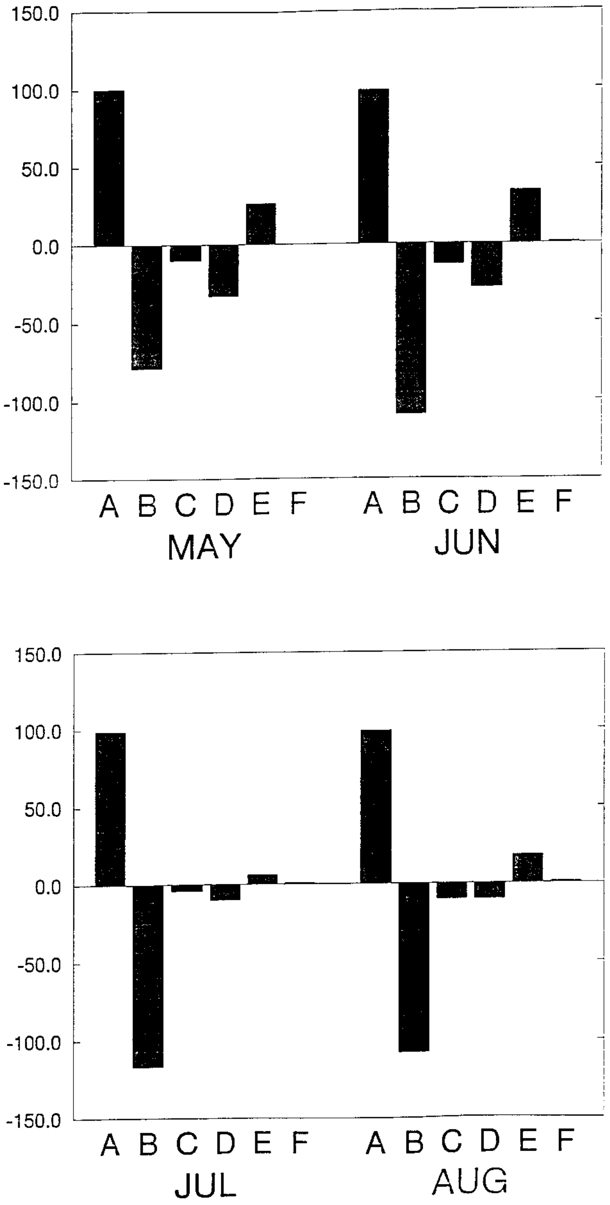

FIG. 11. Monthly budget of upper-soil moisture from BATS.

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