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Control of Dry Season Evapotranspiration over the Amazonian Forest as Inferred from Observations at a Southern Amazon Forest Site

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ABSTRACT

The extent to which soil water storage can support an average dry season evapotranspiration (ET) is investigated using observations from the Rebio Jarú site for the period of 2000 to 2002. During the dry season, when total rainfall is less than 100 mm, the soil moisture storage available to root uptake in the top 3-m layer is sufficient to maintain the ET rate, which is equal to or higher than that in the wet season. With a normal or less-than-normal dry season rainfall, more than 75% of the ET is supplied by soil water below 1 m, whereas during a rainier dry season, about 50% of ET is provided by soil water from below 1 m. Soil moisture below 1-m depth is recharged by rainfall during the previous wet season: dry season rainfall rarely infiltrates to this depth. These results suggest that, even near the southern edge of the Amazon forest, seasonal and moderate interannual rainfall deficits can be mitigated by an increase in root uptake from deeper soil.

How dry season ET varies geographically within the Amazon and what might control its geographic distribution are examined by comparing in situ observations from 10 sites from different areas of Amazonia reported during the last two decades. Results show that the average dry season ET varies less than 1 mm day^{-1} or 30% from the driest to nearly the wettest parts of Amazonia and is largely correlated with the change of surface net radiation of 25% and 30%. Thus the geographic variation of the average dry season ET appears to be mainly determined by the surface radiation.

1. Introduction

Over the forested areas, evapotranspiration (ET) contributes about 50% to total Amazon precipitation (Salati 1987; Silva Dias and Marengo 1999), much higher than the 20%–30% estimated previously by atmospheric reanalysis products (Brubaker et al. 1993; Eltahir and Bras 1994). Shuttleworth (1988) estimated that, on an annual scale, half of the precipitation that falls on the forest is returned to the atmosphere by evapotranspiration and that between 20% and 25% of ET is a result of the evaporation of water intercepted by the forest. Field experiments at several Amazonian forest sites indicate that ET rates are as high during the

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dry season as they are in the wet season (e.g., Shuttle-worth 1988; Nepstad et al. 1994; Sommer et al. 2002; Vourlitis et al. 2002; da Rocha et al. 2004; von Randow et al. 2004; Souza-Filho et al. 2005). Conversely, ET over pastures adjacent to forests declines significantly in the dry season compared to the wet season (Hodnett et al. 1995; von Randow et al. 2004).

Numerical simulations suggest that the high rates of forest ET in Amazonia effectively cool the local average climate by 4 K or more (Kleidon and Heimann 2000). ET is also the main source of water vapor for the atmosphere during the dry season (Fu and Li 2004). The ability of forest to sustain high ET during the dry season is a key driver for the transition from dry to wet season. Thus a better understanding of the controls on forest ET during the dry season is important for predicting the timing and variability of the wet season onset. Dry season ET is mainly contributed to by transpiration, which in turn is linked to primary production of forests.

Several major field experiments in Amazonia over the last two decades have focused on understanding the controls and climatic implications of forest ET. Observations provided by the Anglo–Brazilian Amazonian Climate Observation Study (ABRACOS) and the more recent Large-Scale Biosphere–Atmosphere experiment (LBA) in Amazonia have increased understanding of the controls of ET on seasonal and interannual time scales (Gash et al. 1996; Large Scale Biosphere–Atmosphere Experiment in Amazonia 1996; Avissar et al. 2002; Keller et al. 2004). These field studies have shown not only a higher ET in dry seasons than in wet seasons but also a higher ET over the areas with less rainfall during dry seasons in eastern and central Amazonia (e.g., Shuttleworth 1988; Nepstad et al. 1994; Malhi et al. 2002; Sommer et al. 2002; Souza-Filho et al. 2005). These previous field measurements further suggest that available deep soil water, the plant's ability to extract this water through a deep root system, and hydraulic lifting (Burgess et al. 1998) through aquaporins (Kaldenhoff et al. 1998; Kjellbom et al. 1999) can provide plants with sufficient soil water to maintain a higher photosynthetic and ET rate during the dry season. During the dry season in southern Amazonia, characterized by recurrent cold fronts during June and July (Fisch et al. 1996), ET tends to be similar to, or lower than, that in the wet season.

A deep soil moisture reservoir provides a necessary condition for maintaining a relatively high ET in the dry season. Previous in situ soil moisture data have shown a smooth seasonal cycle of soil moisture below 2 m, with an annual maximum in late wet season (March to May) and a minimum at the beginning of the wet season (November to December; Hodnett et al. 1996a; von Randow et al. 2004; da Rocha et al. 2004). This implies that the deep soil moisture reservoir is recharged during the wet season. On the other hand, given sufficient soil moisture, ET during the dry season is controlled by the net radiation (Shuttleworth 1988; da Rocha et al. 2004; Werth and Avissar 2004) or by other meteorological conditions such as the vapor pressure deficit (VPD) and wind speed (Souza-Filho et al. 2005; Costa et al. 2004). Thus it remains unclear as to whether the deep soil moisture, which is influenced by wet season rainfall, or dry season atmospheric conditions, for example, rainfall, solar radiation, temperature, or vapor pressure deficit, would have a more important control on the dry season ET.

Previous studies have compared wet and dry season ET at individual sites, but it remains unclear as to whether the deep soil moisture storage would be sufficient to maintain ET in a dry season over southern Amazonia where dry season rainfall is particularly low. At the Cuieiras reserve (CRS) site in the eastern Amazonia (see Table 1), Harris et al. (2004) observed that soil moisture was not sufficient to support a normal ET, contrary to other observations (e.g., Shuttleworth 1988; Nepstad et al. 1994). Here we examine the evolution of ET and soil moisture during the dry season at the Rebio Jarú (RJA) site (i) to determine the influences of soil moisture storage and rainfall on the dry season ET and (ii) to clarify the relative influences of rainfall and surface meteorological conditions between the previous wet seasons and current dry season on ET. We also explore the geographical distribution of dry season forest ET within Amazonia using in situ observations from 10 sites and the relationship between ET and the length, total rainfall, and surface radiation of the dry season. We also explore the implications of the results from the RJA site for the underlying processes that may control the geographic distribution of mean dry season ET.

2. Site, measurements, and methods

a. Site and climatology

The RJA site (10.0784°S, 61.9337°W; 100–150 m MSL) is located in the Jarú Biological Reserve, a *terra firme* forest in the southern Brazilian Amazon forest, about 100 km north of Ji-Paraná, Rondônia.

The overall reserve encompasses 26 800 ha of undisturbed tropical forest with a canopy mean height of 35 m (von Randow et al. 2004). This site was established in 1998 with a 60-m tower. At a nearby site, about 700 m distant, McWilliam et al. (1996) have reported botanical families such as *Meliaceae*, Legumino-

TABLE 1. List of experimental sites (all in Brazil) used in this study.

Site	Station	Lat (°S)	Lon (°W)	Dry season[a]	Source (period of study)
Caxiuanã National Forest (Belém, Pará)	CAX	1.7175	51.4600	Aug–Nov	Souza-Filho et al. (2005) (1999)
Bragantina[b] (Igarapé-Açu, Belém, Pará)	BRG	1.1850	47.5706	Sep–Dec	Sommer et al. (2002) (Apr 1997–Mar 1998)
Cuieiras reserve (Manaus, Amazonas)	CRS	2.5894	60.1153	Jun–Aug	Malhi et al. (2002) (Sep 1995–Aug 1996)
Cuieiras reserve (Manaus, Amazonas)	K34	2.6090	60.2093	Jun–Aug	Araújo et al. (2002)[c] (Jul 1999–Sep 2000)
Ducke Reserve (Manaus, Amazonas)	DCK	2.9500	59.9500	Jun–Aug	Shuttleworth (1988) (Sep 1983–Sep 1985)
Tapajós National Forest (Santarém, Pará)	K67	2.8853	54.9205	Jul–Dec	Hutyra et al. (2005)[d] (Feb 2000–Dec 2004)
Tapajós National Forest (Santarém, Pará)	K83	3.0502	54.9280	Jul–Dec	da Rocha et al. (2004)[e] (Jul 2000–Dec 2002)
Paragominas (Paragominas, Pará)	PRG	2.9833	47.5166	Jun–Nov	Nepstad et al. (1994) (1992 dry season)
Biological Reserve of Jarú (Jí-Paraná, Rondônia)	RJA	10.0784	61.9337	Jun–Aug	von Randow et al. (2004)[e] (Jan 2000–Dec 2002)
Sinop[f] (Sinop, Mato Grosso)	SIN	11.4125	55.3250	Jun–Sep	Vourlitis et al. (2002) (Aug 1999–Jul 2000)

[a] As defined by the authors listed in source column.

[b] Secondary vegetation, with height of 2.3 m in April 1997 and 3.5 m in March 1998.

[c] Data available at http://beija-flor.ornl.gov/lba/.

[d] Data available at http://www.as.harvard.edu/data/lbadata.html.

[e] Data available at http://www.ess.uci.edu/%7Elba/.

[f] Transitional (ecotonal) tropical forest.

sae-Mimoseaceae, *Leguminosae-Papilloniaceae, Loganiaceae, Burseraceae, Violaceae, Crysobalanaceae, Erythroxyllaceae, Sterculaceae*, and *Palmae* surrounding the site. The dry season lasts from June to August. The nearest meteorological station to RJA is at Porto Velho (8.46°S, 63.05°W), which has an annual precipitation of 2353.7 mm, an annual mean temperature of 25.2°C, and mean annual maximum and minimum temperatures of 31.1° and 20.9°C, respectively, based on observations over a 16-yr period (1975–90). Southern Amazonia is affected by occasional cold fronts from June to July (Fisch et al. 1996; Fig. 1b). Hodnett et al. (1996a) carried out extensive soil water monitoring as part of the ABRACOS project at the same site as McWilliam et al. (1996) in the Jarú Biological Reserve. The soil at the ABRACOS site was classified as a medium-textured red–yellow podsoil that merged into saprolite/weathered granite at depths varying between 1 m and more than 4 m. The soils at the RJA site appear to be very similar.

b. Data

Weather variables were collected using an automatic weather station on the 60-m tower, and the eddy correlation technique was used to calculate 60-min fluxes (footprint of 2–5 km) of latent heat (λE), sensible heat (H), and CO_2 (Fc). At the ABRACOS site, measurements of soil moisture were made weekly at eight locations using a neutron probe (Model IHII Didcot Instrument Company, United Kingdom) at 0.1-, 0.2-, and then at 0.2-m depth intervals to a maximum 3.4 m. For a complete description of this data, see Hodnett et al.

(1996a) and von Randow et al. (2004). A leaf area index (LAI) derived from Moderate Resolution Imaging Spectroradiometer (MODIS) data was also used in this study. MODIS LAI data (Yang et al. 2006) with horizontal resolution of 7 km × 7 km was obtained from the Oak Ridge National Laboratory Distributed Active Archive Center (available at http://www.modis.ornl.gov/modis/index.cfm). The period of study is from January 2000 to December 2002. The ET calculated by the eddy correlation technique will be denoted as ET_{EC}.

The accuracy of measurements of H and λE was checked by energy balance closure against the available energy ($Y = R_n - G - S$) that includes the net radiation (R_n), the soil heat flux (G), and the heat storage in the biomass and canopy (S). Here S is calculated using the empirical relationship proposed by Moore and Fisch (1986) for tropical forest in Manaus. Figure 2 shows that ($H + \lambda E$) is 28% less than Y. Even with the inclusion of the angle of attack correction (the angle that the wind vector makes with the horizontal axis of a sonic anemometer) (Gash and Dolman 2003; van der Molen et al. 2004) and the use of longer (15, 30, 60, 120, 240, 360, 480 min) averaging time (Finnigan et al. 2003), von Randow et al. (2004) showed that an imbalance of about 15% persists. While specific reasons for the energy imbalance are unclear, it is known that at the RJA site the terrain heterogeneity can promote mesoscale circulation with turbulent flow emerging in lower frequencies (Kruijt et al. 2004), important for the eddy fluxes (Sakai et al. 2001; Foken et al. 2006). Von Randow et al. (2004) and Kruijt et al. (2004) have presented a detailed discussion of eddy fluxes used in this work.
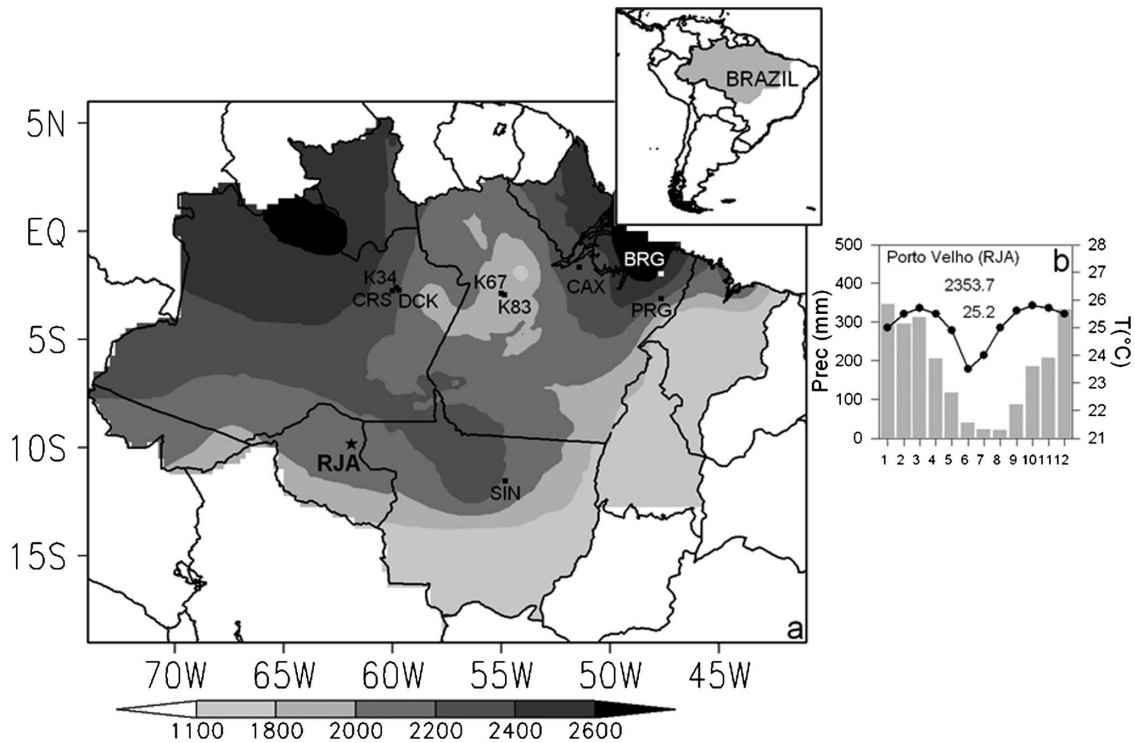
FIG. 1. (a) Climatological (1961–90) annual precipitation (mm; Instituto Nacional de Meteorologia 1992) over the Brazilian Legal Amazon and location of the RJA as well as other sites used for comparison and described in Table 1. (b) Monthly climatological values of temperature (°C) and precipitation (mm) at the nearest meteorological station of RJA, Porto Velho. Also shown are climatological annual total precipitation and average temperature.

Due to a clear underestimation of turbulent fluxes or overestimation of the available energy, Foken et al. (2006) have recently suggested that the surface energy imbalance should not be used as an indicator of eddy
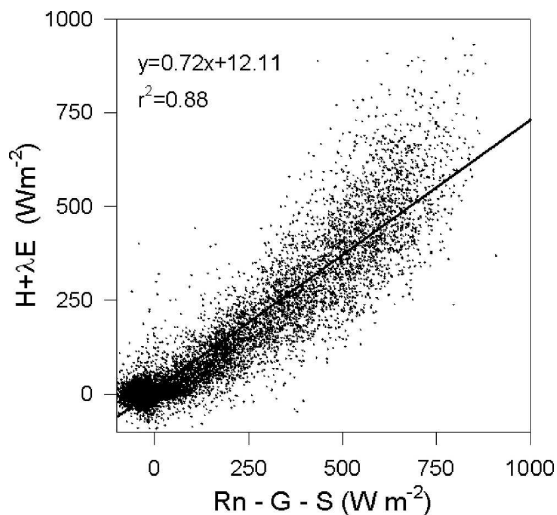

FIG. 2. Sum of sensible (H: W m^{-2}) and latent (λE: W m^{-2}) heat fluxes vs the available energy Y net radiation (R_n) minus soil heat flux (G) minus heat storage in the canopy and biomass (S: W m^{-2}) for 60-min measurements at RJA.

flux accuracy. Under the worse case scenario, the lack of energy closure shown in Fig. 2 implies a possible underestimate of the ET$_{EC}$ by about 28%. The observed imbalance is well within the ranges of other previous studies using flux tower data using the eddy correlation technique. For example, Wilson et al. (2002) reported an underestimation between 1% and 47% over 50 sites of the FLUXNET network (http://www-eosdis.ornl.gov/FLUXNET/). Thus the RJA flux data are as consistent as other flux tower measurements reported in recent literature.

We have also used data from other terra firme sites in Amazonia. The locations and references for these data are shown in Fig. 1 and Table 1.

c. Potential evapotranspiration

The equilibrium evapotranspiration (ET$_{eq}$), the theoretical lower limit of evaporation from a wet surface, is expressed as in (Priestley 1959; Slatyer and McIlroy 1961)

$$\mathrm{ET}_{eq} = \Delta Y/(\Delta + \gamma), \qquad (1)$$

where Δ is the slope of the saturation vapor pressure curve at the air temperature (kPa °C^{-1}), Y is the avail-

able energy (W m^{-2}), and γ is the psychometric constant (kPa °C^{-1}). A simple means to calculate ET avoiding the specification of a turbulent transfer mechanism was developed by Priestley and Taylor (1972), suggesting that ET over a saturated surface can be calculated as

$$ET_{PT} = \alpha_e ET_{eq}, \qquad (2)$$

where α_e depends on surface characteristics. Using hourly data α_e was adjusted to get the best fit between ET$_{EC}$ (W m^{-2}) and ET$_{PT}$ (W m^{-2}). The best fit (ET$_{EC}$ = 1.00ET$_{PT}$ − 10.64, r^2 = 0.9, RMSE = 49.32 W m^{-2}) was obtained with α_e = 0.8. This value is lower than that (1.26), suggested by Priestley and Taylor (1972), obtained for conditions of minimum advection and large saturated surface. However, in the tropical forest of Manaus in the Brazilian state of Amazonas, Viswanadham et al. (1991) found that α_e varied from 0.6 to 3.12, and, over a transitional forest in the Brazilian state of Mato Grosso, Vourlitis et al. (2002) found α_e values between 0.57 and 1.07.

d. Water balance

Von Randow et al. (2004) have suggested a relatively large root uptake of soil water by forests during the dry season. However, their study focused on the impact of soil moisture on root uptake. Thus it remains unclear as to how root uptake contributes to dry season ET qualitatively. We explore this question by analyzing the soil water balance and its relation to ET. The soil water balance can be expressed as

$$P = R + ET + D + \Delta S, \qquad (3)$$

where P is the rainfall, R is the surface runoff, ET is the evapotranspiration, D is drainage, and ΔS is the change in profile water storage to the depth of interest, all during the same period of time—usually one week (Hodnett et al. 1996b). In the dry season, rainfall is zero for many weekly periods so that during a subsequent rainfall event the water budget can be simplified to

$$P - \Delta S = ET + D. \qquad (4)$$

As we will show in Fig. 4, infiltration to deeper soil layers is negligible, so the soil water budget can be further simplified to

$$-\Delta S = ET + D. \qquad (5)$$

3. Results

a. Seasonal changes of ET

The seasonal changes of ET and factors that could influence ET at the RJA site during the period of 2000 to 2002 are examined in Fig. 3. Figure 3a shows that the monthly total rainfall varies from 500 mm during peak
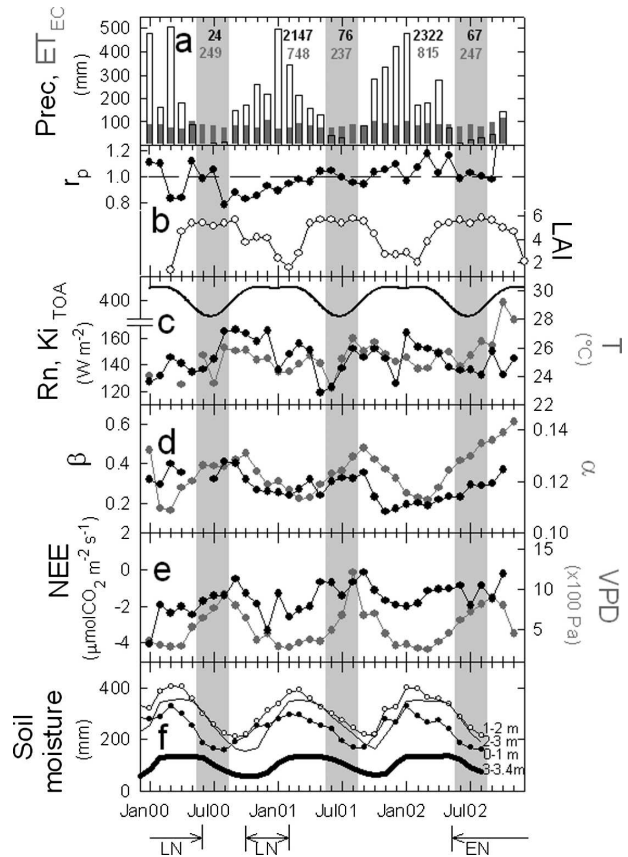

FIG. 3. Monthly values for RJA of (a) precipitation (Prec: mm, in black) and evapotranspiration from the eddy correlation technique (ET$_{EC}$: mm, in gray); (b) r_p (=ET$_{EC}$/ET$_{PT}$) (in black) and MODIS LAI data (open circles); (c) average incoming solar radiation at the top of atmosphere (Ki$_{TOA}$: W m^{-2}, solid line), average net radiation (R_n: W m^{-2}, in black), and average temperature (T: °C, in gray); (d) average Bowen ratio (β; in black) and canopy albedo (α, in gray); (e) average NEE: μmol CO$_2$ m^{-2} s^{-1}, in black) and VPD (×100 Pa, in gray); and (f) average soil moisture (mm) for different layers. LN (EN) indicates La Niña (El Niño). Dry season is highlighted by shaded area.

wet season to near zero in peak dry season, whereas monthly total ET$_{EC}$ only varied from 100 mm in early wet season to 80 mm in late wet season. The seasonal average rainfall was 8.2 ± 0.5 mm day^{-1} (± standard deviation) for the wet season, compared to 0.6 ± 0.3 mm day^{-1} for the dry season. In comparison, the average ET$_{EC}$ was 2.9 ± 0.3 mm day^{-1} during the wet season and 2.7 ± 0.2 mm day^{-1} in the dry season. The total rainfall is about 2235 mm for the wet season and 56 mm for the dry season, whereas ET$_{EC}$ is about 781 mm for the wet season and 245 mm for the dry season. The ET$_{EC}$ for the dry seasons from 2000 to 2002 were 249, 237, and 247 mm, respectively, whereas precipitation was 24, 76, and 67 mm, respectively. Thus during the dry season, ET$_{EC}$ changed less than 5% despite differ-

ences in rainfall of up to 38% between these three years. The observed variability in precipitation is associated with the La Niña event observed in 2000 (Lawrimore et al. 2001), the drought event in most of Brazil in 2001 (Waple et al. 2002), and the El Niño event in 2002 (Waple and Lawrimore 2003). Figure 3a also shows that, during the 2000 dry season, the total precipitation was 24 mm, which was lower than those in 2001 (76 mm) and 2002 (67 mm), as well as the climatological value (83 mm). From September to December 2000, even though the monthly rainfalls were higher than the mean (except in December), the slow increase of ET rate suggests that the ET is sensitive to previous climate conditions.

Figure 3b shows that monthly LAI has minimum values during the wet season and maximum during the dry season, consistent with measurements of albedo (α: Fig. 3d) and net ecosystem exchange (NEE) (Fig. 3e). The ratio r_p (=ET_{EC}/ET_{PT}), an indicator of surface/vegetation resistance, was mostly maintained approximately at 1.0 during the dry seasons, except from the end of the 2000 dry season to the early wet season (June 2000 to January 2001). During this period the minimum value of r_p was 0.8 (Fig. 3b), corresponding to anomalously lower rainfall (Fig. 3a), higher surface net radiation (R_n: Fig. 3c), and higher Bowen ratio (Fig. 3d). These parameters together suggest an occurrence of water stress, induced by interannual anomalously lower rainfall.

The air temperature varied less than 2°C except during the dry season when cold fronts passed by (Fig. 3c). During the latter part of 2002 (an El Niño year), air temperature and the Bowen ratio (Fig. 3d) were substantially higher compared to those in 2000 and 2001. These indications of surface dryness followed the rainfall deficit during the latter half of the previous wet season (Fig. 3b) and persisted through the subsequent dry season despite a normal dry season rainfall and lower net surface radiation (Fig. 3c). The net radiation (R_n) at RJA reaches a maximum during the wet season and a minimum during the dry season (Fig. 3c), following the calculated incoming solar radiation at the top of the atmosphere (Fig. 3c) (Stull 1988). Daily values of ET_{EC} exhibited a moderate dependence on R_n during the wet season (ET_{EC} = 0.49 × R_n +0.279, r^2 = 0.6, RMSE = 0.64: units in mm day^{-1}) but a lower dependence during the dry season (ET_{EC} = 0.42 × R_n + 0.49, r^2 = 0.2, RMSE = 0.61: units in mm day^{-1}). This result indicates that during the wet season ET uses about 50% of R_n. Although the seasonal cycle of the Bowen ratio (Fig. 3d) appears to correlate with R_n, with a lag of about one month, it is not entirely determined by R_n (Fig. 3c).

Previous studies suggested that the seasonal pattern of canopy albedo (α) is strongly correlated with soil water content rather than with cloudiness or changes in the solar elevation angle (Culf et al. 1995). Thus canopy albedo may indicate changes of certain physiological or phenological aspects of the forest (e.g., Malhi et al. 2002; Goulden et al. 2004). Figure 3d shows that the canopy albedo follows LAI (Fig. 3b) and tends to be in phase with the Bowen ratio (Fig. 3d) and NEE (Fig. 3e), suggesting that a change in canopy physiology may contribute to changes of ET (Fig. 3a). During 2002, the average NEE (Fig. 3e) was 0.7 and 0.1 μmol CO_2 m^{-2} s^{-1} lower with respect to 2000 and 2001, respectively, corresponding to the surface dryness shown by a higher surface temperature (Fig. 3c) and Bowen ratio (Fig. 3d). Daily values of ET_{EC} in the wet season (from November to May) were moderately correlated with VPD (ET_{EC} = 3.34 × DPV + 1.66, r^2 = 0.4, RMSE = 0.74 mm day^{-1}, ET_{EC} in mm day^{-1}: DPV in kPa), but no clear relation was observed during the dry season. VPD (Fig. 3e) tends to be negatively correlated with ET on a seasonal scale, suggesting that both are responding to changes of surface dryness rather than ET being controlled by VPD.

Soil moisture storage peaks during the late wet season and is depleted through the dry season. In the layer between 1 and 3.4 m, there is a steady increase of soil moisture storage during the wet season as the soil profile is recharged by rainfall and a steady decrease in storage in the dry season as the soil moisture is depleted by drainage and root uptake (von Randow et al. 2004). During the dry season, rainfall infiltrated to the soil layer below 1 m. The reduction of the soil moisture below 2 m lags that of the top 2-m soil layer for approximately one to two months (Fig. 3f). The flat tops to the storage curve in the 2–3- and 3–3.4-m layers are an indication that the profile below is saturated. The water storage in the upper 2 m of soil varies from ~690 mm in the wet season to ~400 mm in the dry season and in the 2–3.4-m layer from ~500 mm in the wet season to ~200 mm in the dry season. Although the large variations in soil moisture storage may be partly caused by drainage from the saturated layers (Hodnett et al. 1996a), they are also the result of forest root uptake of soil water. In the 2000 dry season, total precipitation was only 24 mm. Strong drying of the soil profile during the dry season meant that recharge in the 3–3.4-m soil layer was delayed until the profile above had rewetted in December.

To summarize, despite large changes of rainfall, VPD, and R_n, mean ET varies less than 5%–10% on both seasonal and interannual scales during the period from 2000 to 2002. During the dry season, soil moisture
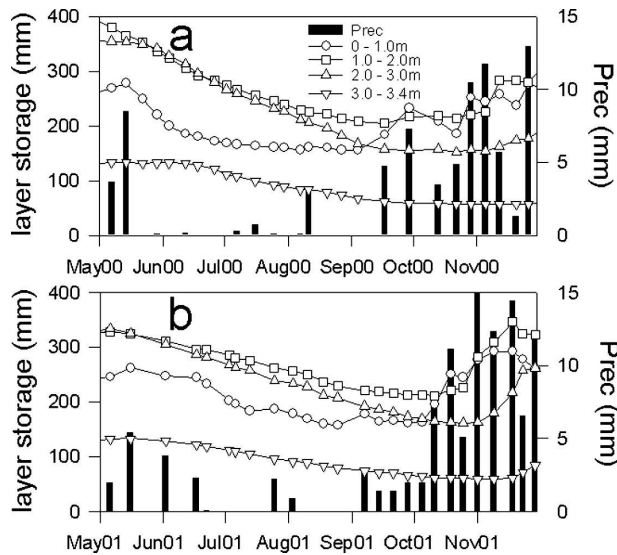
FIG. 4. Water storage in the 0–1.0- (○), 1.0–2.0- (□), 2.0–3.0- (△), and 3.0–3.4-m (▽) layers from May to November of (a) 2000 and (b) 2001. The accumulated precipitation between each interval of soil moisture observations is shown by the black bar.

storage decreased steadily as ET_{EC} was maintained close to its wet season rate. This relation is consistent with that expected from the root uptake, as suggested previously (von Randow et al. 2004). On an interannual scale, dry season ET_{EC}, surface temperature, and the Bowen ratio do not appear to be influenced by changes of rainfall, R_n, and VPD for the same season.

b. Soil water and ET

Although surface micrometeorological conditions can affect the daily to synoptic fluctuation of ET, our results from RJA show that the dry seasonal average ET appears to be insensitive to the dry season rainfall. Figure 4 shows the soil water storage in different layers within the soil profile from May to November (end and beginning of the rainy season, respectively) of 2000 and 2001. The accumulated precipitation between observation dates is also shown. The upper 1-m layer exhibited a strong sensitivity to the precipitation events on a synoptic scale. However, the average and minimum soil moisture over the entire dry season did not seem to be influenced by dry season rainfall. In the dry seasons of 2000 and 2001, soil moisture in the top 1-m layer decreased from 280 to 180 mm before mid-June, and from 270 to 180 mm before mid-July, respectively, within a month after the end of the previous wet season. The dry season rainfall causes increases of soil moisture content in this layer but only in the upper part of it. Water storage is higher and depletion rates are greater in the 1–2-m and 2–3-m layers than in 0–1-m layer, reflecting

the combined impact of uptake and drainage losses as the water table falls. In the 1–2-m layer, soil moisture storage decreases from about 400 to 240 mm by October 2000 and from 340 to 220 mm by October 2001, at the beginning of the wet season for both years. In the 2–3-m soil layer, soil moisture storage in the wet season is similar to that in the 1–2-m layer, but depletes to about 180 mm in November. The recharge in this layer lags that of the 1–2-m soil layer by 2 to 4 weeks. Overall, the dry season depletion of soil moisture in the top 3 m of the profile was 440 mm in 2000 and 370 mm in 2001, compared to $ET_{EC} - $ Prec totals of 225 and 161 mm, respectively (Fig. 3b). Even allowing for drainage losses, the soil water storage in the top 3-m soil layer appears to be sufficient to support the evaporative demand during the dry seasons studied. The patterns of soil water content change suggest that the root uptake starts in the upper soil layers and progressively shifts to the deeper layer as the layers above are depleted. Similarly, there is a progressive rewetting from the top down after the beginning of the wet season.

In the 3–3.4-m layer, soil moisture storage remains at its saturation value of ~130 mm in the early dry season (until the beginning of July) and then decreases to about 60 mm in late November, with a lag of 2 to 4 weeks after the 2–3-m soil layer. It is of note that soil water storage changes at a depth of 3.4 m were still significant, implying that changes were occurring in the weathered granite below the maximum depth of measurement.

Figure 5 shows a series of soil moisture profiles from 0.1- to 3.4-m depth. The profiles start in the late wet season (May) and end in the late dry season (September) of 2000. These sequential profiles illustrate the progress with time and depth of the seasonal variation in water content caused by both drainage and root uptake. On 7 May the profile was well wetted throughout the profile with a maximum value of 0.4 $m^3 m^{-3}$ at a depth of 1.8 m. In the upper 1-m layer, the moisture content decreases to its minimum by mid-July, and does not decrease further through August to mid-September, indicating that the abstraction limit has been reached (no more available moisture). Near the surface (0.1 m), the driest soil moisture value (~0.07 $m^3 m^{-3}$) was observed on 16 July. Below the 1-m layer the profile is depleted to its minimum by mid-September. Because the total rainfall from mid-May to mid-September was only 10 mm, ET_{EC} was maintained by root water uptake. Figure 5 indicates that, except for the first month, root uptake from soil layers deeper than 1 m is the main water supplier for dry season ET_{EC}.

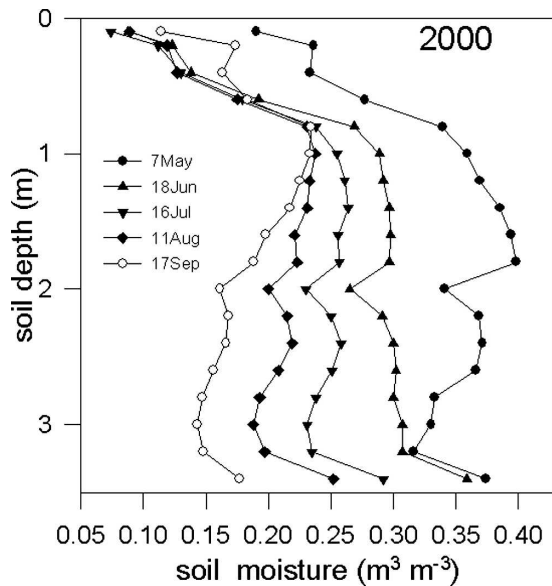Figure 6 shows the ET_{EC} and the rate of soil water

FIG. 5. Profiles of water content for different dates through the 2000 dry season for the RJA site.

could also be a result of possible underestimation of ET_{EC}. Through the course of the dry season $ET + D$ declines gradually as the drainage rate decreases. In the 0–1-m and 0–2-m layers, the $ET + D$ rate becomes less than ET_{EC} about one to one-and-a-half months after the end of the previous wet season, depending on the early dry season rainfall. This suggests that the available surface soil water becomes insufficient to support ET_{EC} and that forest roots have to take water from soil below 2 m. Later in the dry season, after mid to late July, the $ET + D$ rates for the 0–3-m and 0–3.4-m layers are about equal or slightly higher than ET_{EC}, suggesting that the available soil water in these layers is sufficient to support ET_{EC}. Since ET_{EC} is about twice as high as the $ET + D$ for the top 2-m soil layer, the root uptake from the soil below 2 m must have contributed to at least half of the total ET_{EC}. The drainage, as inferred from the difference between $ET + D$ and ET_{EC}, is much lower during the late dry season than during the early dry season. Figure 6 also suggests that in 2001, when dry season rainfall was higher than that in 2000 and 2002, $ET + D$ in the top 2-m soil layer was greater than ET_{EC} through most of the dry season. However, ET_{EC} and the minimum values of soil water storage in all soil layers are about the same in 2001 as in 2000 during the dry season (Fig. 4). Thus the excessive $ET + D$ in the top 2-m soil layer in the 2001 dry season probably indicates that drainage was higher in this season.

4. Discussion

a. What controls the average dry season ET over the Amazonian forest?

Figure 7 compares the dry and wet season ET, rainfall, and net surface radiation in different parts of Ama-
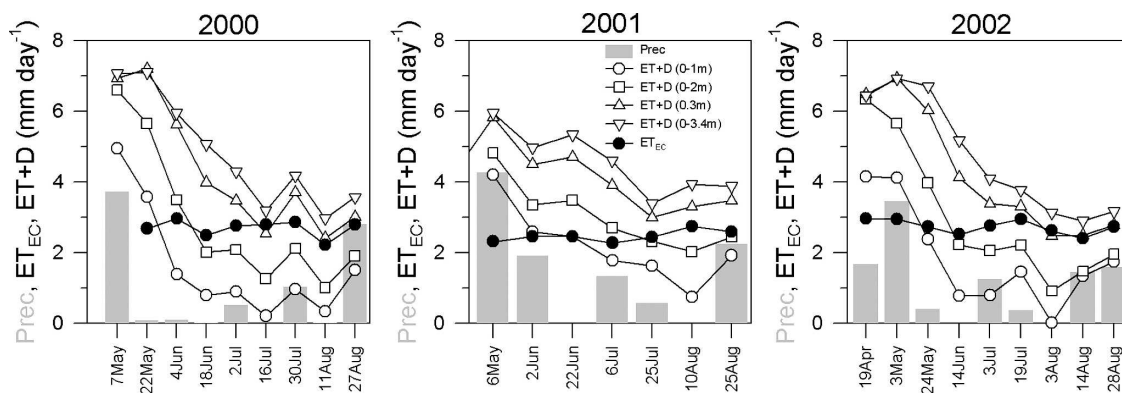
depletion caused by $ET + D$ for the top 1-, 2-, 3-, and 3.4-m soil layers, respectively, obtained from the soil water balance method from May to September 2000, 2001, and 2002. Time intervals are typically two to three weeks. The accumulated precipitation for each time interval is also shown. In the early dry season, $ET + D$ rates in the top 3 and 3.4 m are similar to that in the top 2-m soil layer, suggesting that $ET + D$ occurs mainly from the top 2-m soil layer. The $ET + D$ for the top 2-m soil layer is typically 6–7 mm day^{-1} during early dry season (May to June) of which 4–5 mm day^{-1} occurs in the 0–1-m soil layer. During this period, $ET + D$ is about twice as high as ET_{EC}, suggesting a possibly large drainage. However, this apparent large drainage

FIG. 6. Comparison of soil water depletion ($ET + D$) obtained from the soil water balance of the 0–1- (○), 0–2- (□), 0–3- (△), and 0–3.4-m (▽) layers, and the ET from the eddy correlation technique, ET_{EC}, (●) for different periods including the 2000, 2001, and 2002 dry seasons. The accumulated precipitation is shown between each interval of soil moisture observations by a black bar.
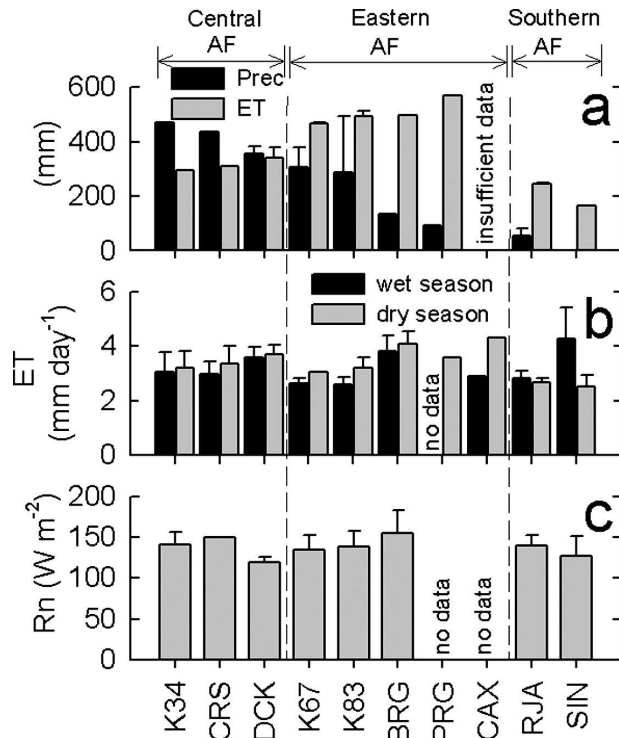
FIG. 7. (a) Total precipitation (Prec: mm) and ET during dry season; (b) average daily ET during the dry and wet seasons, respectively; and (c) averaged dry season surface net radiation (R_n) for different sites in the Amazon Forest (AF).

TABLE 2. Seasonal and annual rates of ET for different LBA sites (see Table 1 for references and locations).

Sites	Dry season ET (mm day^{-1})	Wet season ET (mm day^{-1})	Annual ET (mm day^{-1})
CAX	2.9[a]	4.3[b]	No data
BRG	4.1 ± 0.4	3.8 ± 0.6	3.9 ± 0.5
CRS	3.4 ± 0.7	2.9 ± 0.5	3.1 ± 0.5
K34	3.2 ± 0.6	3.0 ± 0.7	3.1 ± 0.7
DCK	3.7 ± 0.3	3.6 ± 0.4	3.6 ± 0.4
K67	3.0 ± 0.3	2.7 ± 0.2	2.8 ± 0.1
K83	3.2 ± 0.4	2.6 ± 0.3	2.9 ± 0.4
PRG	3.6	No data	No data
RJA	2.7 ± 0.2	2.9 ± 0.3	2.8 ± 0.3
SIN	2.5 ± 0.4[c]	4.3 ± 0.9[c]	2.8 ± 0.3

[a] 29-day period in the dry season.
[b] 39-day period in the wet season.
[c] Months belonging to the transition season were not considered.

tered. These observations imply that during the dry season ET supports the local rainfall and minimizes the decrease of atmospheric humidity.

Figure 7b compares mean daily ET for the different sites for the dry and wet seasons. Despite changes of mean daily rainfall between the wet and dry season and changes in dry season length from three to six months between these sites, the average difference in the values of mean daily ET between sites and seasons was less than 1 mm day^{-1} or about 30%. Mean daily ET is greater in the dry season than in the wet season over central and eastern Amazonia, as reported previously. In southern Amazonia, dry season ET is similar to that of the wet season ET at RJA. SIN is the only site where ET is significantly lower in the dry season than in the wet season.

What maintains a relatively small change of dry season ET against strong changes of rainfall across Amazonia? This question can be addressed by clarifying what maintains ET under the driest conditions. Based on Fig. 7a, RJA is the second driest site, but of the few sites where simultaneous observations of soil moisture and surface fluxes are available, this site has the lowest dry season rainfall. Thus, observations at this site are especially helpful to clarify the aforementioned question.

Our results shown in section 3 for RJA have two important implications: 1) soil water available for root uptake within the top 3-m soil layer appears to have been sufficient to support dry season ET, even during the 2000 dry season when rainfall was well below average (Fig. 3b); 2) soil moisture below 1 m is not influenced by dry season rainfall, but is recharged during the previous wet season (Fig. 5). Because one-half to two-thirds of the root uptake needed to support dry season

zonia (Table 1 and Table 2) using published ET data from various Amazonian forest sites in central Amazonia (CRS, DCK, and K34), eastern Amazonia (CAX, BRG, PRG, K67, and K83), and southern Amazonia (SIN and RJA) for different periods. Figure 7a shows that, in central Amazonia, the total dry season ET was 300 mm at K34, 310 mm at CRS, and 350 mm at DCK, corresponding to total rainfalls for the experimental periods of 480 mm to 430 mm, and to 360 mm. In eastern Amazonia, the total dry season ET varied from 480 to 550 mm, for rainfall totals of between 100 and 260 mm. For the two sites in southern Amazonia, total dry season ET ranged from 180 to 250 mm total for total dry season rainfalls of between 0 and 100 mm.

In eastern and central Amazonia, the highest values of ET were observed in the driest regions or those with extended dry seasons. In both eastern and southern Amazonia, dry season ET exceeded the rainfall. For example, in Paragominas, Pará, measurements by Nepstad et al. (1994) showed that total dry season ET was 400 mm more than total dry season rainfall. At the SIN site in southern Amazonia, Vourlitis et al. (2002) reported that the ET was about 180 mm during the 2000 dry season, even though no precipitation was regis-

ET is from the soil layer below 1 m, the dry season ET depends heavily on deep soil water recharged by rainfall in the previous wet season, rather than that of the current dry season. Thus our results suggest that the recharge of deep soil moisture storage during the previous wet season would normally provide sufficient water to maintain ET in the subsequent dry season, mitigating the impact of the dry season rainfall deficit.

Hodnett et al. (1996a) observed that, at a forest site near Marabá in southeastern Amazonia, the soil profile below 2 m was not fully charged during the 1992/93 wet season when rainfall was anomalously low. This observation shows that wet season rainfall deficits can result in reduced storage in the deep soil moisture reservoir. Their result indicates a potential impact of low wet season rainfall on subsequent dry season ET, and the assumption of sufficient soil moisture over Amazonia may not be valid for drought conditions (Harris et al. 2004).

As shown in Fig. 1a, annual rainfall varies geographically from about 1800 mm (K67 and K83) to nearly 2600 mm (BRG) among the sites listed in Fig. 7. The length of the dry season also ranges from three months at Jarú in southern Amazonia, Manuas in central Amazonia, and CAX near the mouth of the Amazon River to about six months at Tapajós, Santarém, in central-eastern Amazonia (Table 1). What process maintains similar rates of dry season ET under such strong differences in annual rainfall and length of the dry season? Previous studies can shed light on this question. Stomatal closure, hence transpiration rate, is determined primarily by solar radiation at the leaf surface and the availability of the water to plants, although VPD and wind speed can also influence ET given sufficient root uptake of soil moisture and solar radiation. The availability of soil moisture for plants depends on the ability of roots to extend toward sources of water, as suggested by observations from different sites (Monteith 1995; Hodnett et al. 1996a) and by the reanalysis of 52 sets of measurements for 16 species by Mott and Parkhurst (1991). Deeper root systems increase the water extraction capability regardless of soil type (Jackson et al. 2000). This is because root systems can respond to soil texture by changing root density, despite differences in the shapes and sizes of root systems for different species or plant families (Schenk and Jackson 2002). VPD and wind speed are also well-known causes.

Forest roots appear to extend deep enough to tap into soil water reservoirs to cope with the long dry season. For example, Nepstad et al. (1994) found roots most abundantly near the soil surface but also found roots at ~18 m near the town of Paragominas in central-eastern Amazonia where the dry season typically lasts six months. At the same site, Jipp et al. (1998) suggested that the water table was >40 m below the soil surface. The forest appears to be well buffered against seasonal and interannual variations in the rainfall due to the deep root system. In the Tapajós National Forest, where the water table is at least 100 m below the surface, Nepstad et al. (2002) found forest roots at 11 m and abundant fine roots in shallow soil. In Paragominas, Jipp et al. (1998) found roots at 8 m with fine roots concentrated near the surface.

Recent studies have confirmed the hydraulic lifting or basipetal sap flux (Dawson 1993) by the forest roots as an efficient mechanism to redistribute soil water. For example, at Tapajós National Forest, Oliveira et al. (2005) observed that, at night, three common species (*Coussarea racemosa*, *Manilkara huberi*, and *Potrium robustum*) showed both upward (hydraulic lift or basipetal sap flux, in the dry season) and downward (acropetal sap flow, in the wet season) hydraulic redistribution (HR). The authors suggested that the increase in soil moisture at different soil depths was the result of HR by roots.

Apparently, the forest root system is deep and effective in taking up sufficient water from deep soil layers. Thus the rate of dry season ET is largely determined by the surface solar radiation that influences both photosynthesis and daytime boundary layer turbulence (e.g., Shuttleworth 1988; da Rocha et al. 2004; Werth and Avissar 2004) and, to some extent, by VPD and winds (Souza-Filho et al. 2005). Figure 7c shows that the average daily surface solar radiation during the dry season varies from 120 to 150 W m^{-2}, or 22%, between the 10 sites. The differences between the sites are also largely correlated with the mean daily dry season ET. Thus the distribution of mean daily dry season ET across different parts and rainfall regimes of Amazonia represented by the 10 sites appears to be mainly linked to surface radiation.

b. The importance of dry season ET to the onset of the wet season

Li and Fu (2004) have suggested that the ability of the forest to sustain high ET during the dry season is a key driver for the transition from dry to wet season. They further found from long-term rain gauges and European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA) data that the changes of Bowen ratio during the dry season has strongest impacts on the onset of the subsequent wet season (Fu and Li 2004). However they validated a trend of increasing ET from the wet to the dry season measurements from only one flux tower at the ABRACOS site in southern Amazonia (700 m from RJA). Whether such an increasing
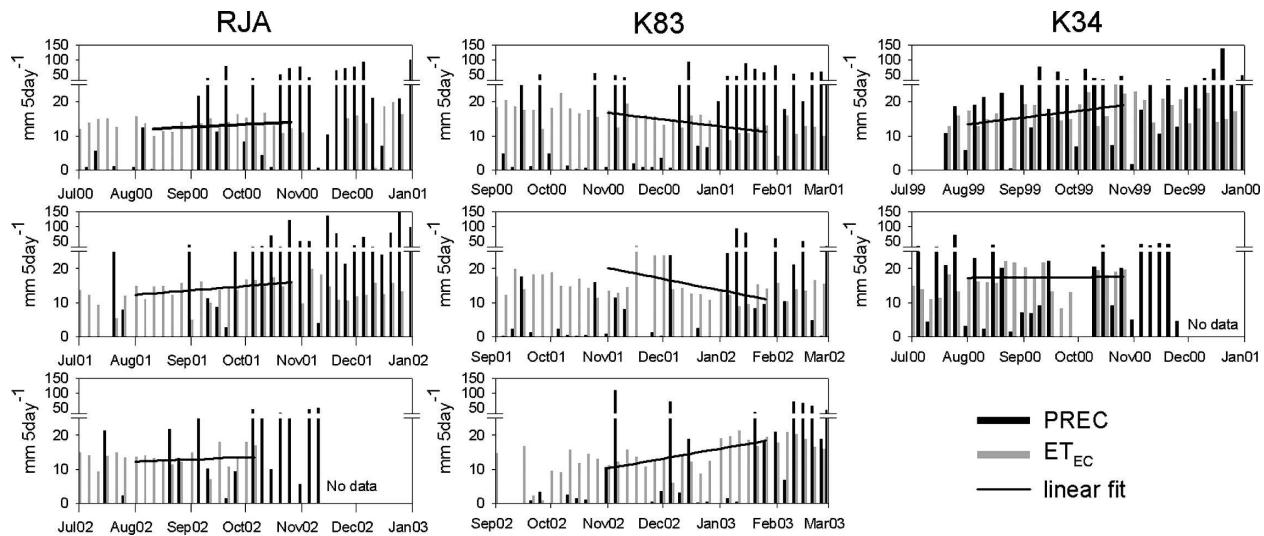
FIG. 8. Five-day total precipitation and ET during the transition seasons at (left) RJA in the southern Amazonia, (middle) K83 in the central-eastern Amazonia, and (right) K34 in central Amazonia for the year (top) 2000, (middle) 2001, and (bottom) 2002. The lines represent a linear fit for change of ET during the transition from dry to wet season.

trend occurs in other parts of Amazonia remains unclear. Figure 8 shows ET during the transition from the dry to wet season at RJA, K83 in equatorial eastern Amazonia, and K34 in central Amazonia for the period of 2000 to 2002. Except for 2000 and 2001 at K83, ET increased during the three transition seasons at all three sites in different parts of Amazonia. These observations provide further support to the hypothesis that ET increases during the transition from dry to wet season, which initiates the transition from dry to wet season and consequently leads to wet season onset (Li and Fu 2004; Fu and Li 2004).

5. Conclusions

Soil moisture and flux flux observations from the RJA site in southern Amazonia for the period 2000–02 suggest that soil moisture storage available for root uptake in the upper 3 m of the soil profile is sufficient to maintain the same or higher ET rates during the dry season even when rainfall is very low compared to that of the wet season. As a result, dry season rainfall deficits, such as that in 2000, can be easily mitigated by an increase in root uptake. Soil water depletion and rewetting occur from the top layer downward with about a one-half to one month phase lag between each 1-m layer. Soil moisture in the top 1-m soil layer reduces to its annual minimum within the first month of the dry season and, apart from minor fluctuations caused by dry season rainfall, stays dry until the following wet season begins. Dry season ET after the first month is

largely supported by root uptake from soil below 1 m. During dry seasons with normal or below average rainfall, more than 75% of the ET is soil water taken from the profile below 1 m, whereas during a rainier dry season this value falls to about 50%.

Previous studies at other sites in eastern and central Amazonia have shown that, in the dry season, forest root uptake from deep soil provides enough water for plant photosynthesis, and seasonal change of ET is largely controlled by surface radiation. Using published data from 10 sites in different areas of Amazonia reported during the last two decades, we found that the average dry season ET varies less than 1 mm day^{-1} (30%) geographically from the driest to almost the wettest parts of Amazonia. At the 10 sites, the dry season length ranges from 3 to 6 months, and total dry season rainfall varied between 0 and 480 mm. The change of dry season ET is comparable to, and largely correlated with, that of the net surface radiation (~30%) between the 10 sites. Thus geographic variation of the mean dry season ET is largely determined by the surface radiation.

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