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Sensible and Latent Heat Storage Fluxes within the Canopy Air-Space in the Amazon Rainforest

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Abstract

Ecosystem–atmosphere exchanges of energy display considerable variability over a range of temporal and spatial scales. This study evaluated the seasonal and annual variations in sensible and latent heat storage fluxes within the canopy air-space in the Amazon rainforest. The data for this study were obtained from the “Long-term drought impact on water and carbon dioxide fluxes in Amazonian Tropical Rainforest Experiment (ESECAFLOR)” which is a subproject of Large Scale Biosphere Atmosphere Experiment in Amazon forest (LBA), carried out in *terra firma* rainforest in Caxiuanã National Forest, Pará, Brazil. The data sets also included observations to obtain the sensible and latent heat storage fluxes within forest collected throughout the 1-year period. The vapor pressure and air temperatures were obtained for each 8 m interval from the surface to 32 m. Results indicated that the cumulative sensible heat storage flux in the Amazon rainforest canopy was 167.9 Wm^{-2} in 2008 and the average daily magnitude was always low for the same period. The latent heat storage flux (ranging from -32.7 to -10 Wm^{-2}) was more influenced by rainfall producing high humidity.

Keywords: Energy fluxes; Energy balance; Air temperature gradient

Introduction

The amount of water intercepted by the Amazon forest canopy during rains is responsible for the replacement of considerable amount of water vapour in the atmosphere, contributing to the local water balance. The biosphere-atmosphere interaction processes in the Amazonian region have been investigated over the last years in order to evaluate their importance for the local and global climate [1]. The large extent of vegetation covering the Amazon forest produces the highest source of energy to the atmosphere from the continental origin. Due the significance of the Amazon forest to biodiversity and global carbon cycle, several studies have focused on the National Forest Reserve Caxiuanã in the framework of the LBA (Large Scale Biosphere Atmosphere Experiment in Amazonia) project [1-4].

Although changes in the biomass of Amazonian region forest represent an important component of the global carbon cycle, the biomass of these forest remains poorly quantified [5]. Other important studies aimed at quantifying the forest biomass in the Brazilian Amazon include those of Brown et al. [6], Sales et al. [7], Fearnside et al. [8], Nogueira et al [9], Alves et al. [10], among others. Researches on the effect of drought episodes on heat storage fluxes within the canopy air-space in the Amazon rainforest have just started. Although changes in the biomass of Amazon region forest represent an important component of the global carbon cycle, the biomass of these forest remains poorly quantified [5]. Using through fall exclusion experiments in the Amazon rainforest, Fisher et al. [11] and Costa et al. [12] investigated forest transpiration by the sap flow method in Caxiuanã National Forest. Fisher et al. [13] concluded that the forest was not able to withstand a 50% reduction in rainfall over 1-2 years without impacting the canopy gas exchange, while Costa et al. [12] found a decrease of 68% in mean transpiration of *E. Coriacea* from control plot to rainfall exclusion plot. The objective of this study was to analyze the surface energy balance, particularly the sensible and latent heat storage fluxes within the canopy air-space Amazon rainforest.

Materials and Methods

Experimental site

This study was carried out at Ferreira Penna Scientific Station (FPSS) in the Caxiuanã National Forest (CNF) in Pará State (Latitude: 1°42’30’’S, Longitude: 51°31’45’’W and Altitude: 62 m above sea level). The ECFPn is located in the 300000 hectare Caxiuanã National Forest, about 400 km to the west of Pará capital city of Belém, Brazil (Figure 1). The region has a well-preserved forest with a canopy of 35 m high. The Amazon is covered predominantly by moist dense tropical forest, but with several other vegetation types, including savannas, montane forests, open forests, floodplain forests, grasslands, swamps, bamboos, and palm forests.

The predominant trees species in the landscape are *Eschweilera coriacea* (White Matá-matá), *Voucapoua americana* (Acapu), *Rotium pallidum* (White Pitch)*, Dinizia excelsa* (angelim-vermelho), *Marmaroxylon racemosum* (angelimrajado), *Couratari guianensis*

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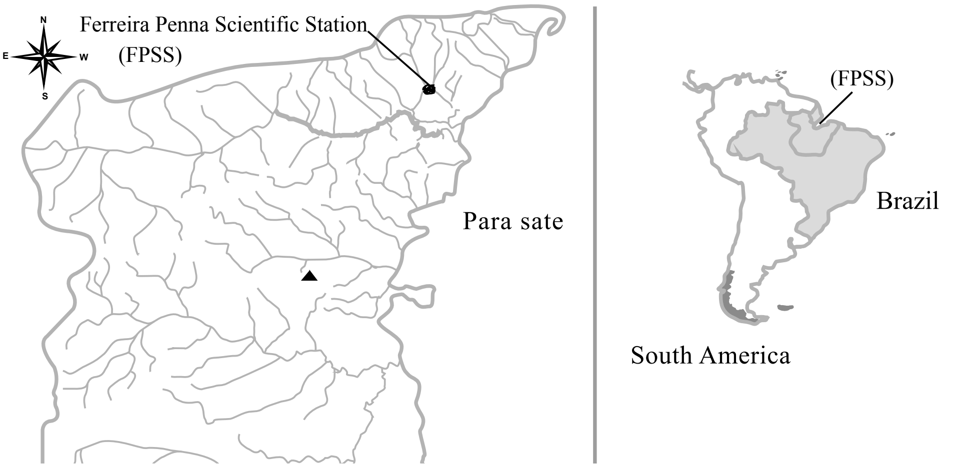

Figure 1: Localization of Ferreira Penna Scientific Station (FPSS) in the Caxiuanã National Forest (CNF) in Pará State (Latitude: 1°42'30''S, Longitude: 51°31'45''W and Altitude: 62 m above sea level).

(tauari), *Bucheniavia grandis* (tanimbuca), *Swartzia racemosa* (pitaíca) and *Dipteryx odorata* (cumaru). The forest is a lowland *terra firme* rainforest. The mean annual temperature is 25.78°C and the mean annual rainfall is 2272 mm, with a dry season when only 555 mm of rainfall occurs on average [13]. The wet season is from January to June while the dry season is from July to December. Most soils are yellow Oxisols (Brazilian classification Latossolo), but there are large differences in texture. The water table has been observed at a soil depth of 10 m during the wet season and the site elevation is 15 m above the river level [13].

Our study analyzed observations of 1-year (2008) of canopy heat storage fluxes. This period is enough to characterize the energy fluxes during rainy and dry seasons in the study area.

Data descriptions

The most predominant tree species in the experimental plot were *Escheweleira, Licania octandra, Lecythis, Pouteria decorticans, Swartzia racemosa, Rinoria guianensis* and *Vouacapoua americana*. On the other hand, the tree species in Plot B included *Escheweleira coriacea, Manilkara bidentata, Swartzia racemosa e Tetragastris panamensis*. The forest tree species diversity varied from 150 to 160 trees per hectare and the individual density ranged from 450 to 550 trees ha^{-1}. The net radiation was measured with a net radiometer (CNR1, Kipp and Zonen, Delft, the Netherlands) and the vapor pressure was calculated based on wet and dry bulb temperatures for each 8 m interval from the surface to 32 m. All data were collected using a data logger (CS10X, Campbell Scientific) for every 10 s and averaged over each 30 min period. The data sets also included observations to obtain the canopy heat energy flux within forest collected throughout the 1-year period. Energy storage flux can be a significant component of the sub-diurnal surface energy budget in a tall forest, owing to the large volumes of air and biomass in the canopy.

Canopy heat storage flux

The large height of native forest with a large volume of air and biomass in the canopy covering water supply catchments in the Amazon basin means that the change in canopy heat storage flux through the change in moisture content of the canopy air play an important role in the energy balance of the ecosystem. The sensible heat storage flux in the canopy air-space (ΔS_h) was obtained following McCaughey [14] as:

$$\Delta S_h = \int_0^{z_r} \rho c_p \frac{\partial T}{\partial t} dz \cong \rho c_p \sum_{i=1}^{n} \left(\frac{\Delta T_a}{\Delta t} \Delta z_i \right) \qquad (1)$$

where ρ is the air density, c_p is the specific heat, z_r is the height of 32 m, T is the air temperature (°K) below r_r, and T_a is a representative layer-average of T in each layer (°K). Since ρ and c_p are approximately constant within the canopy layer, the ratio $\Delta T_a/\Delta T$ can be calculated as an average of measurements at several levels in the canopy [15]. Similarly, the latent heat storage flux in canopy air-space (ΔS_w) was calculated as [14]:

$$\Delta S_w = \int_0^{z_r} \rho L_e \frac{\partial e_i}{\partial t} dz \cong \rho L_e \sum_{i=1}^{n} \left(\frac{\Delta e_i}{\Delta t} \Delta z_i \right) \qquad (2)$$

where L_e is the latent heat of vaporization and *e* is the vapour pressure, calculated from Ta and relative humidity measurements. Both ΔS_h and ΔS_h were calculated in four levels up to 32 m.

Results and Discussion

Climate data

Temporal patterns of meteorological variables throughout the 1-year of experimental period in 2008 are shown in Figure 2. The total rainfall of 2230 mm was close to the long-term mean of 2272 mm [11]. The amount of low precipitation from July to November coincided with a decrease in relative humidity, but differed markedly in air temperature and wind speed. Higher air temperature and lower relative humidity through the dry season were mainly due to the small amount of rain as well as the increase in global solar radiation and consequently in the net radiation. Therefore, the climate did not show any remarkable differences between other years and the experimental period in 2008. The global solar radiation had a similar seasonal course to that of the net radiation with maximum and minimum in dry and wet seasons, respectively.

Canopy heat storage flux

Sensible heat flux: The sensible heat storage flux values were generally low through the experimental period ranging from 4.94 to -2.22 Wm^{-2} (Figure 3). Although the canopy heat storage was important for

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diurnal and seasonal time scales, their seasonal integration accounted for only a small portion of the net radiation. The average canopy heat storage flux within the canopy air-space over the experimental period in 2008 was 0.46 Wm^{-2}. The daily total heat storage flux resulted in the annual total canopy heat storage flux of 167 Wm^{-2} year^{-1}.

Analyzing seasonal variations of energy and water vapour fluxes above a tropical seasonal rainforest in China, Junxia et al. [16] also found low values of the heat storage flux ranging between 0.9 and 0.8% of the net radiation. The maximum and minimum values in the sensible heat storage flux occurred in the dry and rainy seasons, respectively, because the differences of temperature within the canopy are mostly driven by differences in radiation penetration to the ground, governed by canopy density.

The sensible heat storage flux was eventually an important sink or source of energy, with a typical daily maximum value of about 43 Wm^{-2} in dry season, but because the term usually changed signs between daylight and nighttime hours, the average daily magnitude was always low through the whole experimental period. Similar results were obtained by Wilson and Baldocchi [17] who analyzed the components of surface energy balance over a broadleaf deciduous forest in North America. Results obtained in this study, however, were not consistent with that reported Moore and Fisch [18] and Silberstein et al. [19]. They found maximum absolute hourly canopy storage fluxes of around 80 Wm^{-2} for forests in the Amazonian tropical and Western Australia. This difference is probably because a good estimate of heat storage requires a large number of temperature and humidity measurements throughout the canopy air space, as well as temperatures for each of the biomass components (leaves, twigs, fruit, branches, stems and litter) [19]. The sensible heat storage flux in the surface-air space cannot be neglected on an hourly basis. However, it represents a little proportion of the net radiation on a daily basis. Similar results were obtained by Sánchez et al. [20] for hourly sensible heat storage flux using radiometric temperature observations for estimating energy balance fluxes above a boreal forest. The cumulative sensible heat storage flux in the wet season was 6% of that in the dry season. The lower value of sensible heat storage flux in the canopy air in January-June than that in June-December was a consequence of high rainfall and low vapour pressure deficit in the wet season of that year. Wang et al. [21] also found similar values who analyzed seasonal variations in energy and water fluxes in a pine forest in Finland.

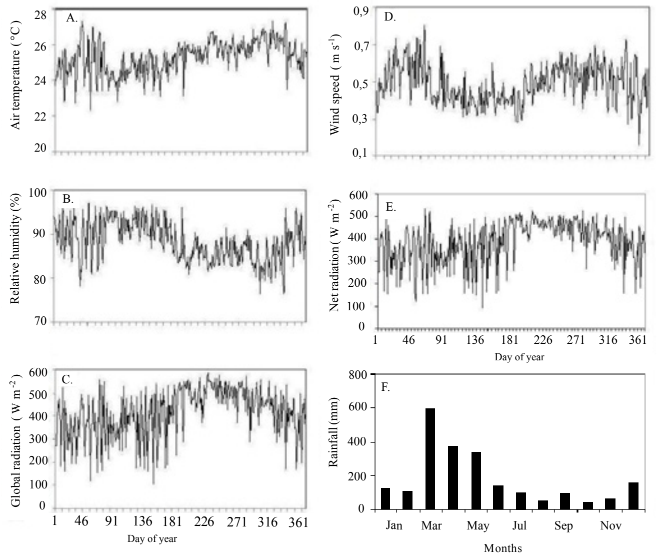

Figure 2: Daily average of weather variables in 2008 at Caxiuanã National Forest, Pará state, Brazil. Data include air temperature (A), relative humidity (B), global radiation (C), wind speed (D), net radiation (E) and rainfall (F).

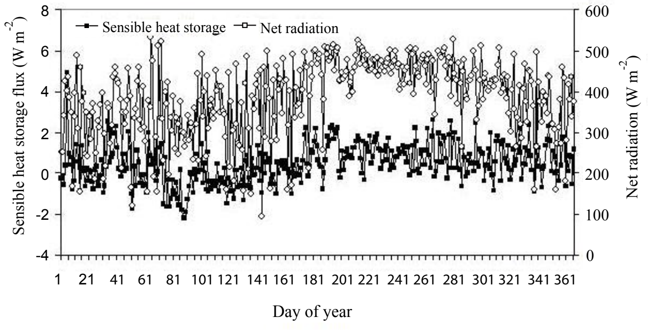

Figure 3: Seasonal sensible heat storage flux and net radiation during the experimental period in 2008 at Caxiuanã, PA, Brazil.

Seasonal variation of sensible heat storage flux and net radiation in dry and wet seasons are shown in Figure 4 which indicates a close link between canopy heat storage and net radiation throughout the wet season in which the sensible heat storage flux and net radiation were on average -0.08 and 340 Wm^{-2}, respectively (Figure 4A). However, results of this study also indicate that these variables do not exhibit a similar performance throughout the dry season (July to November). For this season, the sensible heat storage flux and net radiation were on average 0.83 and 430.7 Wm^{-2}, respectively (Figure 4B). As expected, the net radiation was greater in the dry season than in the wet season due to the increase in the atmospheric demand and this effect was estimated to have reduced the sensible heat storage flux to 9.4%. The mean values of the net radiation in the wet season decreased 21% when compared to the dry season. This difference in the net radiation between seasons was the main source of variability in the sensible heat storage flux. Since the net radiation is mainly affected by global solar radiation, the seasonal change in cloud cover was the main controlling factor of the net radiation.

The transition from dry to wet season coincided with a marked reduction in the incoming radiation. The seasonal net radiation values presented here are greater than those reported by Rocha et al. [22] for the Amazon region, Santarém, PA. This difference between the mean values of net radiation can be attributed to the variability in cloud cover in the region. The net radiation was the most important source of energy, with typical daily maximum values for both seasons between 520-540 Wm^{-2}, while the daily minimum values varied from 120.8 to 263.4 Wm^{-2}. Similar results were obtained by von et al. [23] who analyzed the scale variability of atmospheric surface layer fluxes of energy and carbon over a tropical rainforest in southwest Amazon. During the experimental period in 2008 the proportion of energy storage within the canopy was, on average, only 1.23% of the net radiation. The very low consumption of net radiation during the day is attributed to the widely open canopy and high wind speed regime.

The sensible heat storage flux in 2008 was 167.93 Wm^{-2}, which equals 14.5 MJm^{-2}year^{-1}. Similar values were obtained by Oliphant et al. [24] who analyzed heat storage and energy balance fluxes for a temperate deciduous forest in south-central Indiana, USA. They found that the annual storage heat balance for the three complete years showed a small but consistent deficit averaging about 16.18 MJm^{-2}year^{-1}. This study indicates that the cumulative values of energy storage within the canopy air-space for wet and dry periods were 76.1 and 91.8 Wm^{-2}, respectively. This means that less net radiation was available for turbulent energy dissipation within the canopy during the wet season.

Latent heat flux: Figure 5 shows the seasonal latent heat storage flux within the canopy air-space in 2008, indicating that the seasonal course of latent heat storage followed a pattern inverse of the net radiation during the whole year. The storage flux had a maximum absolute value of 32.7 Wm^{-2}, while the net radiation had a lowest value of 171.2 Wm^{-2} in the wet season (day of year 166). On the other hand, the net radiation had a maximum value of 526.7 Wm^{-2} and the latent heat storage flux had a lowest value of 12.9 Wm^{-2} in the dry season (day of year 280). Therefore, the latent heat storage flux within canopy is most likely due to rainfall amount summing to 1652 mm during the wet season.

The mean values of air temperature and relative humidity in 2008 was 25°C and 88%, respectively. On the other hand, the cumulative rainfall during the dry season was 477.8 mm. The latent heat storage flux was influenced by the low atmospheric demand but mainly by the high amount of water vapour in the canopy air-space through the wet season. The net radiation followed the temporal variation in global solar radiation but became more irregular with depth in the forest because of the highly variable penetration of beam radiation in space and time. The solar radiation pattern into the forest canopy is a fundamental process of energy exchange which regulates the availability of water for evaporation. Although solar elevation continues to rise each day until the summer solstice, the amount of net radiation and its variability affect water storage within the canopy forest.

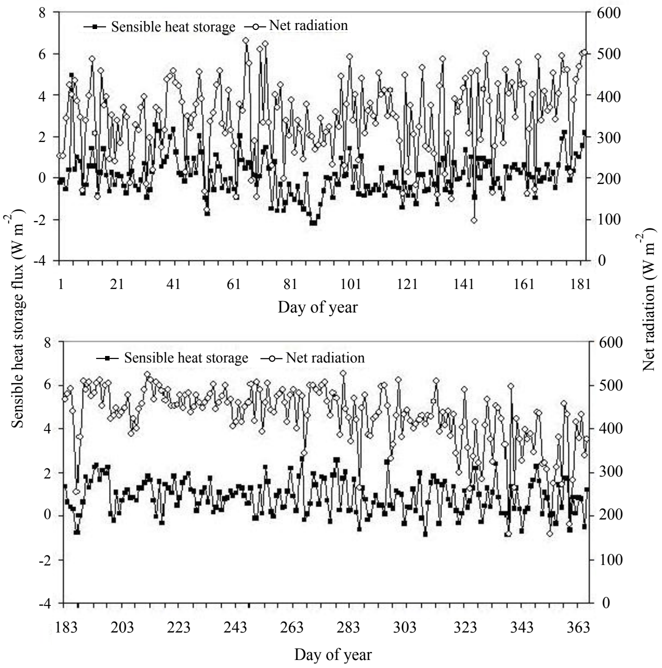

Figure 4: Comparison between mean daily patterns of sensible heat storage flux and net radiation in wet (A) and dry seasons (B) in Caxiuanã, Pará, Brazil.

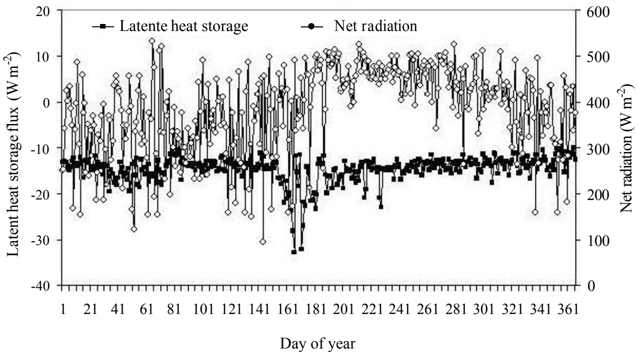

Figure 5: Seasonal latent heat storage flux and net radiation during the experimental period in 2008 at Caxiuanã, PA, Brazil.

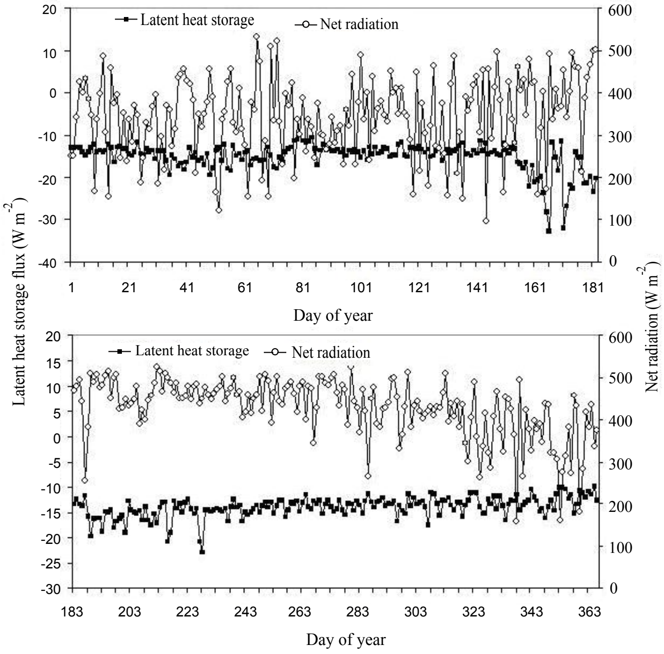

Figure 6: Seasonal latent heat storage flux and net radiation in Caxiuanã, PA, in 2008.

Despite a reduction in the net radiation from the dry season to the wet season of around 20%, on average, the latent heat storage flux had similar values, 4.4% of the net radiation for the wet season and 3.3% for the dry season (Figure 6). Although the maximum values of latent heat storage flux were nearly the same during both seasons, the minimum values declined by 30% from the wet to the dry season. The average annual latent heat storage flux was nearly 15 Wm^{-2} for both periods, suggesting ample water vapour storage within the canopy air during the whole year. The daily total latent heat storage flux resulted in the seasonal total latent heat storage of 2750.80 and 2581.19 Wm^{-2} for wet and dry seasons within canopy air-space, respectively. The net radiation, consumed by the latent heat storage within the forest canopy, varied from 6.1 to 27% during the experimental period. The net radiation was greater in the dry season than the wet season, but this did not seem to have increased the latent heat storage.

Despite the net radiation pattern into forest canopy being a fundamental process of energy exchange which regulates the availability of water for evaporation, the difference in the net radiation among months was only a minor source of variability in the latent heat storage, while the high annual rainfall interaction with forest canopy was responsible for transport of water within forest.

Conclusions

Although sensible heat storage flux is important on a diurnal time scale, its annual value integrated within the canopy air space is rarely more than 1% of the net radiation. The sensible heat storage flux in the surface-air space can be neglected on a daily basis, but not on an hourly basis. However, the latent heat storage flux represents a considerable proportion of the net radiation on both hourly and daily bases. The latent heat storage flux within canopy is most likely equal to the amount of water vapour in canopy air-space, summing to 1652 mm during the wet season. The difference in the net radiation among months, because of the highly variable penetration of beam radiation, is only a minor source of variability of latent heat storage, while the high annual rainfall interaction with forest canopy is responsible for the high quantity of water transported within forest. Despite a reduction of around 20% in the net radiation from the dry season to the wet season, maximum values of latent heat storage flux are nearly the same for both seasons. However, their minimum values are reduced by 30% from the wet season to the dry season.

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