

## Comparative Evaluation of BATS2, BATS, and SiB2 with Amazon Data

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(Manuscript received 25 June 1999, in final form 6 December 1999)

### ABSTRACT

Over the last decade, improved understanding of plant physiological processes has generated a significant change in the way stomatal functioning is described in advanced land surface schemes. New versions of two advanced and widely used land surface schemes, the Biosphere–Atmosphere Transfer Scheme (BATS) and the Simple Biosphere Model (SiB), reflect this change in understanding, although these two models make different assumptions regarding the response of stomata to atmospheric humidity deficit. The goal of this study was to evaluate the new, second version of BATS, here called BATS2, using Amazon field data from the Anglo–Brazilian Amazonian Climate Observational Study (ABRACOS) project, with an emphasis on comparison with the original version of BATS and the new, second version of SiB (SiB2). Evaluation of SiB2 using a 3-yr time series of ABRACOS data revealed that there is an unrealistic simulation of the yearly cycle in soil moisture status, with a resulting poor simulation of evaporation. Improved long-term simulation by SiB2 requires specification of a deeper rooting depth, and this requirement is general for all three models. In general, the original version of BATS with a revised root distribution and rooting depth gave good agreement with observations of the surface energy balance but occasionally showed excessive sensitivity to large atmospheric vapor pressure deficit. Evaluation of BATS2 revealed that changes are required in the parameters that determine stomatal behavior in the model for realistic simulation of transpiration, time-averaged respiration, and net carbon dioxide (CO<sub>2</sub>) uptake. When initiated with default values for carbon stores, BATS2 takes several hundred years to reach an equilibrium carbon balance. Aspects of the model's representation of instantaneous carbon allocation and respiration processes indicate that BATS2 cannot be expected to provide a realistic simulation of hourly variations in CO<sub>2</sub> exchanges. In general, all three models have weaknesses when describing the field data with default values of model parameters. If a few model parameters are modified in a plausible way, however, all three models can be made to give a good time-averaged simulation of measured exchanges. There is little evidence of sensitivity to the different forms assumed for the stomatal response to atmospheric humidity deficit, although this study suggests that assuming that leaf stress is related linearly to relative humidity is marginally preferred.

### 1. Introduction

The earth's land surface interacts with the overlying atmosphere, and modification of the vegetation covering the soil affects land surface–atmosphere interaction processes and hence the exchange of energy, water vapor, and other trace gases. Rapid replacement of rain forests by pasture, therefore, has the potential to affect the regional and global climate systems. Studies have been conducted (e.g., Dickinson and Henderson-Sellers 1988; Nobre et al. 1991; Lean and Rowntree 1993) on the effect of rain-forest clearing on regional and global climates, using general circulation models (GCMs). The results vary considerably depending on the land surface parameterization scheme used in the GCM (Henderson-Sellers et al. 1993). Because these experiments essen-

tially are analyses of the sensitivity to the land surface parameterization, the credibility of the results depends on how well the land surface submodels represent the vegetation cover and soil. Field observations fortunately have proved valuable for improving the representation of land surfaces in global model experiments (Henderson-Sellers 1991; Shuttleworth et al. 1991; Gash et al. 1996).

Over the last decade, there has been a major change in the way stomatal functioning is described in advanced land surface models (LSMs). There is controversy, however, over whether it is best to use relative humidity or to use vapor pressure deficit when describing the response to atmospheric humidity deficit (e.g., Ball et al. 1987; Ball 1988; Jacobs 1994; Leuning 1995; Dewar 1995; Monteith 1995; Franks et al. 1997). New versions exist for two important and widely used LSMs, namely the Simple Biosphere Model (SiB) (Sellers et al. 1986, 1996) and the Biosphere–Atmosphere Transfer Scheme (BATS) (Dickinson et al. 1981, 1993, 1998). These new versions reflect the change in understanding of stomatal functioning, but the two models make different as-

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sumptions about the detailed form of the factors used to describe the response to atmospheric humidity deficit.

In the past, field studies in the Amazon River basin have provided a rich resource of relevant field data that have been used successfully to evaluate LSMs (e.g., Sellers et al. 1989; Shuttleworth and Dickinson 1989; da Rocha et al. 1996; Arain et al. 1997). This paper uses data taken from the Amazon River basin during the Anglo–Brazilian Amazonian Climate Observational Study (ABRACOS; Shuttleworth et al. 1991; Gash et al. 1996) to evaluate the new, second version of BATS, hereinafter called BATS2 (Dickinson et al. 1998). The emphasis of this paper is on comparing the descriptive performance of BATS2 with that of the original version of BATS (Dickinson et al. 1981, 1993) and the new, second version of SiB (SiB2; Sellers et al. 1996), an LSM with complexity comparable to that of BATS2.

## 2. Models, data, and approach

### a. Models

As described above, the three models used in this study are the original version of BATS (Dickinson et al. 1981, 1993), the revised version of BATS (BATS2; Dickinson et al. 1998), and the revised version of SiB (SiB2; Sellers et al. 1996). Because the original versions of BATS and SiB already are documented well in the literature, only the major differences between the original and new versions of these two models are summarized below.

The modifications made to BATS between the original and revised versions include a revised stomatal conductance model and the inclusion of a growth model. The standard version of BATS represents 15 types of vegetation cover by prescribing a seasonally varying fractional vegetation cover, albedo, and leaf area index (LAI); LAI is calculated as a function of temperature between prescribed maximum and minimum values. In BATS2, this prescribed LAI behavior is replaced with a modeled seasonal evolution, and the whole-canopy stomatal resistance is obtained by dividing the average stomatal resistance by LAI.

In BATS2, the average stomatal resistance is the average value for one direct-light canopy layer in addition to four diffuse-light canopy layers. For each layer, the essential form of the function used to describe stomatal resistance follows that introduced by Jarvis (1976), with some modifications from the form used in BATS, thus:

$$r_s = r_{s\min} M_f F(R_f, T_l, V_{pd}), \quad (1)$$

where  $r_{s\min}$  is a prescribed value for minimum stomatal resistance,  $M_f$  is a soil water stress term, and  $F$  is a function that describes the dependence of stomatal resistance on factors that include the radiation flux  $R_f$  in the visible portion of the spectrum, the canopy temperature  $T_l$ , and the vapor pressure deficit  $V_{pd}$  (VPD; hPa) at the leaf surface.

In Eq. (1),  $r_{s\min}$  is defined to be the minimum stomatal resistance at the top of the canopy in BATS2, whereas it was the average value for the whole canopy in BATS. Dickinson et al. (1998) suggested that, for evergreen forest vegetation classes, the value of  $r_{s\min}$  consequently might be 20%–30% lower in BATS2. In practice, however, the default values of  $r_{s\min}$  used in the BATS2 model simulations described by Dickinson et al. (1998) were the same as those used for BATS. In BATS2, the concepts used to describe carbon assimilation follow those of Farquhar et al. (1980). The link between carbon assimilation and the reciprocal of stomatal resistance (i.e., stomatal conductance) is described by a derivative of that given by Ball et al. (1987), hereinafter referred to as the Ball–Berry equation, that is,

$$g_s = m(A_n/C_s)F(e)P + g_o, \quad (2)$$

where  $g_s$  is stomatal conductance for water vapor transfer,  $g_o$  is a prescribed minimum stomatal conductance,  $m$  is a slope parameter (equal to 9 for  $C_3$  plants),  $A_n$  is the net carbon assimilation,  $C_s$  is the carbon dioxide ( $CO_2$ ) partial pressure adjacent to the leaf,  $P$  is atmospheric pressure, and now  $F$  is a humidity-dependency stress factor that, in the case of BATS2, is expressed as a function of vapor pressure deficit that is described in more detail later.

In BATS2, leaves exposed to sunlight and those in the shade are treated separately because on clear days leaves in bright sunlight can be light saturated but may be light limited if shaded. In this respect, BATS2 differs from the earlier version of BATS, which considered all light to be diffuse. The light-loading calculation for diffuse radiation in BATS2 retains the BATS four-layer structure, but the leaf area exposed to direct sunlight is calculated analytically by a canopy radiative transfer model. The light-attenuation calculations assume a spherical distribution for leaf orientation and assume also that a fraction of the attenuated direct sunlight is transformed into downward-scattered radiation in the canopy, with a downward scattering coefficient of 0.1. In practice, BATS2 calculates an average leaf conductance for shade leaves in each layer and leaves receiving direct sunlight (assuming the air is saturated) and then applies a vapor pressure–dependent stress factor to calculate the effective value of leaf stomatal resistance.

As mentioned earlier, BATS2 substitutes for the prescribed seasonal behavior used in BATS a simulation of the growth and loss of the green foliage, by describing leaf  $CO_2$  assimilation in addition to leaf water use. The assimilated carbon is allocated to other parts of the plant in addition to the leaves, while the death and decay of leaves and other plant parts release  $CO_2$  back to the atmosphere. The total ecosystem respiration is the sum of four contributions corresponding to maintenance respiration for leaves, wood, roots, and soil, and three contributions corresponding to growth respiration for leaves, wood, and roots. In each case, the maintenance respiration is assumed to be a function of temperature,

specifically canopy temperature for leaves and wood respiration, deep soil temperature for root respiration, and soil surface temperature for soil respiration. In each case, growth respiration is assumed to be a specified fraction of the instantaneous carbon assimilation. BATS2 uses soil surface temperature (as opposed to a temperature deeper in the soil) to calculate soil respiration and assumes that growth respiration for the roots is related to instantaneous (as opposed to time-averaged) carbon assimilation. As demonstrated later, these two model features necessarily result in an overly strong diurnal cycle in the simulated respiration, and, consequently, BATS2 is not expected to simulate plant and soil respiration and net carbon uptake at less than the daily average timescale.

Like BATS2, SiB2 is a revised form of the earlier SiB model (Sellers et al. 1986). Unlike SiB, however, which has two canopy layers, SiB2 describes only one canopy layer. The new model still simulates three soil layers—a surface soil layer, a rooting zone, and a deep soil layer—but some of the original vegetation classes are combined to reduce the number of distinct vegetation classes from 12 to 9. A canopy photosynthesis submodel (Collatz et al. 1990, 1991, 1992; Sellers et al. 1992) is incorporated. This submodel has a prognostic stomatal conductance and makes explicit calculation of the photosynthetic  $\text{CO}_2$  flux between the atmosphere and the land surface.

The leaf photosynthesis–conductance model used in SiB2 is similar to that used in BATS2, with, however, somewhat different implementation. Unlike BATS2, SiB2 includes description of  $\text{C}_4$  photosynthesis in addition to  $\text{C}_3$  photosynthesis. In SiB2, the photosynthetic rate of the canopy as a whole is estimated from that of the uppermost leaves by multiplying by a factor that allows for the absorption of photosynthetically active radiation through the canopy (this factor could be estimated from satellite observations). The canopy conductance then is estimated using the Ball–Berry equation [Eq. (2)], with the humidity stress factor set equal to relative humidity. Canopy transpiration thus is related directly to the whole-canopy carbon assimilation via the canopy conductance, but transpiration itself may feed back on the canopy conductance by influencing the canopy environment. The net  $\text{CO}_2$  flux is assumed to be the difference between the soil respiration  $R_{\text{soil}}$  and the net carbon assimilation rate  $A_n$ . To estimate the soil respiration in this study, we follow H. R. da Rocha (1999, personal communication) and use the expression originally developed by Meir et al. (1996):

$$R_{\text{soil}} = \exp(0.08357T_s - 0.20941), \quad (3)$$

where  $T_s$  ( $^{\circ}\text{C}$ ) is the soil surface temperature. In the model simulations, downward longwave radiation is calculated as a residual from measured net radiation and outgoing longwave radiation for all three models.

## b. Data

Field observations carried out under ABRACOS provided accurate, representative data for forested and deforested areas in the Amazon River basin. Detailed studies of surface climate, micrometeorological conditions, plant physiology, and soil hydrological processes were made at three different forest and adjacent clearing sites across the Amazon River basin (Shuttleworth et al. 1991; Gash et al. 1996). The location of these sites was chosen to represent different climate zones. Hourly measurements of incident solar radiation, wind speed, air temperature, specific humidity, and precipitation were made with automatic weather stations at all three ABRACOS forest sites. Data collection started in late 1990 and ended in December 1993. A brief description of the Reserva Jaru site and the data collected at this site is given below. For further details, see Shuttleworth et al. (1991) and Gash et al. (1996).

The data used in this study were taken at the Reserva Jaru forest site, which is near Ji-Parana in Rondonia close to the southwestern edge of the Amazon forest. At this site, there is a pronounced dry period, lasting for several weeks between June and August, for which the rainfall is less than  $10 \text{ mm month}^{-1}$ . December through April is the wettest season. In this region, the forest has been cleared progressively in an organized way over the last two decades, resulting in a “fishbone” pattern of clearings. The Reserva Jaru forest site ( $10^{\circ}5'S$ ,  $61^{\circ}55'W$ , altitude 120 m) is located 80 km northeast of Ji-Parana. It is in an ecological reserve of the Brazilian Environmental Protection Agency. Meteorological measurements were made on a 52-m-high tower. The average tree height is 33 m, but some trees reached 44 m. The soil at the Reserva Jaru forest site is a medium-textured, red–yellow podzol (Hodnett et al. 1995).

The data used in this study are from November 1991 to December 1993. Over this period, reasonably consistent hourly average data were collected using the automatic weather station, but there were some periods without data. The longest gap in the dataset is a period of 20 days in early 1992, and there are additional gaps of approximately six days in May 1992 and five days in March–April 1993. There are also some minor gaps in the data, mainly lasting less than a day, that often occur just before or just after the longer gaps. Because testing model performance requires that the model be provided with continuous forcing data, synthetic data were generated to fill the data gaps. If the missing data period was 2 h or less, intermediate values were generated by linear interpolation. If the period was longer than 2 h, the appropriate hourly average value for the month in which the data gap occurred was substituted. Model-calculated values for periods in which synthetic data were used to force the models were not included in flux data comparisons or optimization procedures.

Latent and sensible heat flux measurements were

made in intensive observation periods between August and October in 1992 and between April and July in 1993. These measurements were used to evaluate model-calculated fluxes in this study, along with 30-min-average CO<sub>2</sub> flux measurements that were made continuously for a period of 44 days during the second of these two intensive observation periods.

As mentioned earlier, BATS2 makes separate calculations of stomatal resistance for leaves that are exposed to direct and exposed to diffuse solar radiation, the relative proportion of these two fluxes normally being provided by the GCM in which the model is applied. As demonstrated later, the performance of BATS2 is sensitive to the proportion of solar radiation that arrives in diffuse form, but the ABRACOS data do not include observations that document this ratio. In the absence of such observations, it was assumed arbitrarily that 50% of solar radiation was diffuse during the evaluations of BATS2, and sensitivity studies were made to investigate the effect of this assumption on the preferred value of minimum stomatal resistance.

### *c. Strategy and methods*

Systems engineering methods currently are being developed that promise the capability to determine simultaneously the model-specific set of parameters that allows complex LSMs (such as BATS and SiB) to give an optimum description of the field data (e.g., Gupta et al. 1999; Bastidas et al. 1999). In future work, we intend to apply these methods to give the optimum set of values for model parameters for tropical forests for the three models investigated in this study. The purpose of the current study was not to carry out a systematic parameter estimation exercise but rather to seek insight into the credibility and relevance of the physics and biophysics represented in the different models and to investigate which model features and model parameters are most critical in determining the calculated fluxes and their comparability with observations. Some parameters were adjusted when relevant site-specific knowledge (e.g., vegetation height and measurement height) was available, however, and to ensure that, when more than one of the models included representation of a similar feature, the parameter values in the formulas representing these processes were the same in different models. Moreover, optimization of certain key parameters was made by minimizing the root-mean-square error (rmse) between simulated and modeled latent heat fluxes to demonstrate that merely changing the value of these critical parameters allowed the models to reproduce the observations adequately. Latent heat flux was used in the optimization because it is the largest component of the energy balance and it is related closely to the minimum stomatal resistance, the parameter that is optimized.

The same hourly meteorological data are used to force all three models, and the model outputs then are com-

pared with each other and with observations, either as hourly, daily, or monthly averages, as appropriate. However, measured CO<sub>2</sub> fluxes are known to include substantial random errors. Moreover, the trapping of CO<sub>2</sub> in the forest canopy can mean that CO<sub>2</sub> leaves the forest in rapid bursts, the timing of which is not related to the time at which carbon exchange processes occurred in the vegetation (see, e.g., Grace et al. 1996). For this reason, when describing carbon fluxes, the cumulative carbon uptake was used to evaluate the performance of the models.

The first step in the model evaluation was to reproduce the evaluation of SiB2 carried out by da Rocha et al. (1996). Then, to evaluate the long-term performance of SiB2, a model run was made with forcing data from November 1991 to December 1993. As demonstrated later, this long-term simulation revealed the need to modify the rooting depth used in SiB2. The model aerodynamic parameters also were revised to give consistency with the vegetation and measurement heights at the Ji-Parana site. (In practice, the simulated fluxes showed little sensitivity to this minor change in aerodynamic parameters.)

The same site-specific, morphology-related aerodynamic parameters and increased value for rooting depth also were used in the BATS evaluation, but otherwise the prescribed default values for BATS were used, with a site-appropriate specification of soil class. In fact, BATS already has been evaluated with different Amazon rain forest data (e.g., Arain et al. 1997). As expected, therefore, BATS gave a reasonable description of the current data once the rooting depth had been revised.

Last, an offline version of BATS2 was derived from the coupled version described by Dickinson et al. (1998). For consistency with the other two models, the evaluation of BATS2 was made using site-specific soil and aerodynamic parameters and an increased value for rooting depth, but, initially, default values were used for the other BATS2 parameters. As demonstrated later, this first evaluation revealed the need for an investigation of the most appropriate value for minimum stomatal resistance. The ability of BATS2 to simulate observed carbon assimilation and respiration rates and vegetation growth model then was evaluated in detail.

## **3. Results**

### *a. Reevaluation of SiB2*

Da Rocha et al. (1996) calibrated SiB2 for the Reserva Jaru site using field data collected during 44 days in the wet season of 1993. They optimized the value of  $V_{\max}$ , the maximum leaf catalytic capacity at the canopy top, and the slope parameter in the Ball–Berry equation (Ball et al. 1987) that relates stomatal conductance to canopy assimilation. They then ran the SiB2 model for three forest sites, namely, Reserva Ducke, Reserva Jaru,

TABLE 1. Values of parameters used in SiB2 in model runs for the Ji-Parana forest site. The values in column 3 are those specified by da Rocha et al. (1996), and those in column 4 are the revised values used in this study ( $R_b$  is the canopy airspace aerodynamic resistance, and  $R_d$  is the ground-to-air-space aerodynamic resistance).

Parameter	Units	da Rocha et al. (1996) parameter value	Revised parameter value
Canopy top height	m	35	33
Reference height for wind	m	45	52
Reference height for temperature	m	45	52
Roughness height	m	2.02	2.56
Zero plane displacement height	m	28.81	25.2
Canopy source height for heat	m	24.81	22.42
Coefficient of $R_b$	( $s\ m^{-1}$ ) <sup>0.5</sup>	5.59	8.92
Coefficient of $R_d$	none	1177.14	386.6
Rooting depth	m	3.5	8
Maximum leaf catalytic capacity	$\mu\text{mol}\ m^{-2}\ s^{-1}$	81.8	79.4

and Reserva Vale, for selected time periods between October 1990 and December 1994, but they constrained the soil-moisture status to high values in these runs. (The fact that soil moisture was constrained in these runs is important, as described later.) Da Rocha et al. (1996) also carried out an additional run for the Reserva Ducke site using the meteorological data collected between September 1983 and August 1985 during the Amazon Region Micrometeorological Experiment (ARME; Shuttleworth, 1988).

Unlike in the da Rocha et al. (1996) study, forest morphology parameters and observation heights were used in this study that were specific to the study site. At the Ji-Parana site (Gash et al. 1996), the meteorological measurements used as forcing variables in this study were made at the top of a 52-m-tall tower, and the heights of the canopy top and canopy bottom were estimated as 33 and 1 m, respectively. After Sellers et al. (1989), it was assumed that peak leaf area occurs 80% of the way up (at 26.6 m) from the bottom toward the top of the canopy. LAI was treated as being constant and equal to  $4.7\ m^2\ m^{-2}$  for Reserva Jaru in the SiB2 model runs, as in da Rocha et al. (1996). With this specification of the canopy structure, and the use of other relevant parameters such as leaf length and leaf width from Sellers et al. (1989), the MOMOPT code (Sellers et al. 1996) calculates roughness length and zero plane displacement height to be 2.56 and 25.2 m, respectively (Table 1). As did da Rocha et al. (1996), we assumed that the greenness factor  $G$  varied monthly, with its value interpolated between a maximum value of 0.89 in March and a minimum value of 0.80 in November. The initial soil wetness fractions are taken as 0.75, 0.75, and 0.85 for surface, rooting, and recharge layers, respectively.

The results of the long-term reevaluation of SiB2 showed that, when the SiB2 model is run continuously for 26 months with the parameter set defined by da Rocha et al. (1996), it calculates an increasing soil-moisture stress that dramatically reduces the evaporative fluxes to below observed values during the dry season in 1993 (Fig. 1a). In fact, ABRACOS results in general

do not suggest that there is soil-moisture stress or significantly reduced evaporation during periods without rain (Wright et al. 1996). Moreover, there is evidence (Hodnett et al. 1995; Nepstad et al. 1994) that, in the Amazon River basin, trees can access soil moisture from depths greater than 3.5 m, which is the rooting depth specified for SiB2 in the da Rocha et al. (1996) parameter set. Nepstad et al. (1994) reported that most root water extraction occurred between 2 and 8 m during the dry season in the eastern Amazon, and Delire et al. (1998) used an 8-m rooting depth in an Interactions among Soil, Biosphere, and Atmosphere model calibration study for the Reserva Jaru site. In this study, a rooting depth of 8 m and uniform rooting to this depth therefore were adopted in the simulations. This change substantially improved the modeled latent heat fluxes (Fig. 1a).

A progressive increase in the soil-moisture deficit (and reduction in evaporation) was not reported by da Rocha et al. (1996) in their long-term evaluation of SiB2 because, in that study, the soil moisture status in SiB2 was constrained artificially to maintain soil-moisture content greater than 70%. In fact, the phenomenon of soil moisture stress and the consequent reduction in transpiration may be particular to the southwestern portion of the Amazon River basin where there is an extended period with little rain. Multiyear simulations using SiB2 with 3.5-m-or-shallower rooting depths and forcing data from ARME (Shuttleworth 1988) for a site near Manaus (where the dry season is less extreme) do not show a marked decline in latent heat flux during the dry season. At the Manaus site, rainfall is high enough to maintain a reasonably small soil-moisture deficit even during the dry season, and, in fact, SiB2 (and other LSMs investigated in this study) can give a reasonable simulation of the surface energy balance even with assumed rooting depths shallower than 1.5 m.

A detailed comparison of hourly average fluxes was made between observations and the calculated values given by SiB2 using the Ji-Parana site-specific aerodynamic parameters and an 8-m-deep rooting zone, but otherwise using the parameters given for SiB2 by da

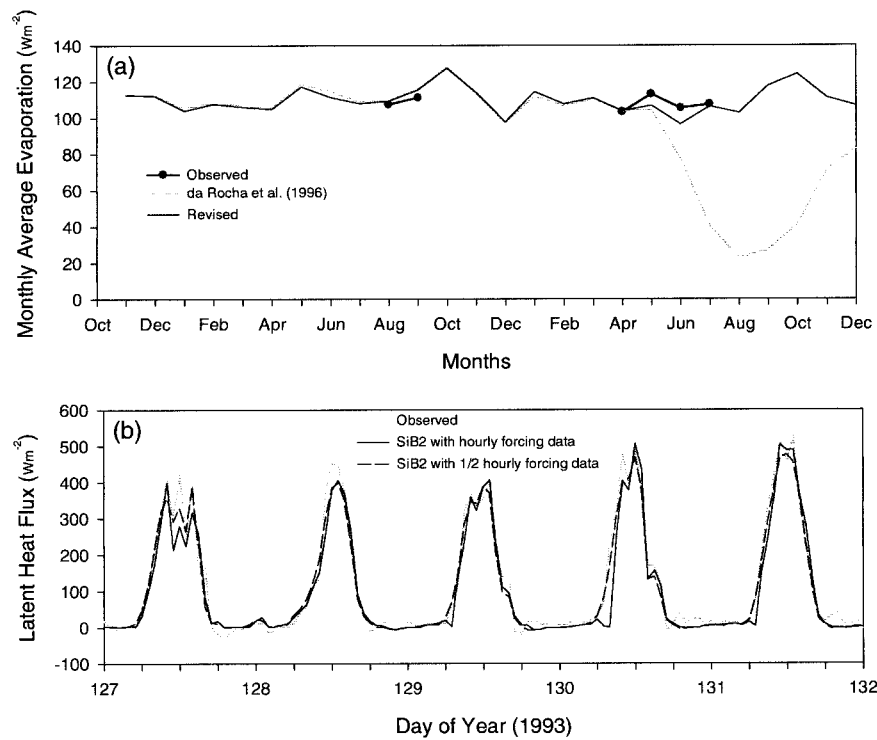


FIG. 1. (a) Monthly average latent heat flux simulated by SiB2 (Sellers et al. 1996) for the 26 months for which meteorological data are available at the Ji-Parana site. The fluxes calculated using the parameters as specified by da Rocha et al. (1996) are shown as a gray line, and the fluxes calculated using the revised parameters are shown as a thin black line. The measured monthly average values for those months in which flux data were taken are shown as a thick black line. (b) Hourly average latent heat flux as simulated by the SiB2 model on five selected days when provided with hourly and half-hourly forcing data in comparison with observed values. The observed fluxes are shown as a thick black line, and the fluxes calculated by SiB2 using hourly and half-hourly data are shown as a thin black line and a broken line, respectively.

Rocha et al. (1996). This comparison revealed that, in the early-morning hours on several (but not all) days, SiB2 sets the latent heat flux to zero (see Fig. 1b). This value is not observed in the field data, nor does it occur with the other land surface schemes (BATS and BATS2) investigated in this study. Analysis showed that this phenomenon is because SiB2 (wrongly) simulates dew formation during this period and sets the latent heat flux to zero while adding the excess available energy to the sensible heat flux. SiB2 is designed to run with a time step of less than 1 h, and dew formation was suppressed in the current analysis by creating a half-hourly time series of forcing data (by linear interpolation), then running the model at this reduced time step (Fig. 1b).

Thus, the reevaluation of SiB2 performance relative to the ABRACOS observations at the Ji-Parana site suggested some adjustments in the parameters given by da Rocha et al. (1996). For consistency with the conditions at the Ji-Parana site, some descriptive features of the canopy and observational environment were adjusted, resulting in a small change in the aerodynamic properties of the canopy. More important, if SiB2 is to be used in simulations lasting more than one year, it re-

quires a much deeper (in this study, 8 m) rooting depth. Adoption of these changes in SiB2 parameters and use of half-hourly forcing data to remove the unrealistic early-morning simulation to allow optimum simulation of the measured fluxes results in the preferred value of  $V_{\max}$  being slightly lower than the value derived by optimization by da Rocha et al. (1996). The suggested preferred value of  $V_{\max}$  is 79.4 rather than 81.8  $\mu\text{mol m}^{-2} \text{s}^{-1}$ . The equivalent value of  $r_{\text{min}}$  can be calculated using the expression  $r_{\text{min}} = 3\rho_a/(c_f V_{\max})$  (Dickinson et al. 1998), where  $\rho_a$  is density of air, and  $c_f$  is a conversion factor (in  $\text{g } \mu\text{mol}^{-1}$ ). Thus, a value of 79.4  $\mu\text{mol m}^{-2} \text{s}^{-1}$  for  $V_{\max}$  is approximately equal to a value of 60.3  $\text{s m}^{-1}$ . The plausibility of this value is discussed at the end of section 3c(1).

The rmse between observed and model-calculated evaporation flux is 29.3  $\text{W m}^{-2}$  when these revised parameters are used in a model run in which soil moisture is initiated at the beginning of the period in 1993 for which flux data are available. This value is comparable to the 32.9  $\text{W m}^{-2}$  obtained when the parameters recommended by da Rocha et al. (1996) are used. When the SiB2 parameters suggested by this study are used,

TABLE 2. Measures of relative performance of land surface models for evaporative flux relative to data. Columns 3 and 4 refer to SiB2 (Sellers et al. 1996), using the parameters specified by da Rocha et al. (1996) in column 3 and the revised parameters specified in the text in column 4. Columns 5 and 6 refer to BATS (Dickinson et al. 1993), using the BATS default parameters in column 5 and the revised parameters specified in the text in column 6. Columns 7, 8, 9, 10, and 11 refer to BATS2 (Dickinson et al. 1998). Default parameters are used in column 7. The parameters specified in the text as options 1, 2, 3, and 4 with their respective preferred values for minimum stomatal resistance are used in columns 8, 9, 10, and 11.

Mean monthly $\lambda E$ (all in $W m^{-2}$ )	Observed	SiB2 (Sellers et al. 1996)		BATS (Dickinson et al. 1993)		BATS2 (Dickinson et al. 1998)				
		Da Rocha et al. (1996) parameters	Revised parameters	Default parameters	Revised parameters	Default parameters	Option 1	Option 2	Option 3	Option 4
Aug 1992	107.4	109.9	109.3	66.4	105.3	56.1	110.8	110.0	111.3	113.4
Sep 1992	111.1	115.9	115.3	112.9	117.9	85.7	115.4	115.9	115.0	116.4
Apr 1993	103.2	103.7	103.6	104.9	103.6	78.4	100.8	101.5	100.4	101.6
May 1993	112.9	104.2	106.7	91.7	107.3	78.8	105.2	105.9	104.9	106.3
Jun 1993	105.2	77.3	96.5	45.7	97.5	50.5	98.9	99.0	99.1	100.5
Jul 1993	107.4	40.3	106.2	46.2	102.8	48.1	110.9	108.1	110.5	112.9
Rmse (all data)	—	58.5	29.1	87.1	32.4	93.5	29.4	29.3	29.8	30.3

rmse calculated for fluxes measured in both 1992 and 1993 is  $29.1 W m^{-2}$  when SiB2 is used with all the ABRACOS forcing data available at the Ji-Parana site. The equivalent rmse is  $58.5 W m^{-2}$  when the parameters recommended by da Rocha et al. (1996) are used, because of the progressive buildup in calculated soil-moisture stress they cause. Table 2 (columns 3 and 4) documents the difference in model performance with the original and revised set of parameters.

### b. Evaluation of BATS

Most of the parameters used in this evaluation of (the original version of) BATS were the model's default values for tropical rain forest, but some parameters were modified to ensure compatibility with SiB2 during the evaluation. The default parameters for evergreen broadleaf forests assume a rooting depth of 1.5 m and that 80% of the roots are in the upper 10 cm of soil, which means that most of the root water uptake occurs in the upper layer. Use of these default values, however, causes a progressive decline in modeled latent heat flux at the Reserva Jaru site near Ji-Parana during long-term simulations that is similar to that reported above for SiB2. The rooting depth consequently was increased to 8 m in the BATS evaluation, and all the roots were assumed to be distributed uniformly throughout this rooting layer that also included the surface layer. The initial values of soil moisture in the three soil layers described in BATS also were initiated to be consistent with the SiB2 model runs, and the same (site specific) values were used for aerodynamic roughness length and zero plane displacement height.

The BATS default value for soil texture in the Amazon River basin is 10, that is, very close to pure clay. (Note: in BATS, the soil texture class for sand is 1, and that for clay is 12.) Wright et al. (1996), however, classified the soil in Reserva Jaru as being coarse with a high sand content. Field observation shows that the soil is 50% sand to a depth of 1.5 m and that sand content

can reach 85% at the soil surface. Moreover, the reported values for saturated soil-moisture content (Wright et al. 1996) indicate that soil porosity is  $0.305\text{--}0.483 m^3 m^{-3}$ , and measurements in the upper 1 m show that the saturated hydraulic conductivity is in the range of  $0.0027\text{--}0.018 mm s^{-1}$ . Class 4 was selected from among the BATS soil texture classes for use in this BATS evaluation to reflect these field observations.

The original version of BATS uses a Jarvis (1976)-type model to describe stomatal resistance. Thus, a prescribed, cover-specific minimum stomatal resistance is increased by stress factors that are functions of temperature, solar radiation, vapor pressure deficit, and soil-moisture content. The default value of minimum stomatal resistance given for evergreen broadleaf forests is  $150 s m^{-1}$ . Minimization of the rmse between observed and BATS-modeled latent heat flux suggests a lower value ( $140 s m^{-1}$ ) for minimum stomatal resistance. Although this value is slightly smaller than the default value, it still is much higher than the values indicated by Wright et al. (1996). Table 2 (columns 5 and 6) documents the difference in model performance obtained with BATS when the default parameters are replaced with the revised values recommended on the basis of the current evaluation. In practice, as was the case for SiB2, most of the reported improvement shown in Table 2 is a result of using an 8-m rooting depth.

In the comparison between modeled and simulated stomatal resistance, there is evidence that BATS can, on occasion, show excessive sensitivity to high values of atmospheric vapor pressure deficit. This evidence is discussed in greater detail in section 3d.

### c. Evaluation of BATS2

#### 1) EVAPOTRANSPIRATION

In the evaluation of BATS2, the model's default values for tropical rain forest mainly were used, but the same (8 m) rooting zone and the same site-specific soil

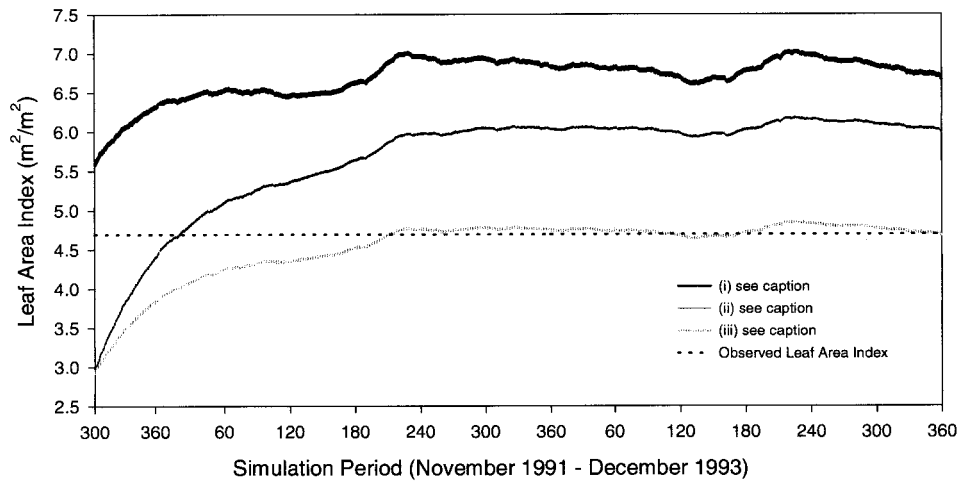


FIG. 2. Estimated leaf area over the period for which forcing data were available in this study. The results shown correspond to estimated values given with (i) default values of specific leaf area ( $25 \text{ m}^2 \text{ kg}^{-1}$ ) and canopy optical depth coefficient (0.25), (ii) specific leaf area of  $13 \text{ m}^2 \text{ kg}^{-1}$  and default canopy optical depth coefficient (0.25), and (iii) specific leaf area of  $13 \text{ m}^2 \text{ kg}^{-1}$  and a canopy optical depth coefficient of 0.34.

and aerodynamic parameters used with BATS were adopted. There are additional parameters defined in BATS2 (leaf freezing temperature, etc.) that are not relevant in BATS, and, in general, in this study, these new parameters were assigned the values suggested in Dickinson et al. (1998). As mentioned earlier, however, in BATS2 the value of LAI is not prescribed as it is in BATS; rather, it is calculated by a growth model. Some of the parameters used in this leaf growth model were adjusted from those given by Dickinson et al. (1998) to improve consistency with observations. Specifically, the assigned values of specific leaf area (SLA) and the reciprocal optical depth for  $e^{-1}$  light decay (TAUHF, used to describe carbon allocation to the leaves) were assigned on the basis of on-site measurements, as follows.

Reported values of LAI for the Ji-Parana study site include 4.4 and  $4.7 \text{ m}^2 \text{ m}^{-2}$  and, for consistency with the evaluation of SiB2 reported earlier, the value  $4.7 \text{ m}^2 \text{ m}^{-2}$  was selected as representative of the study site. Figure 2 shows LAI calculated by the BATS2 growth model during the period for which forcing data are available. With the default values of SLA and TAUHF suggested by Dickinson et al. (1998), the leaf area index given by the BATS2 growth model asymptotically approaches values in the range  $6.5\text{--}7.0 \text{ m}^2 \text{ m}^{-2}$ , that is, to values much greater than observed values. Meir et al. (1996) gave the value of 3.6 metric tons  $\text{ha}^{-1}$  for the leaf mass at this site, which, for a leaf area index of  $4.7 \text{ m}^2 \text{ m}^{-2}$ , corresponds to a specific leaf area of  $13 \text{ m}^2 \text{ kg}^{-1}$ . Using this value in BATS2 indeed does give a lower asymptotic estimate of LAI (Fig. 2). The value remains higher than the preferred value of  $4.7 \text{ m}^2 \text{ m}^{-2}$ , however, because the growth model increases the proportion of carbon allocated to the leaves in response to the reduced value of specific leaf area. To regain the original partitioning of carbon to the leaves, it is nec-

essary to increase the optical depth coefficient (used in the carbon partitioning) from 0.25 to 0.34. Such an increase arguably is more consistent with the resulting asymptotic value of LAI, which, as Fig. 2 shows, is itself more consistent with the preferred value of  $4.7 \text{ m}^2 \text{ m}^{-2}$ . The value of optical depth coefficient adopted in this study falls in the range of reported values for six broadleaf forests given by Jarvis and Leverenz (1983). In practice, however, these modifications of BATS2 parameters have little effect on the calculated assimilation and transpiration because the model has little sensitivity to the variations at higher values of LAI (Yang et al. 1999).

In BATS2, stomatal resistance and  $\text{CO}_2$  assimilation are related via an equation of the Ball–Berry type (Ball et al. 1987), as they are in SiB2. SiB2, however, retains the linear relationship with respect to the relative humidity  $r$  used in the original Ball–Berry equation. In BATS2, this relationship is replaced by a function of atmospheric VPD:

$$F(\text{VPD}) = 1/(1 + 0.05\text{VPD}). \quad (4)$$

Figure 3a shows a comparison between the values of  $F$  and  $r$  when calculated from the leaf-level specific humidity estimated by BATS2 when forced by Ji-Parana ABRACOS data. Near saturation, the value of  $F$  falls more rapidly than does  $r$ , and it then generally remains less than  $r$  except when relative humidity is below 0.4. On some occasions, large-scale air movement results in the air mass overlying the site being atypically cool. When this event happens,  $F$  can be larger than  $r$  even when relative humidity is greater than 0.4. Nonetheless, Fig. 3a shows that  $F$  and  $r$ , in general, are approximately equal. In fact, if the coefficient in Eq. (4) is changed to 0.04, the resulting function  $F'$  is more closely similar to  $r$  (Fig. 3b), and the average values of  $F$  and  $r$  are



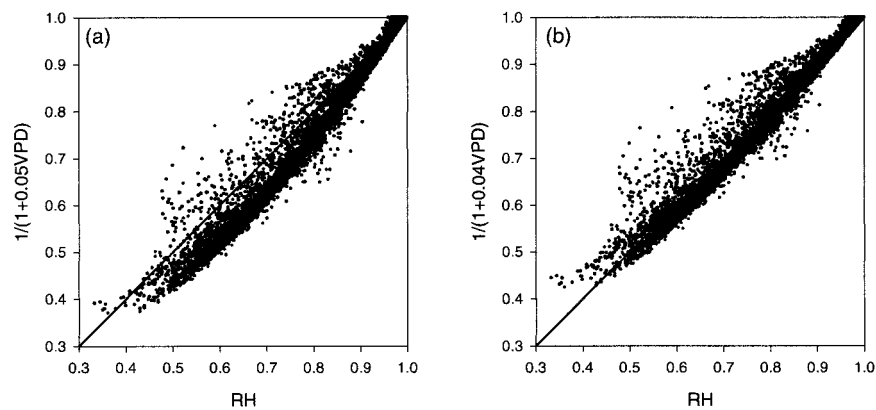


FIG. 3. (a) The stress factor for atmospheric humidity deficit used in BATS2 evaluated for the observed meteorological data at the Ji-Parana site vs relative humidity. [Note: In BATS2, this stress factor is Eq. (4), and SiB2 assumes that the equivalent stress factor is equal to relative humidity.] (b) Same as for (a), except the coefficient in Eq. (4) is 0.04 rather than 0.05.

equal at the Ji-Parana site. Later, the effect of using different humidity stress factors in BATS2 will be explored in greater detail.

The simulations made with the Ji-Parana data using the default value of  $r_{smin}$  ( $150 \text{ s m}^{-1}$ ) consistently underestimate the latent heat flux by about 20%–50% throughout the period for which forcing data are available. Therefore, an investigation was made into what changes were required in the value of  $r_{smin}$  to give improved comparison with observations. In this investigation, rmse between observed and model-calculated hourly average latent heat fluxes was used to evaluate relative performance. Figure 4a shows the variation in rmse as a function of the value of  $r_{smin}$  in four different cases. In all cases, the rooting zone depth was set to 8 m, and BATS class 4 soil parameters and site-specific aerodynamic parameters were used in the BATS2 model runs. Option 1 corresponds to the BATS2 model specification used by Dickinson et al. (1998), that is, the humidity stress function given as Eq. (4) was retained along with the original Ball–Berry parameters. In this case, the preferred value of  $r_{smin}$  is  $48 \text{ s m}^{-1}$ .

In option 2, the humidity stress function used in BATS2 is no longer Eq. (4); relative humidity is used instead. This change slightly decreases rmse and increases the preferred value of  $r_{smin}$  to  $56 \text{ s m}^{-1}$ . Option 3 is the same as option 1, except the parameter used in Eq. (4) is changed from 0.05 to 0.04. Because relative humidity and Eq. (4) with a parameter value of 0.04 are in fairly good agreement (Fig. 2b), the preferred value of  $r_{smin}$  in option 3 ( $54 \text{ s m}^{-1}$ ) remains very close to that of option 2. There is a small increase in the rmse between option 2 and option 3. For the purpose of comparing these two humidity stress functions, the same  $r_{smin}$  value ( $56 \text{ s m}^{-1}$ ) was used for both options. Option 4 is the same as option 3 except that, in this case, the Ball–Berry slope parameter is changed from the original value used by Dickinson et al. (1998) to the value ( $m = 11.948$ ) suggested by da Rocha et al. (1996). In option

4, the concentration of  $\text{CO}_2$  adjacent to the leaf and minimum stomatal conductance also are set to 340 ppm and  $0.0002 \text{ m s}^{-1}$ , respectively, to match the values assumed in SiB2. With these changes, rmse is altered little with respect to option 3, but  $r_{smin}$  is increased to  $61 \text{ s m}^{-1}$ . As previously shown, this value is very close to the value of  $r_{smin}$  used in SiB2.

It is important to recognize that this preferred value of  $r_{smin}$  is sensitive to the diffuse fraction of solar radiation (assumed to be 50% in the current study) because this sensitivity affects the contribution of shaded leaves to the overall canopy conductance. Figure 4b illustrates how the preferred value of  $r_{smin}$  changes with the assumed proportion of diffuse radiation, but there is little change in rmse over the whole range. As expected, the greater the proportion of diffuse radiation, the greater the fractional contribution of shaded leaves (Fig. 4c), providing the leaves are not light saturated. Estimates were made of daily average diffuse radiation from the daily global radiation (Roderick 1999), which suggests that the assumed value (50%) was realistic as an average over the whole period. Moreover, assuming this daily estimate applied at each daylight hour in BATS2 did not alter greatly the preferred value of  $r_{smin}$ .

Table 2 (columns 7–11) documents the difference in model performance obtained with BATS2 with the different parameter options. In Table 2, most of the improvement between using default parameters and parameter options 1–4 results from using an 8-m rooting depth. Option 2 is marginally preferred in that it gives a slightly lower value for rmse and it more commonly calculates a mean monthly latent heat flux closer to observations.

In all the cases considered, optimizing rmse between modeled and observed latent heat fluxes suggests values of  $r_{smin}$  that are much less than the value  $150 \text{ s m}^{-1}$  used by Dickinson et al. (1998). The resulting optimized values, however, are more consistent with estimates given by Wright et al. (1996), which, when interpreted for a

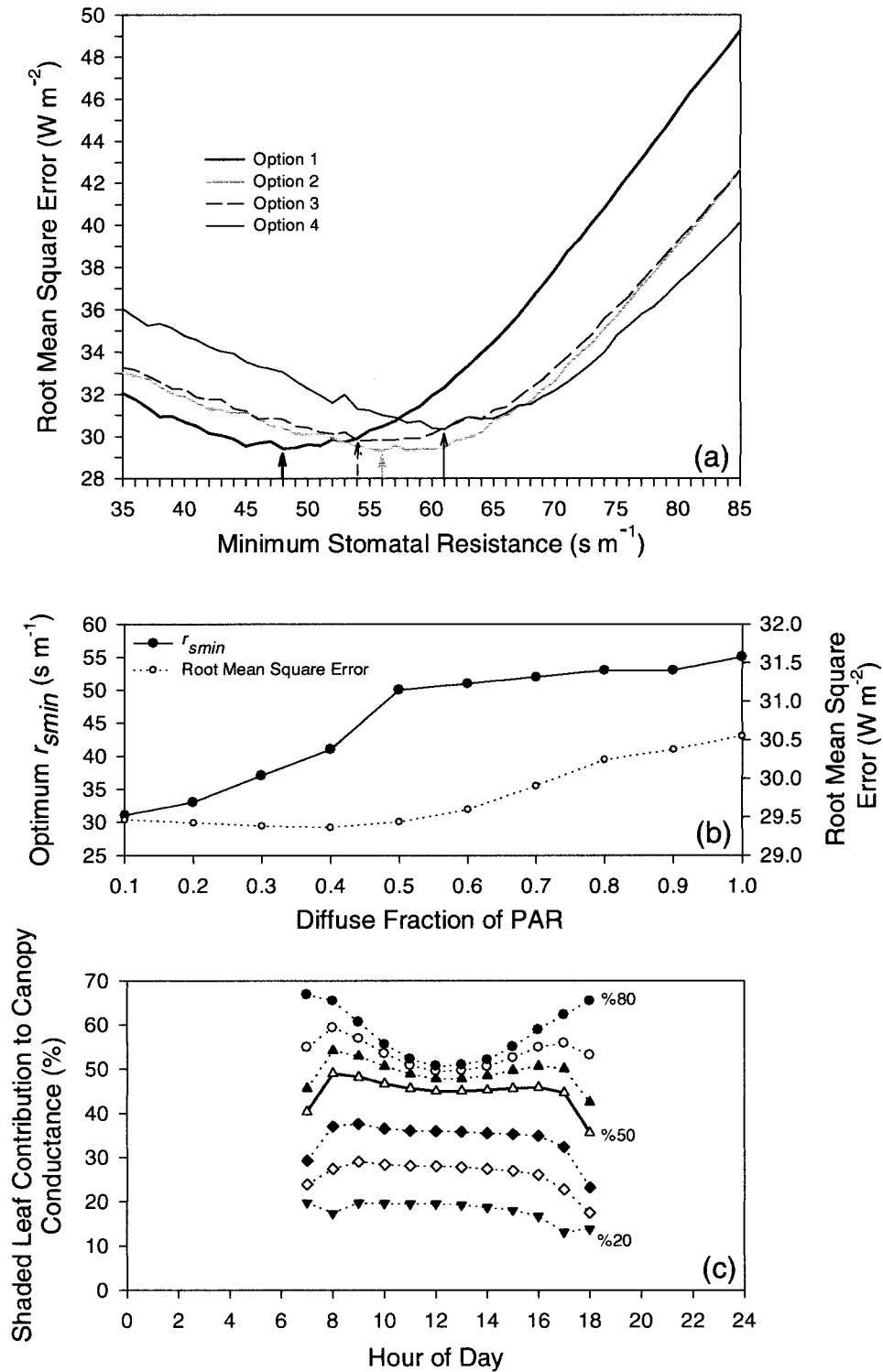


FIG. 4. (a) The rmse between the observed and the model-calculated latent heat flux given by the BATS2 model as a function of the assumed value of minimum stomatal resistance. The four options are explained in the text. (b) Variation of the preferred value of  $r_{smin}$  as a function of the diffuse fraction of photosynthetically active radiation when LAI is held constant ( $4.7 m^2 m^{-2}$ ). Also shown is the equivalent rmse between the observed and model-calculated latent heat fluxes for the preferred value. (c) Contribution of shaded leaves to the canopy conductance with the diffuse fraction of solar radiation increasing from 20% to 80% in 10% intervals.

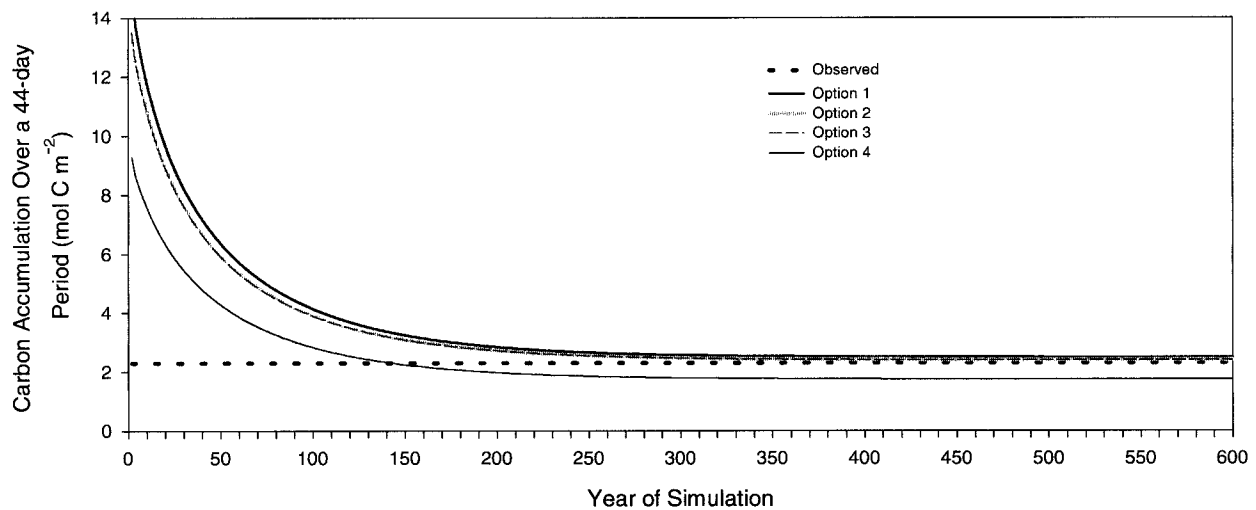


FIG. 5. The net carbon accumulation calculated by BATS2 for the 44-day period (corresponding to the observations in 1993) when the model is forced repeatedly with the 24-month time series of meteorological data. The four options are explained in the text. The dotted line indicates the net carbon accumulation observed at the Ji-Parana site during this 44-day period in 1993.

rain-forest canopy with a leaf area index of 4.7, suggest  $r_{smin} = 59\text{--}72 \text{ s m}^{-1}$ , depending on whether above- or within-canopy meteorological measurements are used to calculate stress factors. Moreover, it is important to remember that the Wright et al. (1996) results relate to the whole canopy, but, as discussed above, the definition of  $r_{smin}$  in BATS2 relates to leaves at the top of the canopy, where light is more abundant and stomatal resistance is lower.

## 2) CARBON EXCHANGE

One of the exciting features of BATS2 is that it includes a growth model that should allow its future use in coupled climate models. In the context of the current study, it is important to evaluate this new portion of the model with respect to observations and in comparison with SiB2. The main products of the growth model are LAI, net primary productivity, and the carbon flux to the atmosphere. In the model, the total  $\text{CO}_2$  flux to the atmosphere is calculated as the difference between carbon assimilation and total respiration, the latter being the sum of soil, root, wood, and leaf maintenance respiration and root, wood, and leaf growth respiration. Later, the daily cycle in observed net carbon exchange will be compared with that calculated by BATS2, but first it is necessary to consider issues related to the initiation and subsequent evolution of the carbon stores represented in BATS2.

In BATS2, assimilated carbon provides the input to an assimilation pool that immediately is allocated to leaves, wood, and roots. (There is, for instance, no allowance for delay between assimilation of carbon in the leaves and the resulting carbon becoming available in the roots.) Carbon released from the plant by root and wood turnover and by leaf death is collected in a fast

soil carbon pool. Of the carbon in this fast soil carbon pool, 10% is then reallocated to a slow soil carbon pool, where it is considered to become part of the soil and no longer is available for release to the atmosphere.

In BATS2, the mass of carbon in plant and soil components of evergreen forest is set initially to default values. Specifically, the leaf biomass is set to 2 metric tons  $\text{ha}^{-1}$ , the above- and below-ground woody biomass is set to 135 metric tons  $\text{ha}^{-1}$ , the fine root biomass is set to 4.5 metric tons  $\text{ha}^{-1}$ , the fast soil carbon store is set to 2 metric tons  $\text{ha}^{-1}$ , and the slow soil carbon store is set to 0 metric tons  $\text{ha}^{-1}$ . When the model is forced with observed data from Ji-Parana starting from these initial values, most of the assimilated carbon is allocated to wood growth. Thus, the modeled forest “grows” and, in so doing, absorbs carbon until it matures. Once mature, most of the assimilated carbon then is allocated to roots, and approximate carbon equilibrium is established, with carbon assimilation in the leaves offset by the (now enhanced) respiration from the roots and soil.

Figure 5 illustrates the change of carbon accumulation during the same 44-day period (corresponding to carbon flux measurements in 1993), when BATS2 is repeatedly forced with the 24-month time series of meteorological data. Calculations are made with different combinations of atmospheric humidity stress factors and Ball-Berry parameters corresponding to the four options specified in section 3c(1), in each case with their preferred values of minimum stomatal resistance (48, 56, 56, and  $61 \text{ s m}^{-1}$  for options 1, 2, 3, and 4, respectively).

In these four model runs, BATS2 produces its equilibrium forest at different rates because the minimum stomatal resistance and, consequently, carbon assimilation by the leaves are different. In each case, the net carbon uptake ultimately asymptotically approaches values that are very similar to those observed during the

44-day validation period, and, in the case of options 2 and 3, the agreement is extremely good. Note, however, that the asymptotic limit for options 1 and 4 can be made equally good merely by changing the fractional allocation from the fast to the slow soil carbon stores from 10% to 8% and 22%, respectively.

In their asymptotic states, each modeled option grows a forest with different amounts of stored carbon. Figure 6 shows the change, during model runs, in the carbon stored as leaves (Fig. 6a), wood (Fig. 6b), and roots (Fig. 6c) in the plants and shows the change in the short-term (Fig. 6d) and long-term (Fig. 6e) carbon stores in the soil. Calculations are made with different combinations of atmospheric humidity stress factors and Ball–Berry stress factors corresponding to the four options specified in section 3c(1), in each case with their preferred values of minimum stomatal resistance. (Note: For simplicity, the figures all show the stored carbon on the last day of the repeated 2-yr cycle in the forcing data. In practice, there is a modeled annual cycle in all of the carbon stores that therefore is not perceptible in these figures.)

All four options give similar leaf masses. There is an asymptotic growth in the carbon stored as wood, roots, and fast soil carbon store toward values that are the greatest for option 1 and the least for option 4 (the higher the minimum stomatal resistance, the lower the asymptotic value of the stored carbon, and vice versa). The long-term stored carbon in the slow soil carbon store also continues to increase in all of the model runs, ultimately doing so at a constant rate that again is greatest for option 1 and least for option 4. Needless to say, for all options, initiating the carbon stores in BATS2 to the appropriate asymptotic values shown in Fig. 6 will eliminate the need for a long “spinup” when using BATS2. The initial value of the slow carbon pool in the soil, however, ultimately is irrelevant to the modeled exchanges.

The time taken for the forest to grow in BATS2 is longer than might be expected (Figs. 6a–e). Moreover, the modeled asymptotic limits for stored carbon as wood and roots are greater than those reported in the literature (e.g., Honzak et al. 1996; Lucas et al. 1996; Meir et al. 1996). Wood turnover in the form of tree death following insect attack, lightning strikes, wind throw, etc., is not modeled in BATS2, and the initial wood respiration rate and wood reservoirs are such that carbon accumulates (Dickinson et al. 1998). It is possible to adjust the final values of wood reservoirs by changing two parameters in the wood-to-root allocation model. We chose not to do this in this study because carbon fluxes ultimately are insensitive to the base rates of root, wood, and soil respiration because the model adjusts reservoir levels in response to changes in this ratio to maintain balance with production (Dickinson et al. 1998).

The CO<sub>2</sub> flux measurements described by Grace et al. (1996) are reasonably continuous for a period of 44 days just before the dry season in 1993. However, as

reported by Grace et al. (1996) and mentioned earlier, CO<sub>2</sub> released by respiration during the night often is trapped in the forest canopy by atmospheric stability and is released rapidly at sunrise when the increasing winds ventilate the canopy. In fact, in the case of BATS2, hourly comparison between model-calculated and observed fluxes also is problematic because aspects of BATS2 mean that the model cannot provide accurate simulation of the diurnal cycle in soil and root respiration and, therefore, of the net CO<sub>2</sub> exchange. Specifically, as mentioned earlier, in BATS2, soil respiration is expressed as a function of the modeled temperature of the soil surface, and this temperature has a stronger diurnal cycle than that of the lower soil layers where most soil respiration occurs. In addition, BATS2 assumes that some carbon assimilated by the leaves immediately is reallocated to the roots where 30% then is released immediately by root growth respiration. Because carbon assimilation occurs during the daylight hours, the modeled root growth respiration consequently has a marked daily cycle that is not observed in the field (Meir et al. 1996).

Figure 7 shows the average daily cycle of net carbon flux calculated by BATS2 for the 44 days for which data are available at the Ji-Parana site in 1993. Calculations are made with different combinations of atmospheric humidity stress factors and Ball–Berry parameters corresponding to the four options specified in section 3c(1), in each case with their preferred values of minimum stomatal resistance. The observed early morning release of carbon buildup during the night is apparent in this figure, as is the greater diurnal cycle in the modeled net carbon flux which results from the model’s simplifying assumptions about soil and root respiration.

#### d. Comparison of land surface models

Figure 8 illustrates the comparison between monthly average latent heat fluxes calculated by BATS2 (with option 1 parameters, after equilibration), BATS, and SiB2 for the Ji-Parana site after their respective model parameters have been modified to give improved performance as described above. In general, all three models are in reasonable agreement with each other over the 26-month period for which forcing data are available and with the observations when available. All three models overestimate monthly evapotranspiration in September 1992 and underestimate monthly evapotranspiration in May and June 1993. No distinct, causal feature common to the three models could be identified to explain this.

Figure 9a compares the hourly average latent heat fluxes calculated by SiB2 with that given by BATS2, and Fig. 9b gives a similar comparison for BATS and BATS2. In general, the agreement between the three models at the hourly timescale also is reasonable. The comparison between BATS and BATS2 (Fig. 9b) sug-

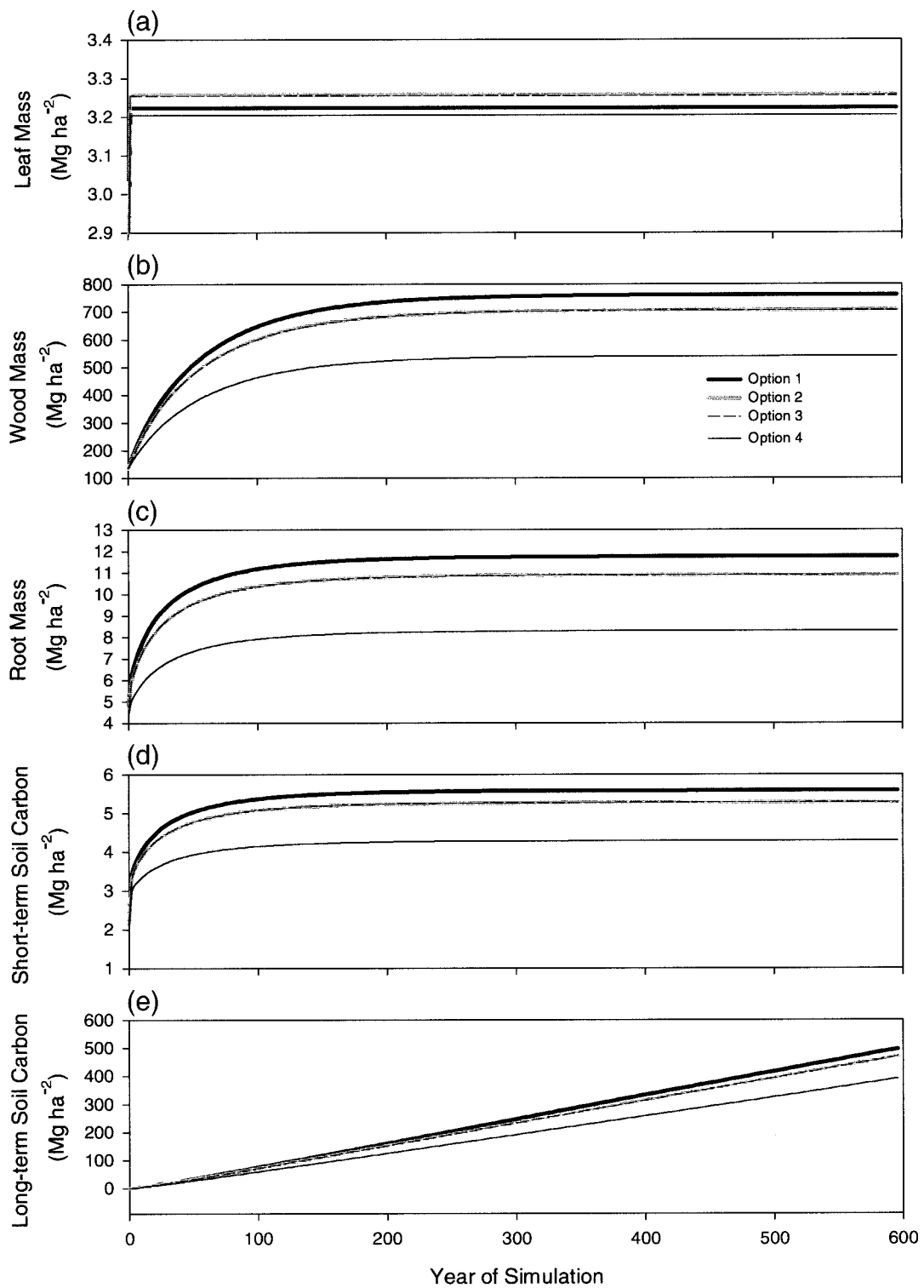


FIG. 6. The carbon stored in the (a) leaves, (b) wood, (c) roots, (d) short-term soil carbon store, and (e) long-term soil carbon store. The values shown are those calculated by BATS2 when it is forced repeatedly with the 24-month time series of meteorological data. All figures show the stored carbon on the last day of the repeated 2-yr cycle.

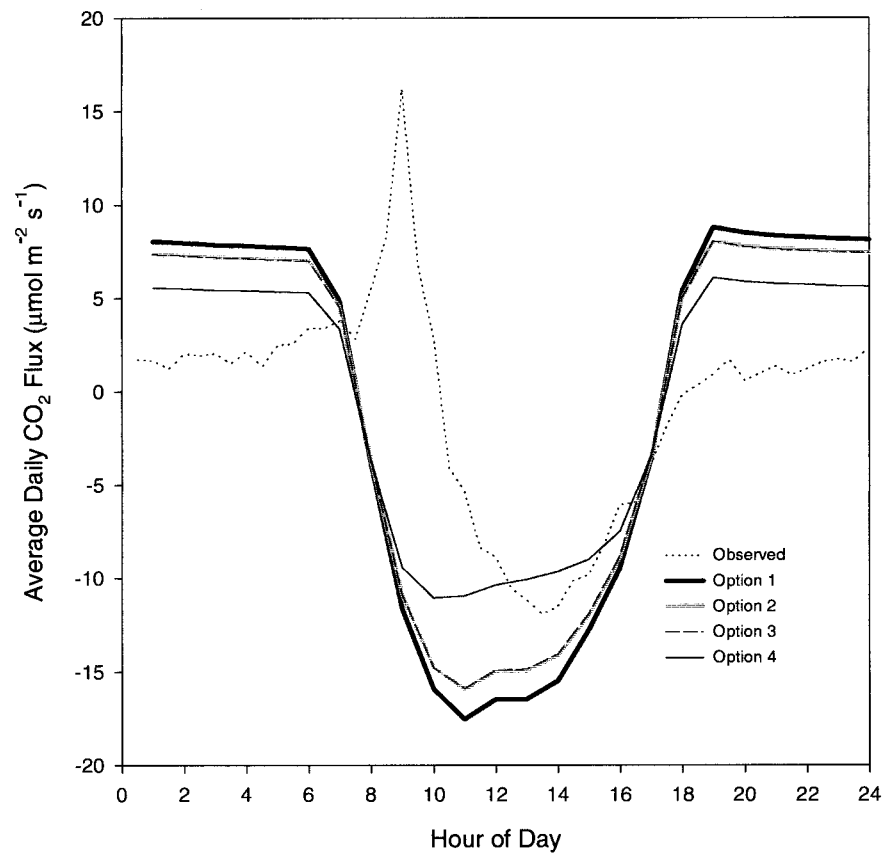


FIG. 7. Average daily cycle of net carbon flux calculated by BATS2 for the 44 days for which data are available in 1993. Also shown in this figure (as the dotted line) is the average daily cycle of net carbon flux observed at the Ji-Parana site during this 44-day period.

gests, however, that there are occasional hours when the model-calculated fluxes disagree noticeably, the tendency being for BATS to calculate much less latent heat flux than does BATS2. Figure 9c illustrates a 5-day time series of the latent heat flux calculated by BATS,

BATS2, and SiB2 that illustrates the occurrence of this phenomenon. In some situations at the Ji-Parana site, BATS can simulate a positive feedback between the stomatal resistance and the model-calculated vapor pressure deficit adjacent to the leaf surface, as follows. High

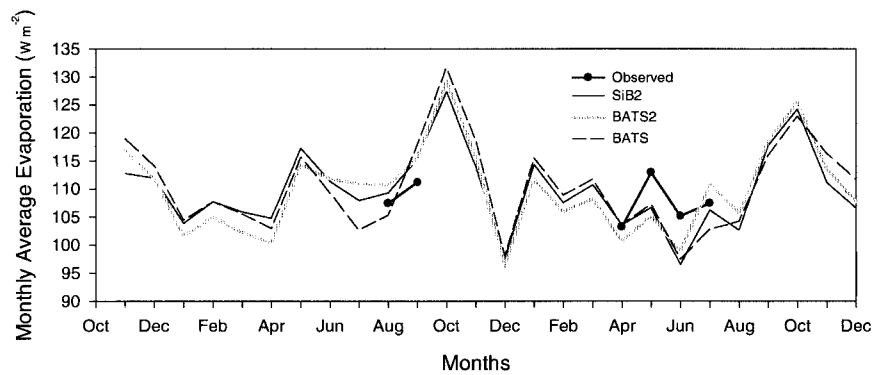


FIG. 8. Monthly average latent heat flux calculated by BATS2 using option-1 parameters (heavy continuous line), BATS (thin broken line), and SiB2 (thin continuous line) for the Ji-Parana site over the 26 months for which meteorological forcing data are available. In these simulations, the model parameters have been modified to give the best performance for each model, as described in the text.

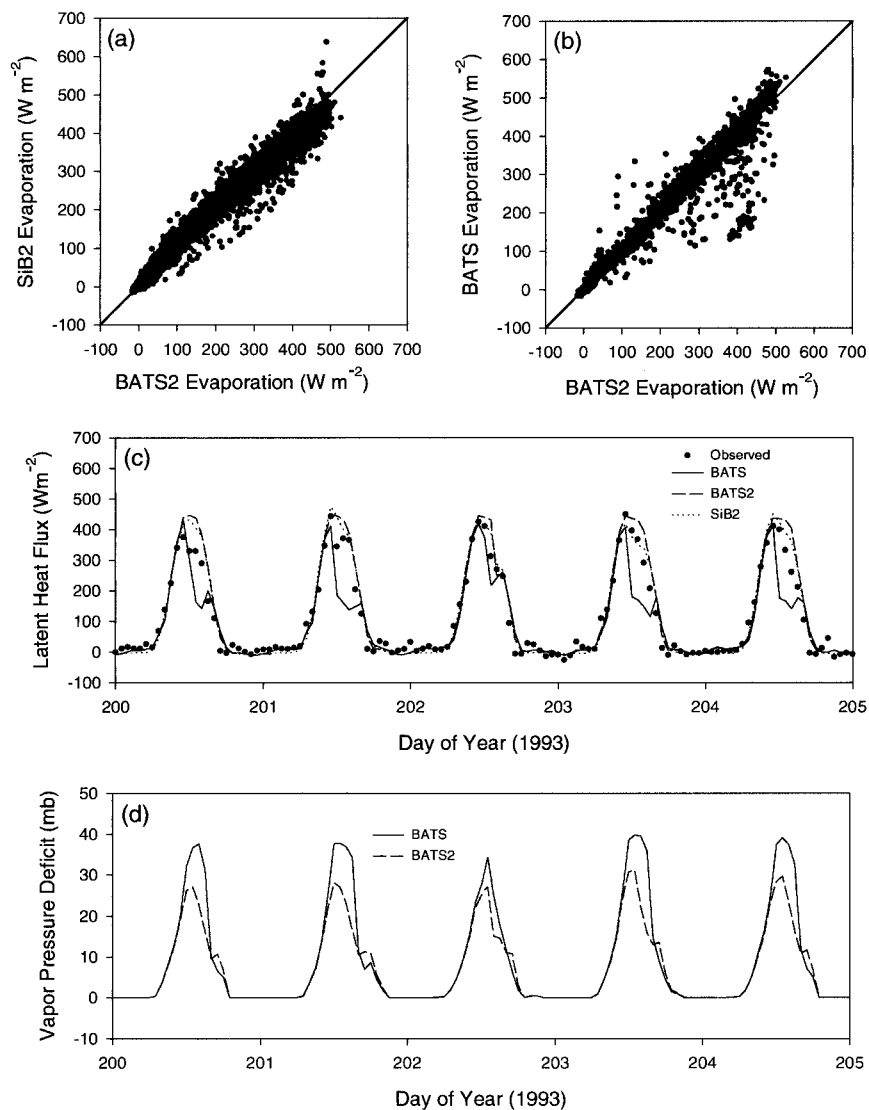


FIG. 9. Comparison between hourly average latent heat fluxes calculated by BATS2 relative to those calculated by (a) SiB2 and (b) BATS from the meteorological data available at the Ji-Parana site during 1993. (c) Hourly average latent heat flux on five selected days. The observations are shown as black dots. Also shown are the calculated values given by BATS, BATS2, and SiB2. (d) Calculated vapor pressure deficit at the surface of the leaves as calculated by BATS and BATS2 on these same five days.

ambient vapor pressure deficit causes the model's stomata to close, thus reducing the modeled latent heat flux and causing the leaf temperature to rise to maintain the surface energy balance. The increased leaf temperature, in turn, increases the vapor pressure deficit adjacent to the leaf, thus further closing the stomata and raising leaf temperature. Consistent with this explanation, Fig. 9d illustrates that the periods in which BATS calculates latent heat fluxes that are exceptionally low (Fig. 9c) relative to BATS2 and SiB2 are also periods when BATS is calculating exceptionally high (and unrealistic) values of vapor pressure deficit adjacent to the leaves. [Note: a similar phenomenon has been reported in simulations

made with the original version of SiB; see Sato et al. (1989).]

Figures 10a–c show the 7-day running mean for net carbon assimilation, net respiration, and the net  $\text{CO}_2$  flux to the atmosphere as calculated during 1993 by SiB2 and using four parameter options in BATS2 (at the end of 600-yr runs). Figure 10d is an expanded version of Fig. 10c for a time period that includes that during which  $\text{CO}_2$  flux measurements were made. The net assimilation rate and the net respiration rates both decrease from option 1 to option 4 in such a way that the net  $\text{CO}_2$  flux is broadly similar for all four options. Of the four BATS2 options, option 4 calculates the net

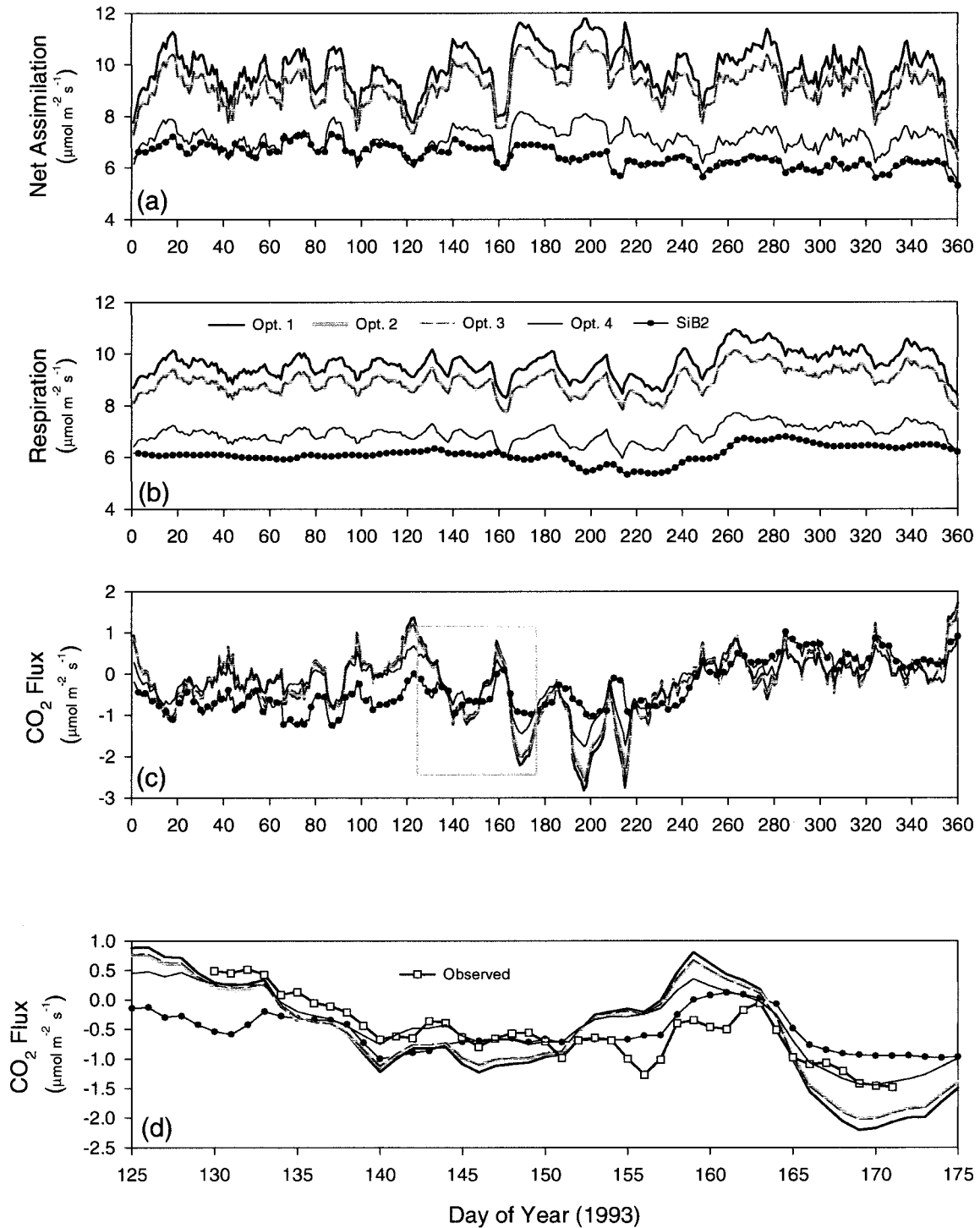


FIG. 10. Seven-day running mean of (a) net carbon assimilation, (b) net respiration, and (c) net carbon exchange for the whole forest stand calculated for the Ji-Parana site during 1993 by BATS2 for the four options specified in the text. Also shown as a thin continuous line with symbols are the values calculated by SiB2 with the revised parameters specified in the text. (d) Expanded version of (c) for a time period that includes that period during which flux measurements were made. The observations are shown as a continuous line with open squares.



assimilation rate that most closely resembles that given by SiB2. This result is not surprising given that they both use the same values in the Ball–Berry equation.

Figure 10b shows the total ecosystem respiration for SiB2 and the four BATS2 options (at the end of 600-yr runs), although, in the case of SiB2, wood respiration is ignored in the model. However, in the Amazon rain forest, wood respiration is approximately  $0.7 \pm 0.3 \mu\text{mol m}^{-2} \text{s}^{-1}$  during the night (Meir et al. 1996), and, being temperature dependent, it is likely to be greater during the day. It might be argued that the fact that SiB2 makes no representation of wood respiration indirectly was responsible for the need for a modified Ball–Berry slope parameter in the da Rocha et al. (1996) evaluation of SiB2. In that study, the preferred value of maximum rubisco capacity used in SiB2 (and, consequently, the modeled net assimilation rate) was derived by optimizing against the observed net carbon flux, assuming that the total respiration is given by Eq. (3). Because Eq. (3) is an empirical equation for soil respiration alone, perhaps the resulting carbon assimilation calculated by the calibrated SiB2 model is lower than it would have been had a balance been sought against soil plus wood respiration. Certainly, any systematic underestimation of net assimilation would suggest the use of an increased value for the parameter  $m$  in the Ball–Berry equation to give adequate simulation of transpiration fluxes.

Option 4 has the same Ball–Berry parameters as those used by da Rocha et al. (1996) in SiB2. Following the above argument, but in reverse: because the value of stomatal resistance is optimized best to simulate latent heat fluxes in this analysis, it is to be expected that BATS2 will calculate less net carbon assimilation with these parameters than with the original Ball–Berry parameters. This behavior it does (Fig. 10a). However, the dynamic carbon allocation processes simulated in BATS2 (not least the fact that 10% of the fast soil carbon store is lost to long-term storage in the soil) acts to minimize the consequences of this reduced assimilation rate on the modeled net  $\text{CO}_2$  flux exchange. Nonetheless, applying this option in BATS2 still gives some reduction in the (asymptotic) value for net carbon accumulation rate (Fig. 5).

Figure 10c shows the net  $\text{CO}_2$  flux to the atmosphere calculated during 1993 by SiB2 and BATS2 using four parameter options in BATS2 (at the end of 600-yr runs). Although broadly similar, there are considerable differences between the estimates given by SiB2 and the four BATS2 runs. Specifically, the four BATS2 options all yield somewhat higher values of net  $\text{CO}_2$  flux than does SiB2 prior to the dry season and, on occasion, somewhat lower values of net  $\text{CO}_2$  flux than does SiB2 toward the end of and immediately after the dry season. As previously demonstrated, both models and all the parameter options used in BATS2 simulate the average carbon exchange over the whole 44-day period reasonably well. None is outstanding in its ability to simulate the observed day-to-day variations (Fig. 10d).

#### 4. Summary and conclusions

In this study, three widely used land surface schemes, SiB2, BATS, and BATS2, were evaluated against Amazon field data. All the models were forced with a near-continuous, 26-month set of meteorological forcing data taken at Reserva Jaru during the ABRACOS experiment. The models were evaluated against observations taken during two intensive field missions, one between August and October in 1992, and the second between April and July in 1993. The primary conclusions of this study are as follows.

- With the parameters of da Rocha et al. (1996), SiB2 gives a good description of Amazon rain forest data, providing it is run with a half-hourly time step, and providing the forest's (assumed uniform) rooting depth is increased. Optimum simulation of the measured fluxes is made with the maximum leaf catalytic capacity set to  $79.4 \mu\text{mol m}^{-2} \text{s}^{-1}$ .
- With a deeper rooting depth and a reduced fraction of the roots in the upper soil layer, BATS also gives a reasonable description of Amazon rain forest data using default parameters for evergreen forest, but the description can be improved slightly by optimizing minimum stomatal resistance to  $140 \text{ s m}^{-1}$ .
- In Amazonian conditions, BATS occasionally can exhibit symptoms of positive feedback between the modeled stomatal resistance and modeled vapor pressure deficit adjacent to the leaves. We cannot preclude (but did not observe) a similar phenomenon when BATS2 and SiB2 are used in this environment.
- To improve consistency with observed leaf area index at the study site, in this study it was necessary to modify the specific leaf area and optical depth coefficient used in BATS2 from the default values suggested in Dickinson et al. (1998) to  $13 \text{ m}^2 \text{ kg}^{-1}$  and 0.34, respectively.
- To give a reasonable description of Amazon rain forest transpiration, BATS2 requires specification of a value for minimum stomatal resistance that is substantially less than the default value. The preferred value depends on the assumed form of the atmospheric humidity deficit stress factor and the constants used in the Ball–Berry equation. (Preferred values are given in the text.)
- If the carbon stores in BATS2 are initiated to the default values used by Dickinson et al. (1998), the model must be allowed to spin up for several hundred years, until it grows an equilibrium forest, before the net  $\text{CO}_2$  exchange is similar to that observed in the field. Assumptions made in BATS2 mean that the model cannot be expected to simulate the daily cycle in respiration and net  $\text{CO}_2$  exchange.
- Use of alternative functions to represent the influence of vapor pressure deficit on stomatal resistance had little effect on the performance of BATS2. Using relative humidity as a stress factor (option 2) marginally is preferable to using a vapor pressure deficit depen-

dent stress factor in BATS2 (option 1). This result is because it gives a slightly lower rmse relative to observed latent heat flux and more commonly calculates a mean monthly latent heat flux that is closer to observations (Table 2). It also calculates a net CO<sub>2</sub> balance that is slightly closer to observations (Fig. 5) and requires a value for  $r_{smin}$  (56 s m<sup>-1</sup>) that, although low, is closer to the value suggested by Wright et al. (1996) than is that with option 1. It is important to realize that this preferred value of  $r_{smin}$  depends on the assumed proportion of solar radiation arriving in diffuse form and corresponds to an assumed fraction of 50%.

- BATS2, SiB2, and BATS all can give reasonably realistic simulations of the observations of surface energy balance and carbon exchange at the Ji-Parana site, providing that plausible changes are made in a few critical model parameters.

*Acknowledgments.* Primary support for this study was provided under NASA Grant NAG8-1531. Additional support for O. L. Sen came from NASA Grant NAG5-3854 and for Z.-L. Yang from U.P.N. 428-81-22 and U.P.N. 429-81-22. Our special thanks go to Dr. Humberto da Rocha for providing the SiB2 parameter set, to Dr. Robert E. Dickinson for providing the new version of BATS and for helpful comments on the manuscript, and to Dr. James Collatz for help and advice with the SiB2 code. The field data were collected under the ABRACOS project and were made available by the U.K. Institute of Hydrology and the Instituto Nacional de Pesquisas Espaciais (Brazil). ABRACOS was a collaboration between the Agencia Brasileira de Cooperacao and the U.K. Overseas Development Administration. We appreciate the editorial assistance provided by Corrie Thies.

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