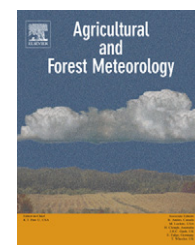


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# Above-ground thermal energy storage rates, trunk heat fluxes and surface energy balance in a central Amazonian rainforest

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## ABSTRACT

The thermal (physical) energy storage rates (ESR) of the above-ground components of a “terra firme” forest site in central Amazonia, Brazil, were determined for a set of typical days during the dry season of 2003 and the wet season of 2004, and their relevance to the surface energy balance was studied. To obtain the ESR for the above-ground part of the biomass (trunks, branches and litter), the temperatures of one trunk of a dominant tree species of the forest site were measured at three height levels and several radial depths. To compute the ESR in the other parts of the above-ground biomass (twigs, leaves and small size components such as palms and lianas) and the ESR atmospheric fraction, the temperature of the air was measured at four different heights inside and above the forest. The air, trunks and other biomass components contributed 35%, 40% and 25% to the total daily ESR of the forest respectively. For the hourly values during the morning, the total ESR was usually observed to be between 30 and 70 W m<sup>-2</sup>, but with maxima that can exceed 90 W m<sup>-2</sup>; during rain events minima as low as –200 W m<sup>-2</sup> were observed. During the night and at dawn and dusk, the total ESR may constitute a sizable fraction of the net radiation, on some occasions equaling, or even exceeding it. On a daily basis, values of the total ESR were observed to be between –40% and 5% of the net radiation, depending on the weather conditions during the day. Further, the inclusion of the ESR to compute the surface energy balance improves its closure, mainly during the daylight period and, particularly, during the morning hours; but the best closure occurs for the days in which the daily balance of the total ESR is positive. Finally, simplified expressions are presented for those components of the ESR which do not depend on trunk temperature.

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## 1. Introduction

The Amazonian forest, with more than 6.3 million km<sup>2</sup>, comprises 37% of the tropical rainforests remaining on Earth. Of this area 80% to 90% consists of several types of non-flooded (“terra firme”) forests, with high biomass values and great biodiversity (Ayres, 1995).

The vastness of this dense and continuous forest, that is subjected to high humidity, strong incident solar radiation and intense convection, has led to several studies and experiments aimed at understanding the exchanges of energy, humidity and carbon between the forest and the atmosphere. The study reported here was part of the “Large Scale Biosphere-Atmosphere Experiment in Amazonia” (LBA), an international

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## Nomenclature

$A_B$	basal area of the trees ( $m^2$ )
$A_G$	ground area of the forest site ( $m^2$ )
$B$	rate of energy absorption for respiration and photosynthesis ( $W m^{-2}$ )
$c_{br}$	specific heat of the branches ( $J kg^{-1} °C^{-1}$ )
$c_{cel}$	specific heat of cellulose ( $J kg^{-1} °C^{-1}$ )
$c_{lv}$	specific heat of the leaves ( $J kg^{-1} °C^{-1}$ )
$c_p$	constant pressure specific heat of air ( $J kg^{-1} °C^{-1}$ )
$c_{tr}$	specific heat of the “average” trunk ( $J kg^{-1} °C^{-1}$ )
$c_{tw}$	specific heat of the twigs ( $J kg^{-1} °C^{-1}$ )
$c_w$	specific heat of water ( $J kg^{-1} °C^{-1}$ )
$d_{bh}$	diameter measured at the height of 1.6 m of each trunk (m)
$E_{BR}$	energy balance ratio (dimensionless)
$E_{IP}$	energy imbalance percentage (dimensionless)
$F$	surface heat flux (W)
$G$	heat flux density in the soil ( $W m^{-2}$ )
$H$	sensible heat flux density ( $W m^{-2}$ )
$L$	latent heat of vaporization of water ( $J kg^{-1}$ )
$LE$	latent heat flux density or evapotranspiration rate ( $W m^{-2}$ )
$m_{br}$	mass of the branches per unit of ground area ( $kg m^{-2}$ )
$M_f$	mass of a tree (kg)
$m_{lv}$	mass of the leaves per unit of ground area ( $kg m^{-2}$ )
$m_{lt}$	mass of organic matter deposited on the ground of the forest per unit of ground area ( $kg m^{-2}$ )
$m_{oc}$	mass of the small size vegetation components per unit of ground area ( $kg m^{-2}$ )
$m_{tr}$	mass of the trunks per unit of ground area ( $kg m^{-2}$ )
$m_{tw}$	mass of the twigs per unit of ground area ( $kg m^{-2}$ )
$N$	number of trees found in the forest site
$P$	rainfall (mm)
$q$	specific humidity of air ( $kg kg^{-1}$ )
$Q_{SD}$	quadratic stand diameter (m)
$q_{br}$	moisture content in the branches ( $kg kg^{-1}$ )
$q_{lv}$	moisture content in the leaves ( $kg kg^{-1}$ )
$q_{tr}$	moisture content in the “average” trunk ( $kg kg^{-1}$ )
$q_{tw}$	moisture content in the twigs ( $kg kg^{-1}$ )
$R$	trunk radius (m)
$R_n$	net radiation ( $W m^{-2}$ )
$r_{pd}$	radius correspondent to the depth $d$ (m)
$S$	total above-ground thermal energy storage rate in the forest ( $W m^{-2}$ )
$S_{air}$	total energy storage rate in the air ( $W m^{-2}$ )
$S_{bio}$	total energy storage rate in the biomass ( $W m^{-2}$ )
$S_{br}$	energy storage rate in the branches ( $W m^{-2}$ )
$S_{lv}$	energy storage rate in the leaves ( $W m^{-2}$ )
$S_{lt}$	energy storage rate in the organic matter deposited on the ground of the forest ( $W m^{-2}$ )

$S_{oc}$	energy storage rate in the small size vegetation components ( $W m^{-2}$ )
$S_q$	energy storage rate in the air related to the specific humidity variations ( $W m^{-2}$ )
$S_T$	energy storage rate in the air related to the temperature variations ( $W m^{-2}$ )
$S_{tr}$	energy storage rate in the trunks ( $W m^{-2}$ )
$S_{tw}$	energy storage rate in the twigs ( $W m^{-2}$ )
$T$	air temperature ( $°C$ )
$t$	time (s)
$T_{tr}$	trunk temperature ( $°C$ )
$V_{cil}$	cylindrical volume of a trunk ( $m^3$ )
$V_{con}$	conical volume of a trunk ( $m^3$ )
$Z_r$	reference level for integration (m)

## Greek letters

$\Delta c$	correction factor due to the moistening heat of the dry cellulose pores ( $J kg^{-1} °C^{-1}$ )
$\eta_r$	relative humidity of the air (%)
$\rho_a$	air density ( $kg m^{-3}$ )
$\rho_{tr}$	fresh trunk density ( $kg m^{-3}$ )
$\vartheta_i$	trunk form factor (dimensionless)

experiment led by Brazil. We studied the surface energy balance, with special emphasis on the above-ground thermal energy storage rates (ESR) and the trunk heat fluxes.

Measuring the surface energy flux density ( $W m^{-2}$ ) over forests is an essential prerequisite to modeling the soil-vegetation-atmosphere interaction. Yet, the lack of closure of the surface energy balance (SEB) remains one of the major concerns in micrometeorology, and is a specially serious problem over tall vegetation (Lee, 1998). Further, it is difficult to measure the energy exchanges in a tropical forest due to the great heterogeneity of species and sizes of their trees (Monteny et al., 1985). Typically, the sum of the measured components of the energy balance represents 70–90% of the measured net radiation (Heusinkveld et al., 2004). Several explanations have been proposed, such as instrumental uncertainties, and the non-inclusion of components which are important for some vegetation covers or certain time scales.

In Amazonian forest, the thermal ESR in the volumes occupied by the above-ground parts of the vegetation and by the adjoining air parcels, may be an important component of the local energy balance for short time periods, generally smaller than one day. According to Stewart and Thom (1973), Aston (1985), McCaughey (1985), Moore and Fisch (1986), McCaughey and Saxton (1988) and Silberstein et al. (2001), the hourly values of the ESR in a forest may constitute a significant fraction of the net radiation, particularly at sunrise and sunset, and during cloudy or rainy periods, when they may be of similar magnitude to the net radiation. Moore and Fisch (1986) determined the total ESR for “terra firme” forest in the Reserva Ducke (central Amazonia), from measured air temperatures and humidity, plus trunk temperatures measured inside a tree whose diameter was close to the mean tree diameter. Its trunk was instrumented at three heights and one radial depth, which was determined by theoretical considerations. They

found hourly values which frequently exceeded  $50 \text{ W m}^{-2}$  and with daily maximum values reaching  $80 \text{ W m}^{-2}$ . Around dusk and dawn the ESR was found to exceed 50% of the net radiation. Moore and Fisch presented simplified expressions for estimating the ESR components from changes in air temperature and humidity above the canopy.

The inclusion of the ESR in soil-vegetation-atmosphere transfer (SVAT) models is an important component of the continuing improvement in numerical weather prediction and climate models: especially for simulating short time-scale phenomena in dense and tall forests. Silberstein et al. (2003), as a first attempt, included the forest ESR in a SVAT model using the “Force-Restore” method (Deardorff, 1978) to parameterize the ESR in the trunks. Recently, Haverd et al. (2007) have presented an analytical method for calculating the ESR in the trunks; it is independent of measured biomass temperatures, and includes the radiation effects on the trunks. This method was incorporated in a multi-layer SVAT model and it was applied to a 40 m tall Australian temperate Eucalyptus forest. The results showed that the inclusion of the total ESR improved both the energy balance closure, and the agreement between measured and modeled fluxes of sensible and latent heats.

The main objectives of the present work were the determination and characterization of the components of the total ESR and the verification of its relevance to the SEB in a “terra firme” central Amazonian forest, using both dry and wet season data. The specific objectives were: (i) to estimate the ESR of all the above-ground components of the forest (litter, palms and lianas, trunks, twigs, branches and leaves); (ii) to obtain simplified expressions for the computation of the total ESR using hourly measurements of air temperature and humidity.

## 2. Site

The measurements were made in the Reserva Biológica do Cuieiras, also known as ZF2 ( $02^{\circ}36'45'' \text{ S}$ ,  $60^{\circ}12'40'' \text{ W}$ , 150 m asl), in central Amazonia, 50 km northwest of Manaus, Brazil. The climate is typical of central Amazonia, with an average monthly rainfall above 150 mm from October to June, with only July to September having lower values; with more than 300 mm per month, March and April are the rainiest months, and August, with values below 100 mm, is the driest. The average relative humidity is always above 80%, and the monthly average temperatures vary between  $25^{\circ}\text{C}$  in July and  $27^{\circ}\text{C}$  in November. The average daily maxima oscillate between  $31^{\circ}\text{C}$  in February and  $33^{\circ}\text{C}$  in September, while the minima are between  $21^{\circ}\text{C}$  in July and  $23^{\circ}\text{C}$  in March (Marques Filho et al., 2005).

### 2.1. Instruments and measurements

The data were collected in two phases: (i) the dry season, between 15 August and 13 September, 2003, and (ii) the wet season, between 14 March and 12 April 2004. Measurements of rainfall, incident and reflected shortwave radiation, incident and emitted longwave radiation, air relative humidity and temperature, and soil heat flux were made using an automatic weather station installed on the 54 m micrometeorological tower ( $02^{\circ}36'31'' \text{ S}$ ,  $60^{\circ}12'31'' \text{ W}$ ) located in the Reserva Biológica do Cuieiras, described as tower K34 by Araújo et al. (2002).

Rainfall was measured with a tipping bucket raingauge (ARG-100 model, Didcot Instruments, Abingdon, UK) installed at 51.4 m. The short and longwave radiations components were measured with two pyranometers and two pyrgeometers (respectively CM-21 and CG-1 models, Kipp and Zonen, Delft, The Netherlands) installed at 44.6 m. The air relative humidity and temperature were measured by a thermo-hygrometer (HMP-35 A model, Vaisala Inc., Helsinki, Finland) installed at 51.1 m. A heat flux plate (SH1 model, Hukseflux Thermal Sensors, Delft, The Netherlands), buried at 1 cm below the ground surface, was used for the measurement of the soil heat flux. These sensors provided measurements every minute and half hour averages were recorded. Sensible and latent heat fluxes data were obtained by an eddy correlation system composed of a three-axis sonic anemometer (1012R2A Solent model, Gill Instruments, Lymington, UK) and a fast-response infrared gas analyzer (6262 model, LI-COR Inc., Lincoln, USA), installed at 53.1 m. Also, a vertical profile of temperature was obtained using resistance thermometers (PT100, HMP-35 A model, Vaisala Inc., Helsinki, Finland) installed at 15.6, 28.0, 35.5 and 42.5 m on the tower. For more details about the site, instruments and measurements, see Andreae et al. (2002) and Araújo et al. (2002).

To compute a vertical humidity profile, the measures of air temperature and relative humidity at 51.1 m height were used to obtain two quadratic regressions, one for the dry season days (Eq. (1),  $R^2 = 0.95$ ) and another for the wet season ones (Eq. (2),  $R^2 = 0.90$ ):

$$\eta_r = -0.11T^2 + 1.43T + 116.71 \quad (1)$$

and

$$\eta_r = -0.30T^2 + 12.37T - 28.86 \quad (2)$$

where  $\eta_r$  and  $T$  are, respectively, the air relative humidity and temperature. These expressions, using the temperatures measured at the 15.6, 28.0, 35.5 and 42.5 m levels, were used to compute the corresponding relative humidity at the same levels.

To obtain the trunk temperatures, one tree of a dominant species was selected from the study by Oliveira et al. (2002) as being representative of the site (see next Section). The north face of its trunk was instrumented with 10 type K (chromium-aluminium) thermocouples, which were inserted at heights of 1.5, 9.0 and 18.0 m. Four of these thermocouples were installed at the first height level (1.5 m) at depths of 0.5, 3.0, 10.0 cm and at the center of the trunk (15.1 cm), with the last one dependent on the diameter at breast height (DBH) of the tree (approximately at 1.6 m). At the second (9.0 m) and the third (18.0 m) height levels, the thermocouples were inserted at depths of 0.5, 3.0 and 10.0 cm. The temperatures were measured once per minute and recorded as 10 min averages on a data logger (CR-10 model, Campbell Scientific Inc., Shepshed, UK).

### 2.2. Characteristics of the forest

The Reserva Biológica do Cuieiras is covered by a typical “terra firme” Amazonian forest, with a large number of tall, thin trees. The heights of most of them are between 14 and 25 m, but there are some reaching up to 44 m (Oliveira et al., 2002).

The canopy is uniform and presents a rough aspect, with contiguous spherical crowns, which results in only about 7% of the shortwave radiation reaching the ground.

Oliveira et al. (2002) effected a survey of all trees with DBH greater than 10 cm, in two East–West transects of  $500 \times 10 \text{ m}^2$  (1 ha in total) of the “terra firme” forest of the Reserva Biológica do Cuieiras. They found 670 trees, distributed among 48 families, 133 genera and 245 species. Among the most frequent species were *Eschweilera micrantha*, *Chrysophyllum sanguinolentum* and *Licania davillifolia*. Using the complete data set of this survey, provided by Oliveira (personal communication, 2003), the spatial parameters, the density and the specific heat were evaluated in order to classify the trees. The “average” one, adequate for the purposes of this work, was then chosen (Section 2.5).

### 2.3. Evaluation of the spatial parameters of the trees

Oliveira et al. (2002) found that the average value of the DBH of the total set of 670 trees was  $20.8 \pm 14.5 \text{ cm}$ , while 494 (74%) of them presented a  $\text{DBH} \leq 23.6 \text{ cm}$ ; the distribution of the DBH was a negative exponential, which is typical in the region and also shows the absence of severe perturbations in the site.

Moore and Fisch (1986) measured the 40 trees with DBH greater than 15 cm lying inside the 30 m circle that included their instrumented tree at Reserva Ducke. They determined that their tree density was  $0.014 \text{ trees m}^{-2}$ , with an average DBH equal to  $41 \pm 3 \text{ cm}$  and an average height of  $30.1 \pm 0.7 \text{ m}$ . For the present Cuieiras site, considering DBHs greater than 15 cm, these values were equal to  $0.037 \text{ trees m}^{-2}$ ,  $28 \pm 4 \text{ cm}$  and  $23.5 \pm 5.7 \text{ m}$ , respectively. There were thus marked differences between the two sites. The basal area of each tree was computed from its DBH ( $d_{bh}$ ) through:

$$A_B = \pi \frac{(d_{bh})^2}{4} \quad (3)$$

giving the total basal area ( $A_{BT}$ ) for the whole set ( $N = 670$ ) as  $33.85 \text{ m}^2$ . Because of the high value of the standard deviation of the DBHs (14.5 cm for the average of 20.8 cm), the average tree was chosen by calculating the quadratic stand diameter ( $Q_{SD}$ ) of the forest (Cummings et al., 2002), i.e.:

$$Q_{SD} = \sqrt{\frac{4 \times (A_{BT}/N)}{\pi}} \quad (4)$$

giving a value of 25.36 cm.

### 2.4. Determination of the density and the specific heat

The density (of fresh biomass) and the specific heat of the trunks were needed to classify the trees and to choose one of them to be instrumented with trunk thermometers. Also, the specific heats of the branches, twigs, leaves, litter and small size components (palms and lianas) were required to carry out the procedures described in the following sections. These were obtained as explained below.

To determine the density of the trunks, cores were collected from some dominant tree species (*Eschweilera micrantha*, *Chrysophyllum sanguinolentum* and *Licania davillifolia*)

and their moisture contents were then determined at a specialized laboratory of the Instituto Nacional de Pesquisas da Amazônia (INPA). In addition, the values of the dry densities presented by Fearnside (1997) and Nogueira et al. (2005) for species of the forests of central Amazonia, and the moisture content presented by Higuchi et al. (1998) for the Reserva Biológica do Cuieiras were used.

The specific heat  $c_{tr,br,tw}$  (trunks, branches and twigs) for the fresh biomass was determined as a function of the specific heat of cellulose  $c_{cel}$ , of the moisture content  $q_{tr,br,tw}$  and of the specific heat of water  $c_w$  through the following equation, given by Marshall (1958):

$$c_{tr,br,tw} = \frac{c_{cel} + q_{tr,br,tw}c_w}{1 + q_{tr,br,tw}} + \Delta c \quad (5)$$

in which  $\Delta c$  is a correction factor due to the moistening heat of the pores of the dry cellulose and  $c_{cel}$  was obtained as a function of the annual average temperature of the air at the Reserva Biológica do Cuieiras, as follows (Moore and Fisch, 1986):

$$c_{cel} = 1113 + 4.85\bar{T} \quad (6)$$

For the calculation of the specific heat of the leaves ( $c_{lv}$ ) the following expression, adapted from Blanken et al. (1997), was used:

$$c_{lv} = q_{lv} + (1 - q_{lv})c_{cel} \quad (7)$$

in which  $q_{lv}$  is the moisture content of the leaves (Higuchi et al., 1998). The specific heat of the twigs was also used for the litter, because no litter moisture content measurements were available. For the small size components, the specific heat of the leaves was used, since these components are mostly palms, which are composed predominantly of leaves.

### 2.5. Evaluation of the distribution of the above-ground biomass and choice of the average tree

The determination of the biomass per unit ground area of the forest is necessary for the calculation of the ESR in each biomass component. This may be achieved using empirical relationships and published data. Thus, with the measured DBH values, the total fresh biomass  $M_f$  was estimated for each individual of the set, through the expressions presented by Higuchi et al. (1998):

For  $\text{DBH} < 20 \text{ cm}$ :

$$M_f = e^{[-1.754 + 2.665 \ln(d_{bh} \times 100)]} \quad (8)$$

and for  $\text{DBH} \geq 20 \text{ cm}$ :

$$M_f = e^{[-0.151 + 2.170 \ln(d_{bh} \times 100)]} \quad (9)$$

According to the results obtained for the Reserva Biológica do Cuieiras by Higuchi and Carvalho (1994), the average contribution of each component to the total fresh biomass of a tree  $M_f$  is: 65.6% for the trunk; 17.8% for the branches; 14.6% for the twigs and 2.0% for the leaves. These values were used to estimate the fresh masses per unit ground area for the trunks  $m_{tr}$ , for the branches  $m_{br}$ , for the twigs  $m_{tw}$ , and for the leaves  $m_{lv}$ .



**Table 1 – Number of trees (N), total basal area (A<sub>B</sub>), quadratic stand diameter (Q<sub>SD</sub>), density (ρ) and specific heat (c) of the dominant tree species, plus fresh masses per unit of ground area (m) for the trunks, branches, twigs, leaves, litter and small size components found in one hectare of the “terra firme” forest of the Reserva Biológica do Cuieiras**

Tree species	N	A <sub>B</sub> (m <sup>2</sup> )	Q <sub>SD</sub> (cm)	ρ (kg m <sup>-3</sup> )	c (J kg <sup>-1</sup> °C <sup>-1</sup> )	m (kg m <sup>-2</sup> )
<i>Aspidosperma oblongum</i>	2	1.48	96.93	1187 <sup>c</sup>	2398	–
<i>Eschweilera micrantha</i>	36	1.36	21.94	1242 <sup>a</sup>	2527	–
<i>Eschweilera atropetiolata</i>	11	1.14	36.29	1138 <sup>c</sup>	2398	–
<i>Pouteria gongrijpii</i>	19	1.01	26.02	1180 <sup>b</sup>	2398	–
<i>Licania davillifolia</i>	11	0.97	33.55	1261 <sup>a</sup>	2396	–
<i>Swartzia reticulata</i>	9	0.96	36.83	1166 <sup>c</sup>	2398	–
<i>Dinizia excelsa</i>	7	0.87	39.80	1410 <sup>b</sup>	2398	–
<i>Chrysophyllum sanguinolentum</i>	17	0.85	25.26	1265 <sup>a</sup>	2473	–
<i>Cariniana decandra</i>	3	0.83	59.40	913 <sup>c</sup>	2398	–
<i>Leonia glycyarpa</i>	2	0.80	71.54	1116 <sup>b</sup>	2398	–
Average trunk	–	–	25.36	1128	2407	43.79
Tree components						
Branches	–	–	–	–	2398	11.88
Twigs	–	–	–	–	2457	9.75
Leaves	–	–	–	–	2769	1.34
Litter	–	–	–	–	2457	3.79
Small size	–	–	–	–	2769	1.80

<sup>a</sup> INPA.

<sup>b</sup> Fearnside (1997).

<sup>c</sup> Nogueira et al. (2005).

The fine litter was estimated by Luizão and Schubart (1987) for the Reserva Biológica do Cuieiras to be approximately 7.9 t ha<sup>-1</sup>. The coarse litter, according to Summers (1998) and Chambers et al. (2000), is up to 30 t ha<sup>-1</sup>. Finally, the average biomass of the small living components of 20 Amazonian sites was estimated by Cummings et al. (2002) as 18 t ha<sup>-1</sup>.

The results for the 10 dominant species (number of trees, quadratic stand diameter, and density), ordered according to their total basal area, are presented in Table 1, together with their specific heats, plus the fresh mass per unit ground area of each of the biomass components.

Finally, a tree of the species *Chrysophyllum sanguinolentum* was selected from the set of Oliveira (personal communication, 2003) to measure the trunk temperatures, because its quadratic stand diameter was very close to the value calculated for the forest, while both its density and specific heat are close to the ones estimated for the average trunk.

### 3. Theory

In this work, the expression “energy storage” is preferred to “heat storage”, because it is conceptually more appropriate. According to its thermodynamics definition, heat is that form of energy in transit due to a temperature difference between the source from which the energy is coming and the sink toward which it is going. Thus, heat is a form of kinetic energy and it is transferred in three ways: conduction, convection and radiation. The energy is not heat before it starts to flow or after it has ceased to flow (see Sears and Salinger, 1975; Parker, 1984, p. 839–842).

Thus, the above-ground thermal energy storage rate *S* is defined as the rate of change of energy stored in a volume *V* due to heat flux *F* through the external surface of this volume per unit ground area *A<sub>G</sub>*. That is:

$$S = \frac{F}{A_G} = \frac{1}{A_G} \frac{d}{dt} \int \rho c T dV \tag{10}$$

in which ρ, c and T are the density, specific heat and temperature, respectively, of the material that composes the volume *V*.

The total ESR in a forest is composed of terms representing storage in the air (*S<sub>air</sub>*) and in the biomass (*S<sub>bio</sub>*), that is:

$$S = S_{air} + S_{bio} \tag{11}$$

The ESR in the air has components, resulting from the changes in the temperature in the air *S<sub>T</sub>* and the specific humidity *S<sub>q</sub>*:

$$S_{air} = S_T + S_q \tag{12}$$

The ESR in the biomass of the forest is subdivided into six parts, as follows:

$$S_{bio} = S_{tr} + S_{br} + S_{tw} + S_{lv} + S_{lt} + S_{oc} \tag{13}$$

where *S<sub>tr</sub>*, *S<sub>br</sub>*, *S<sub>tw</sub>*, *S<sub>lv</sub>*, are the ESR in the trunks (stems), branches, twigs, and leaves, respectively and, *S<sub>lt</sub>* is the ESR in the litter, i.e. the organic matter deposited on the ground of the forest, and *S<sub>oc</sub>* is the ESR in the small size components of the biomass, such as palms and lianas. Among these terms, *S<sub>tr</sub>* is the largest, and its determination is the most difficult, because it depends on the measurement of internal and/or superficial temperatures of the trunks. Moreover, knowledge of the thermal properties and the spatial dimensions of the trunks is necessary. However, the main difficulty is the non-homogeneity caused by the large number of species which occur in natural forests, especially in the humid tropics. This variation gives a large range in the spatial dimensions and thermal properties of the trunks.

### 3.1. Vertical division of the forest

To determine the total ESR, the soil–vegetation–atmosphere interface was divided into layers of different thickness. For this division, the average height of the 670 trees ( $19.0 \pm 6.6$  m) of the hectare was considered. Thus, to calculate the ESR in the air, the interface was divided into five layers. The first layer starts at the surface of the soil,  $z_{1,\text{air}} = 0$ , up to the height of 20 m. The second one initiates at the height  $z_{2,\text{air}} = 20$  m and has a thickness of 11 m. The third layer is between the heights  $z_{3,\text{air}} = 31$  m and  $z_{4,\text{air}} = 40$  m, with a thickness of 9 m; the fourth one has a thickness of 7 m. The fifth layer is between the heights  $z_{5,\text{air}} = 47$  m and  $z_{6,\text{air}} = 53$  m, with a thickness of 6 m. To determine the ESR in the biomass, four layers were considered. The first layer initiates at  $z_{1,\text{bio}} = 0$ , up to 6 m, and it is constituted by the first trunk parcel, plus the litter and the small size components (palms and lianas). The second layer starts at the height  $z_{2,\text{bio}} = 6$  m, has a thickness of 6 m, and it corresponds to the second trunk parcel. The third layer, initiating at  $z_{3,\text{bio}} = 12$  m with a thickness of 6 m, corresponds to the third and last trunk parcel. The fourth layer, which is located between  $z_{4,\text{bio}} = 18$  m and  $z_{5,\text{bio}} = 20$  m, that is, with a thickness of 2 m, was chosen as that one where the branches (basal diameter  $\geq 10$  cm), the twigs and the leaves are concentrated.

### 3.2. Energy storage rate in the air

Considering an elementary volume of air with height  $dz$  and surface area  $dA$  through which the heat flows vertically, the ESR in the air due to the temperature variations  $S_T$ , is given by Eq. (10) as:

$$S_T = \frac{A}{A_G} \int_0^{z_r} \rho_a c_p \frac{dT}{dt} dz \quad (14)$$

in which  $\rho_a$ ,  $c_p$  and  $T$  are the density, the specific heat at constant pressure and the temperature of the air volume, respectively, and  $z_r$  is the reference level for integration. Assuming that the area  $A$  where the vertical flow of heat occurs is approximately equal to the ground area of the forest,  $A_G$ , because the air occupies around 99.7% ( $=100 \times (A_G - A_{BT})/A_G$ ) of the total area of the forest, and also assuming that  $\rho_a$  and  $c_p$  are constants, Eq. (14) reduces to:

$$S_T = \rho_a c_p \int_0^{z_r} \frac{dT}{dt} dz \quad (15)$$

Considering  $l$  horizontal layers of variable thickness  $\Delta z_i$  and with  $\Delta \bar{T}_i$  as the change in average air temperature for each layer  $i$  in a time interval  $\Delta t$  (equal to 1 h), Eq. (15) expressed in finite differences becomes:

$$S_T = \frac{\rho_a c_p (1 + 0.84\bar{q})}{\Delta t} \sum_{i=1}^l \sum_{k=1}^n \Delta \bar{T}_{ik} \Delta z_i \quad (16)$$

in which the index  $k$  represents the time interval over which the ESR is calculated ( $k = 1, 2, \dots, n$ ;  $n = 24$  h), and the term  $0.84\bar{q}$

takes into account the energy storage rate due to the water vapor in  $S_T$  (Silberstein et al., 2001).

Analogously, the ESR in the air due to the variation of specific humidity is given by:

$$S_q = \frac{\rho_a L}{\Delta t} \sum_{i=1}^l \sum_{k=1}^n \Delta \bar{q}_{ik} \Delta z_i \quad (17)$$

where  $L$  is the latent heat of vaporization and  $\bar{q}$  is the average specific humidity of the air.

### 3.3. Energy storage rate in the trunks

Considering the heat that flows through the surface of the representative trunk of a dominant species of the forest  $F_r$ , the ESR in the trunks is given by Eq. (10) expressed in cylindrical coordinates:

$$S_{tr} = N \frac{F_r}{A_G} = \frac{N}{A_G} \int_0^{z_r} \int_0^{2\pi} \int_0^R \rho_{tr} c_{tr} \frac{dT_{tr}}{dt} r dr d\theta dz \quad (18)$$

in which  $\rho_{tr}$ ,  $c_{tr}$ ,  $T_{tr}$  and  $R$  are the fresh density, specific heat, temperature and radius of the trunk, respectively;  $N$  is the number of individuals found in the area studied. Thus, considering that  $\rho_{tr}$  and  $c_{tr}$  are radially and vertically constant, Eq. (18) becomes:

$$S_{tr} = \frac{N}{A_G} 2\pi \rho_{tr} c_{tr} \int_0^{z_r} \left( \int_0^R \frac{dT_{tr}}{dt} r dr \right) dz \quad (19)$$

For a better estimate of the trunk heat flux, the “average” trunk was used: it represents the mean characteristics of the complete set of the 670 trees 1 ha sample in terms of the quadratic stand diameter, density and specific heat (Table 1). So, to compute the ESR in the trunks, the temperature time series measured in the representative trunk of a dominant species (*Chrysophyllum sanguinolentum*) and the properties of the average trunk were used. Each one of the trunk layers was divided into  $m$  concentric cylindrical rings  $j$  of variable widths  $r_j - r_{j-1}$  ( $r_0 = 0$ ), and the average temperature  $\bar{T}_{tr}$  of each ring was measured. Then, the ESR in the trunks was obtained through Eq. (19) expressed in finite differences:

$$S_{tr} = \frac{N}{A_G} \frac{\pi \rho_{tr} c_{tr}}{\Delta t} \sum_{i=1}^l \sum_{j=1}^m \sum_{k=1}^n (\Delta \bar{T}_{tr})_{ijk} (r_j^2 - r_{j-1}^2)_i \Delta z_i \vartheta_i \quad (20)$$

where  $\vartheta_i$  is the trunk form factor (Blanken et al., 1997), which is defined as the ratio of the trunk considered as a conical volume to that assuming the trunk as a cylinder, used to obtain the surface heat flux  $F_r$ . Thus:

$$\vartheta_i = \frac{(V_{con})_i}{(V_{cil})_i} \quad (21)$$

For each layer  $i$ , the conical and cylindrical volumes are given by:

$$(V_{con})_i = \pi \frac{\Delta z_i}{3} (R_{low}^2 + R_{low}R_{upp} + R_{upp}^2)_i \tag{22}$$

and

$$(V_{cil})_i = \pi \Delta z_i R_i^2 \tag{23}$$

where  $(R_{low})_i$  and  $(R_{upp})_i$  are, respectively, the radii measured in the lower and upper levels of the layer and  $R_i$  is the radius measured at the level in which the thermocouples were inserted. The value of  $Q_{SD}$  was used to obtain  $(R_{low})_i$ ,  $(R_{upp})_i$  and  $R_i$  of the average trunk. Thus, for the first layer,  $(R_{low})_1 = R_1 = Q_{SD}/2$ . To calculate  $(R_{upp})_1$  and the radii in the second and third layers, a quadratic regression between the diameters and the measured heights ( $h_m$ ) of the representative trunk was determined, and the intercept was replaced by  $Q_{SD}$ . Thus, the radii ( $R$ ) were estimated through:

$$2R = 0.004h_m^2 - 0.46h_m + Q_{SD} \tag{24}$$

Determining the ESR in the trunks (Eq. (20)), requires the areas of the cylindrical rings, into which the trunks were divided, for each layer. Thus, after the determination of the distances ( $r_{pd}$ ) between the axis of the trunk and each one of the thermocouples, logarithmic averages between neighboring pairs of  $r_{pd}$  were computed and used as the radii of the circles which separate each ring from its neighbor; that is (Coimbra, 1960, p. 250-251):

$$(r_j)_i = \left( \frac{r_{pd} - r_{pd-1}}{\ln r_{pd}/r_{pd-1}} \right)_i \tag{25}$$

Therefore, the area of each cylindrical ring is given by  $A_{ij} = \pi(r_j^2 - r_{j-1}^2)_i$ , for  $j = 1, 2, \dots, m$ ; for  $j = 1$ ,  $r_0 = 0$ , that is, the most central area is a circle. In this way, the inner-most thermocouple measured the temperature series inside the circular area around the axis of the trunk, while the other thermocouples correspond to the cylindrical rings, with thicknesses that decrease toward the external surface of the trunk, because the temperature gradients are higher near this surface.

**3.4. Energy storage rates in the other components of the biomass**

The ESR in the twigs, leaves and small size components (palms and lianas), is obtained through:

$$S_{tw.lv.oc} = \frac{1}{A_G} \int_V \rho_{tw.lv.oc} c_{tw.lv.oc} \frac{dT}{dt} dV \tag{26}$$

in which  $\rho$  and  $c$  are, respectively, the density and the specific heat estimated for each one of these components at the site and  $dT/dt$  is the rate of change of the air temperature at a specific level  $i$ . Assuming that  $\rho$  and  $c$  are constants gives:

$$S_{tw.lv.oc} = \frac{\rho_{tw.lv.oc} V_{tw.lv.oc}}{A_G} c_{tw.lv.oc} \frac{dT}{dt}_i \tag{27}$$

As the fresh biomass per unit ground area is  $m = \rho V/A_G$ , Eq. (27) expressed as finite differences becomes:

$$S_{tw.lv.oc} = \frac{m_{tw.lv.oc} c_{tw.lv.oc}}{\Delta t} \sum_{k=1}^n \Delta \bar{T}_{ik} \tag{28}$$

The air temperature series measured at the level of 28.0 m was used for the leaves, and that measured at 15.6 m was used for the twigs and small size components.

Analogously, the ESR in the branches and litter is given by:

$$S_{br.lt} = \frac{m_{br.lt} c_{br.lt}}{\Delta t} \sum_{k=1}^n (\Delta \bar{T}_{tr})_{ijk} \tag{29}$$

in which  $m$  and  $c$  are, respectively, the fresh biomass per unit ground area and the specific heat estimated for each one of these components at the site. The temperature series measured at the representative trunk at the levels of 18.0 (3.0 cm) and 1.5 m (0.5 cm) respectively were used for the branches and the litter.

**3.5. Calculation of the surface energy balance and its closure**

Considering that the forest is extensive and relatively opaque to radiation, and that the surface is relatively horizontal, its energy balance may be expressed in terms of the vertical fluxes of energy through the canopy (Sellers, 1966; Arya, 2001). Thus, for a dense forest, as this Amazonian one, for short periods of time (generally less than one day), the simplified equation of the energy balance can be written as:

$$R_n = H + LE + B + S + G \tag{30}$$

in which  $R_n$  is the net radiation,  $H$  is the sensible heat flux,  $LE$  is the latent heat flux due to evapotranspiration,  $B$  is the rate of energy absorption for respiration and photosynthesis (biochemical storage),  $S$  is the ESR in the forest, and  $G$  is the heat flux into the soil. Often, the balance does not close, due to errors in the measurements and methodology. For the case of humid forests, among the non-radiation terms, the dominant one is the latent heat flux, which is of similar magnitude to the net radiation, while the sensible heat flux and the heat flux into the soil are smaller; the biochemical storage term is relatively low with values between 0.5% and 5% of the net radiation (Araújo et al., 2002; Malhi et al., 2002). The ESR for forests with tall trees and their associated large biomass, which is the case here, may appear as a significant term, mainly for short periods of time, from a few hours to up to one day.

The energy balance closure was evaluated using two methods adapted from Wilson et al. (2002). The first one was to obtain the linear regression coefficients (intercept and slope) and the coefficient of determination ( $R^2$ ) between one-hourly estimates of the sum of the non-radiation energy flux densities ( $H + LE + S + G$ ) and the net radiation ( $R_n$ ).  $B$  was excluded due to its small value and because there were no carbon flux data available for the days considered in this study. The ideal closure is represented by an intercept of 0, a slope of unity and an  $R^2 = 1$ . The second method was to

calculate the energy balance ratio ( $E_{BR}$ ) between the cumulative sum  $H + LE + S + G$  and  $R_n$  over specified time periods. Here,  $E_{BR}$  is defined as:

$$E_{BR} = \frac{\sum(H + LE + S + G)}{\sum R_n} \quad (31)$$

In addition, the energy imbalance percentage ( $E_{IP}$ ) can be calculated to indicate the magnitude of the SEB non-closure over each specified time period. Where:

$$E_{IP} = |1 - E_{BR}| \times 100 \quad (32)$$

## 4. Results and discussion

All the terms making up the total above-ground thermal energy storage rate ( $S_T$ ,  $S_q$ ,  $S_{tr}$ ,  $S_{br}$ ,  $S_{tw}$ ,  $S_{iv}$ ,  $S_{lt}$ ,  $S_{oc}$ ) and the surface energy balance, were computed for 20 days with complete data, that is, 10 for the period 15–24 August, during the dry season of 2003, and 10 for the period 2–11 April, during the wet season of 2004. Fig. 1 presents the day-averaged hourly variation of the air temperature and relative humidity at 15.6 m. Fig. 2 shows the day-averaged hourly variation of the measured/calculated energy flux densities and of the rainfall during the same period.

The day-averaged hourly behavior of the temperatures measured at 1.5 m in the trunk of the *Chrysophyllum sanguinolentum* specimen is shown in Fig. 3. The amplitude of the temperature series increases from the center toward the surface of the trunk, and the inner-most temperature (at the center) may show a phase delay of up to 8 h relative to the outer-most (in the bark). As expected, there is a difference between the thermal amplitudes of the series measured during the dry and the wet seasons.

### 4.1. Above-ground thermal energy storage rates

The day-averaged hourly variation of the storage terms  $S_{air}$ ,  $S_{tr}$ ,  $S_{um}$  ( $S_{br} + S_{tw} + S_{iv} + S_{lt} + S_{oc}$ ) together with the total ESR,  $S$ , during the selected days, is shown in Fig. 4. When  $S_{air}$  reached

its maximum values, generally at about 08 LT, with peaks up to  $70 \text{ W m}^{-2}$ , it was on average equal to about 60% of the value of  $S$ . The minima of  $S_{air}$  occurred at about 19 LT with values as low as  $-40 \text{ W m}^{-2}$ , corresponding on average to 40% of  $S$ . For periods with rainfall,  $S_{air}$  was found to reach  $-140 \text{ W m}^{-2}$ , corresponding on average to about 40% of  $S$ .

The hourly behavior of  $S_{tr}$  was characterized by small negative values during the night, becoming positive at about 08 LT, and then increasing until about 13 LT at 80% of  $S$ , and reaching values as high as  $30 \text{ W m}^{-2}$ . At about 16 LT  $S_{tr}$  again became negative, reaching a minimum at about 20 LT, with an average of 25% of  $S$ . During rainfall  $S_{tr}$  was found to be negative, with values on average equal to about 25% of  $S$ , and decreasing to  $-40 \text{ W m}^{-2}$ .

Considering their hourly behavior, the highest values observed for  $S_{br}$ ,  $S_{tw}$  and  $S_{iv}$  were 20, 20 and  $5 \text{ W m}^{-2}$ , respectively, while the lowest were  $-10$ ,  $-20$  and  $-2.5 \text{ W m}^{-2}$ , respectively. On rainy days, the values found for  $S_{br}$ ,  $S_{tw}$  and  $S_{iv}$  did not exceed  $-15$ ,  $-30$  and  $-5 \text{ W m}^{-2}$ , respectively. The components  $S_{lt}$  and  $S_{oc}$  were observed to have maxima of about  $5 \text{ W m}^{-2}$ . During days with heavy and daylong cloudiness but without rainfall, the hourly values of  $S_{lt}$  and  $S_{oc}$  did not exceed  $1 \text{ W m}^{-2}$  over most of the day. During rainfall hours, the minima for  $S_{lt}$  and  $S_{oc}$  were about  $-5 \text{ W m}^{-2}$ . The maxima of the sum of these components  $S_{um}$ , were reached at about 09 LT, with peaks of up to  $30 \text{ W m}^{-2}$ , which contributed on average to about 35% of the value of  $S$ . Their minima were reached at about 19 LT with values as low as  $-30 \text{ W m}^{-2}$ , corresponding on average to 40% of  $S$ . For periods with rainfall, these values reached  $-45 \text{ W m}^{-2}$ , that is, on average equal to about 35% of  $S$ .

The hundreds of tree species which comprise the Amazonian Forest present a sampling problem; ideally a great number of them should be instrumented, but in practice this is not feasible. Although we recognize that this introduces some sampling error, the pragmatic solution of selecting an average trunk was adopted. There are also errors in the values chosen as “constants” in the equations. So, considering a height of 50 m for the air column, for each  $1^\circ \text{C h}^{-1}$  and  $1 \text{ g kg}^{-1} \text{ h}^{-1}$  rise in the air temperature and humidity, respectively,  $S_{air}$  changes by  $60 \text{ W m}^{-2}$ . For an average height of 20 m for the trunks, and using the density and specific heat of the average trunk

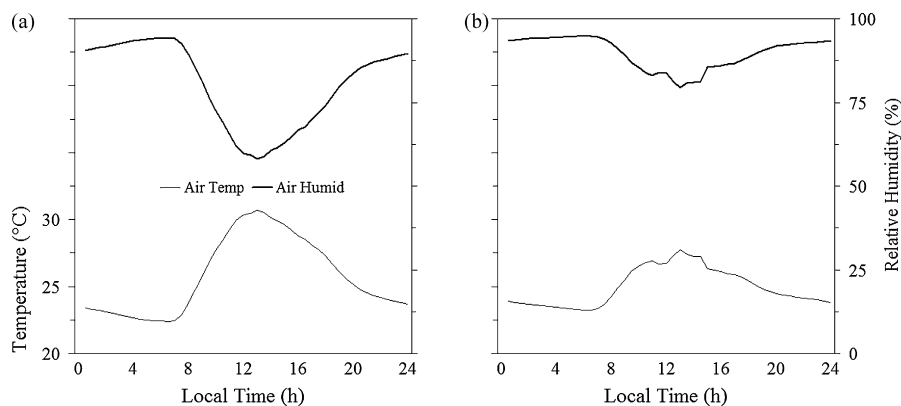


Fig. 1 – Day-averaged hourly variation of the air temperature and relative humidity (computed), at the 15.6 m height, in the forest of the site for (a) the period between August 15 and 24, during the dry season of 2003, and (b) the period between April 2 and 11, during the wet season of 2004.



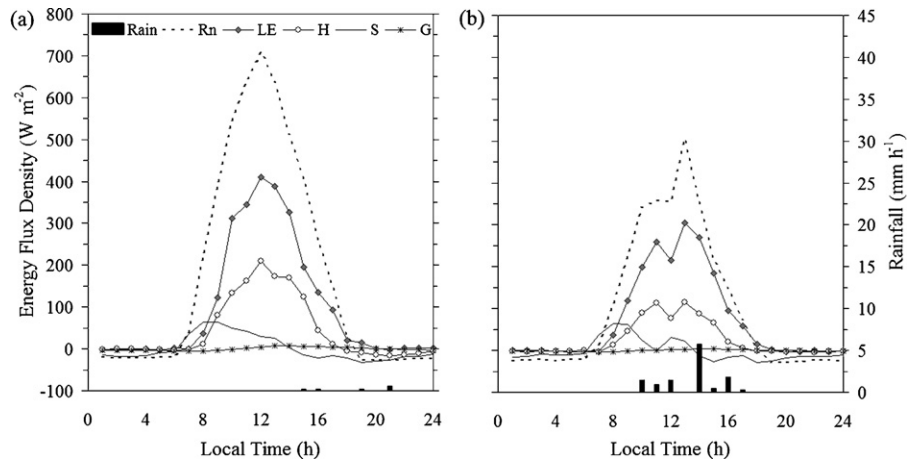


Fig. 2 – Day-averaged hourly variation of the energy flux densities and of the rainfall in the forest of the site, during the same periods as in Fig. 1.

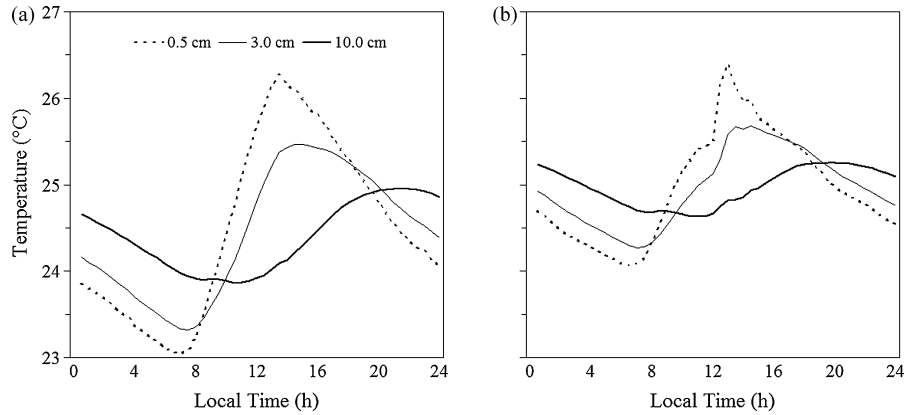


Fig. 3 – Day-averaged temperature series of the trunk of the *Chrysophyllum sanguinolentum* specimen, measured at the depths of 0.5, 3.0 and 10.0 cm, at the 1.5 m height, during the same periods as in Fig. 1.

(Table 1), for each 1 °C h<sup>-1</sup> rise in the average trunk temperature,  $S_{tr}$  changes by 35 W m<sup>-2</sup>; with the same conditions, but introducing an error of 10% in the heights of the air column ( $\pm 5$  m) and trunks ( $\pm 2$  m), results in a variation

of  $\pm 6$  W m<sup>-2</sup> (10%) for  $S_{air}$  and of  $\pm 2.5$  W m<sup>-2</sup> (7%) for  $S_{tr}$ . There are also errors in the calculation of  $S_{tr}$  due to uncertainties in the values of the density. According to Nogueira et al. (2005), the dry densities of the species found in the forests of central

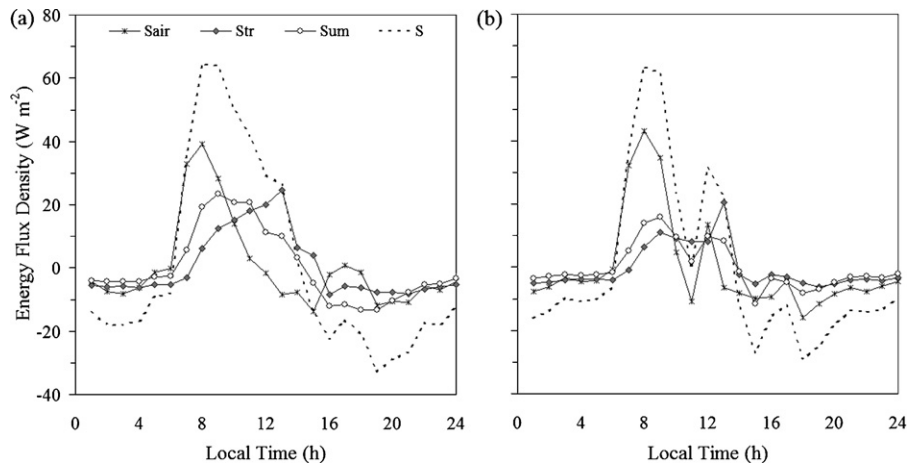


Fig. 4 – Day-averaged hourly variation of the ESR in the air  $S_{air}$ , the trunks  $S_{tr}$ , the rest of the biomass  $S_{br} + S_{tw} + S_{lv} + S_{lt} + S_{oc}$  ( $S_{um}$ ), of the total ESR  $S$ , during the same periods as in Fig. 1.

**Table 2 – Ratios (%) involving  $S$ ,  $S_{\text{air}}$ ,  $S_{\text{tr}}$ ,  $S_{\text{um}}$  and  $R_n$ , plus accumulated rainfall  $P$  (mm), for the periods between August 15 and 24, 2003 (dry season), and between April 2 and 11, 2004 (wet season)**

Season	$S_{\text{air}}/S$	$S_{\text{tr}}/S$	$S_{\text{um}}/S$	$\overline{\left(\frac{S}{R_n}\right)}_{\text{day}}$	$\overline{\left(\frac{S}{R_n}\right)}_{\text{night}}$	$(S/R_n)_{\text{min}}$	$(S/R_n)_{\text{max}}$	$P$
Dry (10 days)	30	40	30	$5 \pm 2$	$88 \pm 35$	-5	4	8
Wet (10 days)	40	40	20	$3 \pm 7$	$54 \pm 12$	-40	5	116
Average	35	40	25	$4 \pm 4$	$71 \pm 25$	-23	4	

Overbar = average.

Amazonia range between 270 and 960 kg m<sup>-3</sup>. Using the average value given by Higuchi et al. (1998) for the water content of the trunks of central Amazonian forests (=0.39 m<sup>3</sup> m<sup>-3</sup>), the actual densities should range between 443 and 1574 kg m<sup>-3</sup>. For the trunks with these densities,  $S_{\text{tr}}$  would vary between 15 and 50 W m<sup>-2</sup>, that is, it may deviate by up to 60% from the average trunk.

The contributions of each one of the main terms of  $S$ , that is,  $S_{\text{air}}$ ,  $S_{\text{tr}}$  and  $S_{\text{um}}$ , for the sum of the 10 days of each season (Table 2) were, respectively, 30%, 40% and 30% during the dry season and 40%, 40% and 20% during the wet season. It is important to point out that, although separately they are minor terms, acting together the daily contributions of  $S_{\text{br}}$ ,  $S_{\text{tw}}$ ,  $S_{\text{iv}}$ ,  $S_{\text{it}}$  and  $S_{\text{oc}}$  are equal to approximately one third of the total storage. Thus it is clear that it is important to include these terms in the calculation of the ESR of forests such as the ones in Amazonia.

The total ESR,  $S$ , was negative before sunrise, on average equal to  $-15 \text{ W m}^{-2}$  and corresponding to 65% of  $R_n$ . It became positive at 07 LT, with a maximum of  $55 \text{ W m}^{-2}$  at this time, and with the ratio  $S/R_n$  normally close to unity. During the morning, between 08 and 12 LT,  $S$  was on average between 65 and  $25 \text{ W m}^{-2}$  corresponding to 30 and 5% respectively of  $R_n$ . Its daily maximum value was reached at about 09 LT, with values of up to  $90 \text{ W m}^{-2}$ , representing on average 15% of  $R_n$ . Typically, at about 15 LT, it became negative again, reaching its daily minimum at about 19 LT, with values down to  $-85 \text{ W m}^{-2}$ , and again the ratio  $S/R_n$  is close to unity. At sunset, when  $R_n$  is close to zero,  $S$  may exceed the net radiation by a factor of up to four. The extreme minima of  $S$  occurred during rainfall hours, with values of

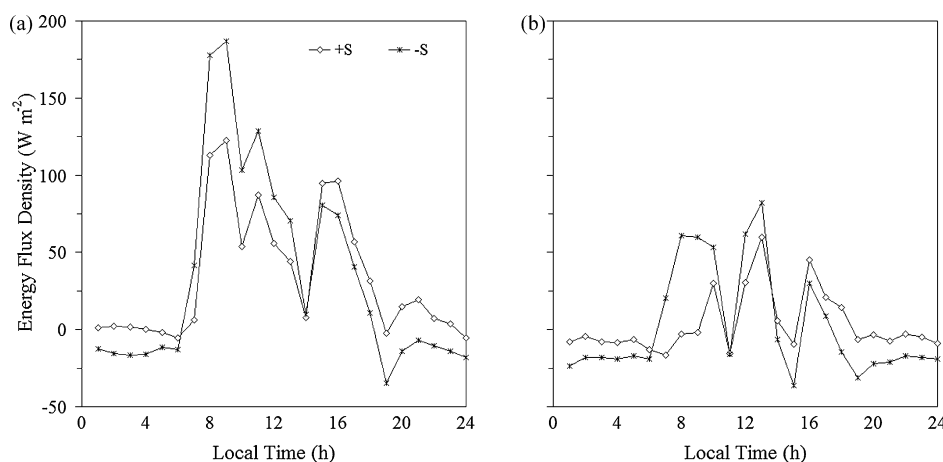
$-215 \text{ W m}^{-2}$ , which on average were 20 times higher than  $R_n$ , in absolute value. The negative values of  $S$  during the heavy rainfall events, which are very common in Amazonia, indicate the importance of  $S$  for releasing part of the energy used for the evaporation of the water intercepted by the foliage of the trees: the rate of evaporation surpasses the net radiation  $R_n$  under these conditions.

During daylight,  $S$  was characterized by generally positive values of up to  $1.4 \text{ MJ m}^{-2} \text{ day}^{-1}$ , representing on average during the dry and wet season days  $5 \pm 2\%$  and  $3 \pm 7\%$  of  $R_n$ , respectively (Table 2). During the night,  $S$  was always negative and, in days without nocturnal rainfall, it reached values of up to  $1.1 \text{ MJ m}^{-2} \text{ day}^{-1}$ , in absolute terms. However, the importance of  $S$  was higher during the night than during the daylight hours, corresponding on average during the dry and the wet season days to  $88 \pm 35\%$  and  $54 \pm 12\%$  of  $R_n$ , respectively. It is also important to note that on 19 August 2003, when rainfall occurred during the night,  $S$  exceeded  $R_n$ .

The daily totals (Table 2) observed depend on the weather conditions, but values of  $S$  were found between  $-5\%$  and  $4\%$ , and  $-40\%$  and  $5\%$  of  $R_n$  for dry and wet season days, respectively. Thus, for days with high totals of  $R_n$ , the values of  $S$  were positive, indicating absorption of energy by the forest. This energy is subsequently released on cloudy days when  $S$  is negative and there is more release than absorption of energy.

#### 4.2. Surface energy balance

Fig. 5 presents the day-averaged hourly variation of the residual difference between the net radiation and the sum of



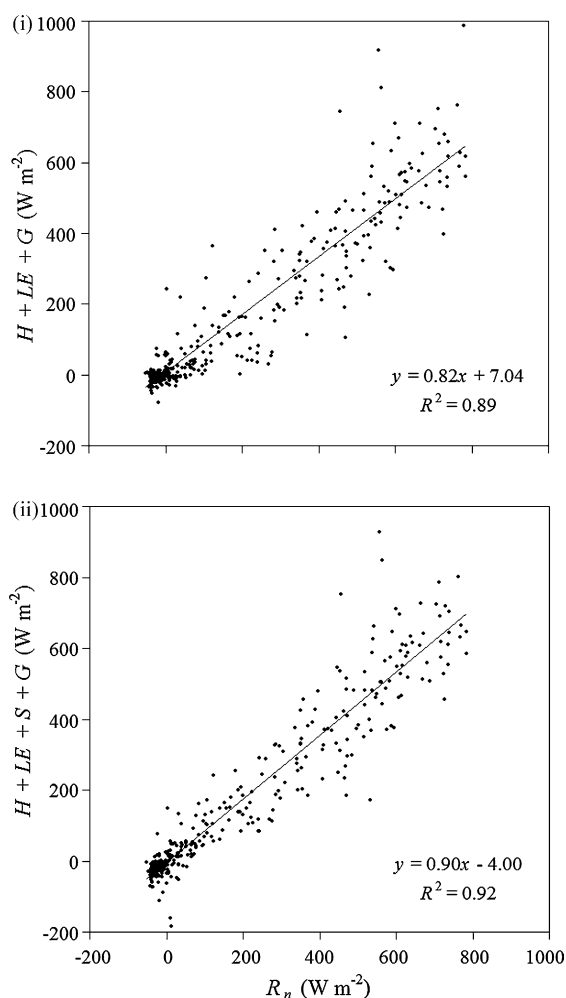
**Fig. 5 – Day-averaged hourly variation of the residual difference between the net radiation  $R_n$  and the sum of the non-radiation energy flux densities including and not including  $S$  (+ $S$  and  $-S$ ), during the same periods as in Fig. 1.**

the non-radiation energy flux densities. For the 10 days of August 2003 (dry season), the absolute average value of the residual was  $50 \pm 65 \text{ W m}^{-2}$ , with a minimum of 0 and a maximum of  $370 \text{ W m}^{-2}$ . For the 10 days of April 2004 (wet season), the average residual, and the minimum and the maximum absolute values were  $35 \pm 50 \text{ W m}^{-2}$ , 0 and  $360 \text{ W m}^{-2}$ , respectively. When S was not included in the calculation of this difference, that is,  $R_n - (H + LE + G)$  was computed, the absolute values of the average residual were  $65 \pm 75$  and  $40 \pm 50 \text{ W m}^{-2}$ , for the dry and wet season days, respectively. Thus, excluding S from the calculation of the SEB increased the average residual by, approximately, 25% and 20% for the dry and wet groups of days respectively. The standard deviation also increased. For both seasons, the hourly average residual was lower during the night and morning hours when S was included in the SEB; however, during the afternoon, this inclusion caused an increase of the absolute value of this residual.

Linear regressions between hourly values of the sum of the non-radiation energy flux densities and the net radiation

**Table 3 – Coefficients (intercept, slope and  $R^2$ ) of the linear regressions between the hourly values of the sum of the non-radiation energy flux densities  $H + LE + S + G$  (or  $H + LE + G$ ) and the net radiation  $R_n$ ; also, the energy balance ratio  $E_{BR}$  and the energy imbalance percentage  $E_{IP}$ , all for the same periods in Table 2**

Period	Intercept	Slope	$R^2$	$E_{BR}$	$E_{IP}$
Dry season					
Daily (-S)	0.3	0.80	0.89	0.81	19.4
Daily (+S)	-13.2	0.89	0.93	0.81	18.9
Daylight (-S)	-34.6	0.87	0.82	0.78	22.3
Daylight (+S)	-38.0	0.93	0.88	0.83	17.0
Nocturnal (-S)	-6.5	0.04	0.00	0.33	67.3
Nocturnal (+S)	-13.8	0.53	0.09	1.13	12.9
Wet season					
Daily (-S)	11.8	0.86	0.88	0.98	2.5
Daily (+S)	2.7	0.94	0.90	0.97	3.3
Daylight (-S)	0.3	0.89	0.83	0.89	11.3
Daylight (+S)	-3.4	0.96	0.86	0.94	6.0
Nocturnal (-S)	-5.3	-0.03	0.00	0.18	82.0
Nocturnal (+S)	-5.3	0.51	0.16	0.72	27.6



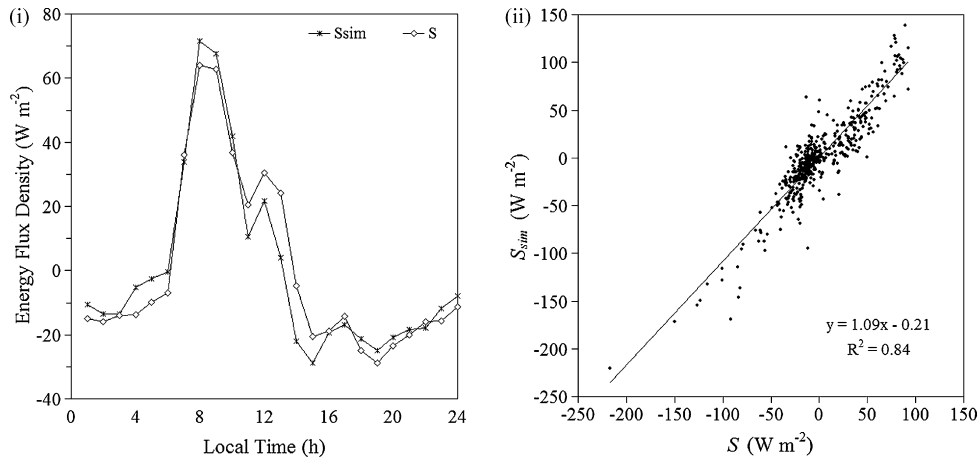
**Fig. 6 – Linear regressions between hourly values of (i) the sum of the energy flux densities  $H + LE + G$  and the net radiation  $R_n$ ; (ii) the sum of the energy flux densities  $H + LE + S + G$  and the net radiation  $R_n$ , for the daily cycles of the 20 selected days ( $n = 480$ ) of the same periods as in Fig. 1.**

for the 10 days of each season considered, verified that the inclusion of S in the calculation of the SEB improved its closure for the daily periods (Fig. 6, 480 points; Table 3, 240 points), as well as for the daylight and nocturnal ones (Table 3, 120 points); notwithstanding, the nocturnal regression still presented a very high dispersion. For the linear regression including all the hourly values of the 20 selected days, the slope and  $R^2$  improved by 10% and 4% respectively when compared to the regression in which S was not included.

The linear regressions with daylight hourly values including S, during the dry and wet seasons days, showed an improvement of about 5% for both the slope and for  $R^2$ . In addition, the calculation of the energy balance ratio (EBR, Eq. (31)) confirmed that the inclusion of S in the calculation of the SEB improved its closure, mainly during daylight hours, and especially during late morning, when S reached its hourly maximum. It was also verified that EBR stayed closer to unity when S was considered in its calculation. The energy imbalance percentage (Eq. (32)) showed that generally for periods when the balance of S was positive, a better closure of the SEB occurred, as for the sum of the values of the dry season days. In contrast, when the S balance was negative, as for the wet season days, the SEB closure tended to be worse if S was included (Table 3).

**4.3. Calculation of the energy storage rates from limited measurements**

The ESR has been shown to be a significant component of the surface energy balance for short time periods in a tall forest (Section 4.2). However, the vertical air temperature and humidity profiles, which are necessary to compute the ESR, are usually not available, and the necessary trunk temperatures, are almost never measured. There is thus a need for a simple method to estimate the ESR components, from the commonly-available above-canopy air temperature and humidity measurements. Moore and Fisch (1986) derived



**Fig. 7 – (i) Day-averaged hourly variation and (ii) linear regression between hourly values ( $n = 480$ ) of the total ESR calculated through the sum of Eqs. (16), (17), (20), (26) and (27) ( $S$ ) and of Eqs. (33)–(35) ( $S_{sim}$ ), for the daily cycles of the 20 selected days of the same periods as in Fig. 1.**

empirical expressions for the ESR terms for a similar forest in Reserva Ducke (some 40 km south of the present site) using linear regressions between, respectively,  $S_r$ ,  $S_q$ ,  $S_{tr}$  and the hourly changes in the air temperature, specific humidity and temperature 1 h in advance, measured above the canopy at a height of 41 m. According to these authors, the method for  $S_{tr}$  does not work when there are rapid temperature variations, which is the case during rainy hours. So, the total ESR was computed using their Eq. (17) and the data obtained during the rainless days of the present study (15, 16, 20, 22, 23 and 24, August 2003 and 05 and 08 April 2004) at the height of 51.1 m. The linear regression intercept, slope and  $R^2$  between the results obtained in this study ( $S$ ), and the ones obtained with the Moore and Fisch formula ( $S_{M \text{ and } F}$ ) were  $-0.37$ ,  $0.63$  and  $0.80$ , respectively. But using the 20 selected days data, the results for intercept, slope and  $R^2$  were  $-0.14$ ,  $0.68$  and  $0.83$ , respectively.

Accounting for the known differences between the Ducke and Cuieiras forests, in terms of dimensions, biomass and thermal properties, should result in a better agreement. Therefore, the hourly ESR in the air was calculated as:

$$S_{air} = \rho_a(c_p \Delta \bar{T}_r + L \Delta \bar{q}_r) \frac{\Delta z}{\Delta t} \tag{33a}$$

in which  $\Delta \bar{T}_r$  and  $\Delta \bar{q}_r$  are, respectively, the changes in air temperature and specific humidity ( $g \text{ kg}^{-1}$ ) measured at the reference height (51.1 m). Using the values  $\rho_a = 1.2 \text{ kg m}^{-3}$ ,  $c_p = 1004 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$ ,  $L = 2.4 \times 10^6 \text{ J kg}^{-1}$ ,  $\Delta z = 53 \text{ m}$  and  $\Delta t = 3600 \text{ s}$ , gives the relationship (with  $R^2 = 0.89$ ):

$$S_{air} = 17.7 \Delta \bar{T}_r + 43.1 \Delta \bar{q}_r \tag{33b}$$

The hourly ESR in the trunks may be obtained through the following simplified expression:

$$S_{tr} = m_{tr} c_{tr} \alpha \frac{\Delta \bar{T}_r(t + \tau)}{\Delta t} \tag{34a}$$

where  $\alpha$  and  $\tau$  represent the attenuation of the air temperature wave, and the phase difference between air and the trunk temperature waves, respectively. So, with the values of  $m_{tr}$  and  $c_{tr}$  given in Table 1, and the linear regressions between  $S_{tr}$  calculated by using respectively Eq. (20) and (34a),  $\alpha$  and  $\tau$  were adjusted. The best regression ( $R^2 = 0.48$ ) was obtained by using the air temperature 1 h in advance ( $\tau = 1 \text{ h}$ ) and the 20 selected days data;  $\alpha (=0.49)$  was adjusted until the slope of this regression became 1. Thus:

$$S_{tr} = 14.3 \Delta \bar{T}_r(t + 1) \tag{34b}$$

To calculate the ESR for the remaining biomass one may use:

$$S_{sum} = [m_{br} c_{br} + (m_{tw} + m_{lt}) c_{tw} + (m_{lv} + m_{oc}) c_{lv}] \beta \frac{\Delta \bar{T}_r}{\Delta t} \tag{35a}$$

in which  $\beta$  represents the same as  $\alpha$  but for the remaining biomass. The best adjustment (slope = 1,  $R^2 = 0.72$ ) for  $\beta$  was 0.76, using the 20 selected days data; with the values presented in Table 1, it yields:

$$S_{sum} = 14.9 \Delta \bar{T}_r \tag{35b}$$

Fig. 7(i) presents the day-averaged hourly variation of the total ESR calculated through the sum of Eqs. (16), (17), (20), (26) and (27) ( $S$ ) and of the simplified Eqs. (33)–(35) ( $S_{sim}$ ). The absolute average value of the hourly difference between  $S$  and  $S_{sim}$  was  $15 \pm 10 \text{ W m}^{-2}$ , with a minimum of 0 and a maximum of  $80 \text{ W m}^{-2}$ . So, it is important to consider the limit of  $\pm 90 \text{ W m}^{-2}$  for the values obtained through the simplified method proposed here. For rainy hours, the adequate lower limit is  $-200 \text{ W m}^{-2}$ . The linear regression between the hourly values of  $S$  and of  $S_{sim}$  (Fig. 7ii) showed a good correlation, with the intercept, slope and  $R^2$  equal to  $-0.21$ ,  $1.09$  and  $0.84$ , respectively. This is an improvement of 30% for the slope, when compared to the regression between  $S$  and  $S_{M \text{ and } F}$ .

## 5. Conclusions

Considering the daily totals, the dominant term in the ESR of the forest was  $S_{tr}$ , corresponding to about 40% of the total. The other five biomass terms ( $S_{br}$ ,  $S_{tw}$ ,  $S_{lv}$ ,  $S_{lt}$  and  $S_{oc}$ ) together contributed approximately 25% to  $S$ , with  $S_{air}$  contributing about 35%. On a hourly basis, the inclusion of  $S$  is critical, particularly (i) during the night, when  $S$  presents values of approximately 70% of  $R_n$ , (ii) during the periods of day-night and night-day transitions, when the ratio  $S/R_n$  frequently exceeds unity and, mainly, (iii) during and after rainfall, when  $S$  is an important energy source for the evaporation of the water intercepted by the forest canopy.  $S$  may reach  $-40 \text{ W m}^{-2}$  during the periods (i) and (ii), and  $-200 \text{ W m}^{-2}$  during (iii). Also, during heavy and short duration rain events, the residual of the SEB may reach values of about  $200 \text{ W m}^{-2}$ ; this “extra” energy is probably used by advective processes between the site studied and its neighborhood.

The closure of the SEB, in hourly, daylight, nocturnal and daily terms, was improved when  $S$  was included in the calculations, except for the days when the daily balance of  $S$  had relatively high negative values. It can be concluded that  $S$  is an important component of the energy balance of the Amazonian Forest, due to its massive biomass, which is combined with the high and fast variability in air temperature and humidity, as well as the short duration of many of its heavy rain events. Finally, it is possible to represent the ESR with simplified and efficient expressions for  $S_{air}$ ,  $S_{tr}$  and  $S_{um}$ , which depend only on above canopy air temperature and humidity measurements.

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