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ORIGINAL ARTICLE

Estimate of evapotranspiration in the eastern Amazon using SEBAL

Estimativa de evapotranspiração no leste da Amazônia usando SEBAL

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ABSTRACT: In this study, we analyzed the estimates of evapotranspiration (ET) and sensible heat flux (H) using the Surface Energy Balance Algorithm for Land (SEBAL) for the ‘Caxiuana’ National Forest located in the municipality of Melgaço, State of Para, Brazil. To this end, we studied orbital images (Acqua/MODIS) combined with observational data from the LBA Project (Experiment of large-scale biosphere-atmosphere in the Amazon) collected in 2008 at the micrometeorological tower located in this forest. Although evapotranspiration was higher in the dry season and lower in the rainy season, it maintained a high rate throughout the year, with an average value very similar to those reported in the literature on the Amazon. The estimated daily ET was overestimated for the rainy season and underestimated for the dry season, but presented maintenance of high rates, just as the observed daily ET. The results also suggest that, because the evapotranspiration was higher in the dry season, the previous season (rainy season) was decisive, being possible to infer that, on the dry season, transpiration is the main source for the regional ET, which, in turn, is linked to the primary production of forests.

RESUMO: *Foram analisadas as estimativas de evapotranspiração (ET) e de fluxo de calor sensível (H), utilizando-se o SEBAL (Surface Energy Balance Algorithm Land) para a Floresta Nacional de Caxiuanã, Melgaço-PA. Para tal, utilizaram-se imagens orbitais (Acqua/MODIS) e dados observacionais do Projeto LBA (Experimento de Grande Escala da Biosfera-Atmosfera na Amazônia). Os resultados mostraram uma taxa de ET relativamente alta durante todo o ano, com valores médios muito semelhantes aos relatados na literatura para a região da Amazônia, apesar de a ET mensal obtida pelo SEBAL ter sido superestimada de janeiro a junho e subestimada de julho a dezembro. A estimativa da ET diária foi superestimada para a estação chuvosa e subestimada para a estação seca, mas apresentou também a manutenção de uma ET relativamente alta, tal qual a ET diária observada. A variação entre os dois fluxos de calor sensível revelou um padrão bastante semelhante, com diferenças pequenas. Os resultados sugerem ainda que, em razão de a ET ter sido maior na estação seca, a estação anterior (chuvosa) teve papel decisivo, sugerindo que no período seco a principal fonte para a ET da região é a transpiração; esta, por sua vez, está relacionada com a produção primária da floresta.*

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1 Introduction

Evapotranspiration (ET) is a major component of the hydrological cycle. Several studies have been conducted in the Amazonia in order to quantify the spatial and temporal variability of evapotranspiration. Observational studies show a higher ET in the dry season than in rainy season, but also a higher ET in areas with less rainfall during the dry season in central and eastern Amazon (NEPSTAD et al., 1994; SHUTTLEWORTH, 1988; MALHI et al., 2002; SOMMER et al., 2002; SOUZA FILHO et al., 2005; NEGRÓN JUÁREZ et al., 2007).

In specific locations on the Amazon forest, Shuttleworth (1988) showed that ET contributes about 50% of total precipitation, calculated by methods of water balance and correlation measures of Foucault. On a small scale, the quantification of water losses to the atmosphere can be obtained by other methods such as Bowen ratio, turbulent correlations and others. However, French et al. (2005) report that the spatial variability of evapotranspiration is large and that even the most advanced ways to measure it, on micrometeorological towers through turbulent vortices covariance systems, is often not the most representative of Evapotranspiration on a regional scale.

To assess the spatio-temporal variability of ET on a regional scale, several methods have been developed and the estimate has been widely studied combining conventional meteorological measurements with remote sensing data. One of these methods have been applied to this purpose is the SEBAL (Surface Energy Balance Algorithm for Land). It was developed by Bastiaanssen (1999) and enables the calculation of latent heat flux as residue of the classical equation of energy balance. SEBAL uses the surface temperature, surface hemispherical reflectance, vegetation indexes and some additional data, obtained on meteorological surface stations. This algorithm has been applied in various ecosystems in the world (ALLEN, 2002; BASTIAANSSEN, 2000; MORSE et al., 2000).

Considering the difficulties and the lack of spatial data of evapotranspiration for areas of native forest and knowing that conventional methods require accurate measurements on surface, which hinder the use on a regional scale, this study aims to estimate the evapotranspiration and sensible heat flux to the Caxiuanã forest, incorporating remote sensing data with the application of SEBAL.

2 Materials and Methods

The area is located in the Caxiuanã National Forest (01° 42' 30" S and 51° 31' 45" W), about 400 km to the West of Belem-PA, Brazil (Figure 1). The forest has an average canopy 40 m, though some trees reach 50 m. The climate of the region is tropical (hot and humid type), with annual average temperatures of 26 °C and extreme averages (minimum and maximum) of 22 and 32 °C, respectively. Caxiuanã Forest has wettest period is from January to May and dry season from September to December. The annual average relative humidity is around 80%. The predominant wind direction is from Northeast (NE) (MORAES et al., 1997).

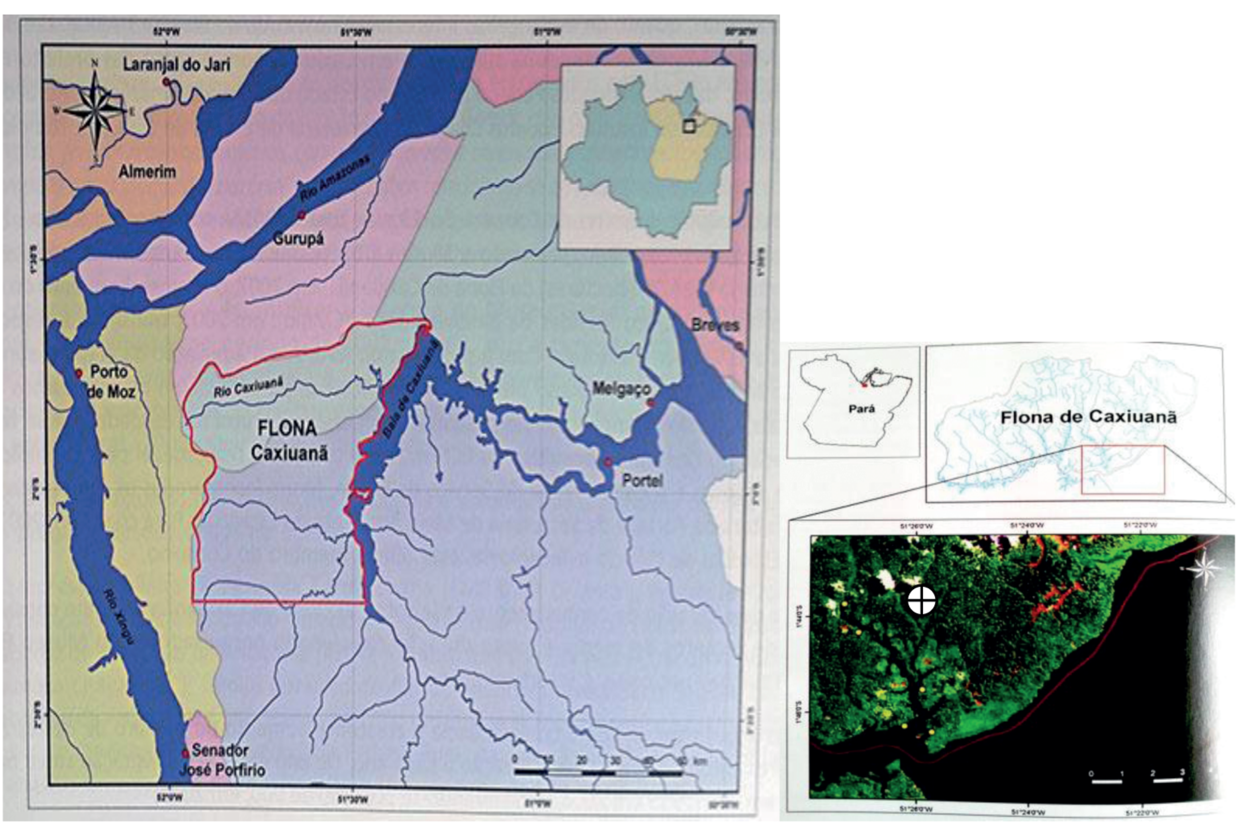

Figure 1. Location of the measurement tower in Caxiuanã National Forest.

Observational data are part of the project Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA). Micrometeorological measurements of energy flux and water vapor concentration were obtained through a system of correlation of turbulent vortices (eddy correlation), which computes the covariance between the fluctuations in the vertical component of the wind speed, temperature and the concentration of water vapor in air sample. Hourly and daily arithmetic averages were calculated of meteorological elements for the period. The analyses of this research include the period from January to December 2008. Acqua/MODIS images for this period are described below. These images represent the averages of 8 (eight) days for the variables of MOD09 and MOD11, and 16 (sixteen) days for MOD13.

The Surface Reflectance has a spatial resolution of 250 m from MODIS sensor and is derived from the bands 1 and 2 in the level 1B of the Earth's surface. The MOD09 is an estimate of the spectral reflectance of the Earth's surface for each band, which is measured near the ground, disregarding the atmospheric effects.

A process of correction is applied to all pixels that pass through quality control in the level 1B, reducing the effects of atmospheric gases, aerosols and little thick clouds, such as cirrus. The surface reflectance L2G 250 m MODIS/Acqua (MOD09) is processed is rendered to all globe daily using the level 2G 250 m Pointer Files (MODPTQKM), locating the level 2 of surface reflectance (MOD09) in a geographical grid. The quality of the MOD09GQK data is provided in three different levels: for each pixel, spectral band and all image files (VERMOTE; VERMEULEN, 1999).

The MOD11 uses as input data the radiance (MOD021KM), the geolocation (MOD03), the cloud mask (MOD35_L2), the quality of ground cover (MOD12Q1) and snow (MOD10_L2). The output file contains the SDSs of ST (surface temperature), quality assurance (QA) of pixels, the error in ST, the emissivity of the bands 31 and 32, the zenith angles, the spatial resolution of 1km, local and global attributes. This product uses the TST split-window algorithm, which has been validated with data from the sensor MAS (MODIS Airborne Simulator), field measurements and the day/night temperature algorithm, which was designed specifically for the MODIS (WAN; LI, 1997). The accuracy of the MODIS TST algorithm is 1 km.

The raw data of MODIS system is not available to users, but rather a series of products. The MOD13 product, level three in the hierarchy, contains, among other data, the NDVI images in compositions of 16 days with a spatial resolution of 250 m. These compositions are generated through the bi-directional reflectance model of Walthall (BRDF), when the number of cloudless images of the set is greater than five. The parameters of BRDF model are used to normalize and interpolate the surface reflectance in the viewing angle to the nadir. When the number of cloudless images is less than five, is used the CV-MVC model (Constraint View angle – Maximum Value Composite), through which are recorded the highest values of NDVI of the series for a given pixel. Thus, factors such as cloud cover, variations of the illumination angle and viewing geometry, water vapor, aerosols etc., are minimized (CARROLL et al., 2003).

The energy balance determined by SEBAL requires little information from the Earth's surface to estimate the components of energy balance through remote sensing. In the SEBAL model, ET is computed from satellite images and weather data using the surface energy balance as illustrated in Figure 2. Since the satellite image provides information for the overpass time only, SEBAL computes an instantaneous ET flux for the image time. The ET flux is calculated for each pixel of the image as a "residual" of the surface energy budget equation:

$$R_n = G + H + \lambda ET \quad (1)$$

$$\lambda ET = R_n - G - H \quad (2)$$

where: λET is the latent heat flux (W m^{-2}), R_n is the net radiation flux at the surface (W m^{-2}), G is the soil heat flux (W m^{-2}) and H is the sensible heat flux to the air (W m^{-2}).

The net radiation flux at the surface (R_n) represents the actual radiant energy available at the surface. It is computed by subtracting all outgoing radiant fluxes from all incoming

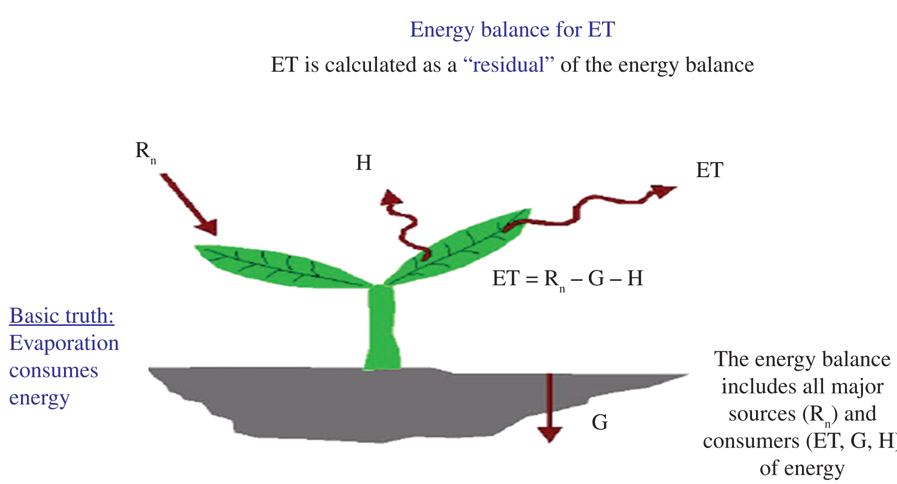

Figure 2. Energy Balance of SEBAL (Advanced Training and Users Manual, 2002).

radiant fluxes. This is given in the surface radiation balance equation:

$$R_n = (1 - \alpha)\ RS\downarrow + RL\downarrow - RL\uparrow - (1 - \varepsilon o)RL\downarrow \quad (3)$$

where: $R_S\downarrow$ is the incoming shortwave radiation (W m^{-2}), α is the surface albedo (dimensionless), $R_L\downarrow$ is the incoming longwave radiation (W m^{-2}), $R_L\uparrow$ is the outgoing longwave radiation (W m^{-2}), and ε_o is the surface thermal emissivity (dimensionless).

Soil heat flux is the rate of heat storage into the soil and vegetation due to conduction. SEBAL first computes the ratio G/R_n using the following empirical equation developed by Bastiaanssen (2000) representing values near midday:

$$G/R_n = T_s/\alpha\ (0.0038\alpha + 0.0074\alpha^2)(1 - .98NDVI^4) \quad (4)$$

where: T_s is the surface temperature (°C), α is the surface albedo, and NDVI is the Normalized Difference Vegetation Index. G is then readily calculated by multiplying G/R_n by the value for R_n computed in Equation 3.

Sensible heat flux is the rate of heat loss to the air by convection and conduction, due to a temperature difference. It is computed using the following equation for heat transport:

$$H = (\rho \times c_p \times dT)/r_{ah} \quad (5)$$

where: ρ is air density (kg m^{-3}), c_p is the specific heat of air (where the product between them is 1155 J m^{-3} K^{-1}), dT (K) is the temperature difference ($T_1 - T_2$) between two heights (z_1 and z_2), and r_{ah} is the aerodynamic resistance to heat transport (s/m).

The sensible heat flux (H) is a function of the temperature gradient, surface roughness, and wind speed. Equation 5 is difficult to solve because there are two unknowns, r_{ah} and dT. To facilitate this computation, we utilize the two "anchor" pixels (where reliable values for H can be predicted and a dT estimated) and the wind speed at a given height.

Once the latent heat flux (λET) is computed for each pixel, an equivalent amount of instantaneous ET (mm h^{-1}) is readily calculated by dividing by the latent heat of vaporization (λ). These values are then extrapolated using a ratio of ET to reference crop ET to obtain daily or seasonal levels of ET.

$$ET_d = 3600 \times \lambda ET/\lambda \quad (6)$$

where: ET_d is the instantaneous evapotranspiration (mm h^{-1}), 3600 is the conversion of seconds to hours, and λ is the latent heat of vaporization and/or the absorbed heat in one kilogram of evaporated water (2,45 mJ kg^{-1}).

3 Results and Discussion

Our results showed that observed ET, in two seasons, had a relatively high rate and the difference in their values between these two stations was small. However, estimated ET presented a marked seasonal difference: ET on the rainy season was overestimated and underestimated for the dry season (Table 1).

In the study of Souza Filho et al. (2005), which used data by eddy correlation and didn't use estimates by remote sensing, the seasonal pattern of observed ET is similar to our pattern of observed ET in 2008, presenting also a higher ET in the dry season and a lower ET in the rainy season as has also been shown by Shuttleworth (1988), Nepstad et al. (1994), Malhi et al. (2002) and Sommer et al. (2002). In the study of Sousa et al. (2007) using SEBAL and eddy correlation data showed that ET in Caxiuanã in the dry season was lower than ET in the rainy season. However, the results obtained by SEBAL showed a higher ET in the dry season. This difference in the characteristics of ET shown by eddy correlation may be related to a peculiarity of the climatic characteristics of 2000, which was under the influence of an El Niño.

The monthly variability of the observed and estimated ET is presented below. In general, it shows that the ET in the period January to June was overestimated and July to December was underestimated. This overestimated by SEBAL may be due to the characteristics of rainfall during the rainy season having been above normal since the year 2008 was under a strong influence of La Niña. During the rainy season, when there is a wide availability of water, SEBAL simulated with significant similarity the variations on observed ET. These results show not only a higher ET in the rainy season, but also maintaining a high ET rate in the forest even in the dry season (Figure 3).

The results of evapotranspiration estimated by SEBAL were consistent with the values reported for the region, showing the largest rates evapotranspirativa from June to December, that is, during the months of the dry season. According to Negrón-Juarez et al. (2007), ET in various points of the Amazon range from 2.5 ± 0.4 to 4.1 ± 0.4 mm d^{-1} during the rainy season and 3.8 ± 0.6 to 4.3 ± 0.9 mm d^{-1} during the dry season. Furthermore, Hasler and Avissar (2007) to investigate the temporal and spatial variability of ET, using eddy covariance flux measurements in eight different towers of the LBA in Amazonia, have concluded that the evapotranspiration at stations close to the Ecuador (2-3° S) feature strong seasonality, with an increase during the dry season and decrease in the rainy season.

Several studies have shown that the surface radiation balance is mainly responsible for the ET and the evapotranspiration

Table 1. Average values of ET in Caxiuanã for the rainy and dry seasons[1].

Period	Caxiuanã-Pa (2008)**	Sousa et al. (2007)	Souza Filho et al. (2005)
Wet $_{OBS}$	3,05 mm day^{-1}	4,18 mm day^{-1}	2,9 mm day^{-1}
Dry $_{OBS}$	3,40 mm day^{-1}	3,40 mm day^{-1}	4,3 mm day^{-1}
Wet $_{RS}$	4,34 mm day^{-1}	3,00 mm day^{-1}	
Dry $_{RS}$	3,97 mm day^{-1}	3,10 mm day^{-1}	

[1]The values of Sousa et al. (2007) are for the year 2000. Dataset of Souza Filho et al. (2005) refer to year 1999. The first column shows the data of the ET 2008. **To make up the monthly average of ET_{OBS}, we used authors used 3 months during the rainy season and only 2 months to compose the average ET_{OBS} of the dry season.

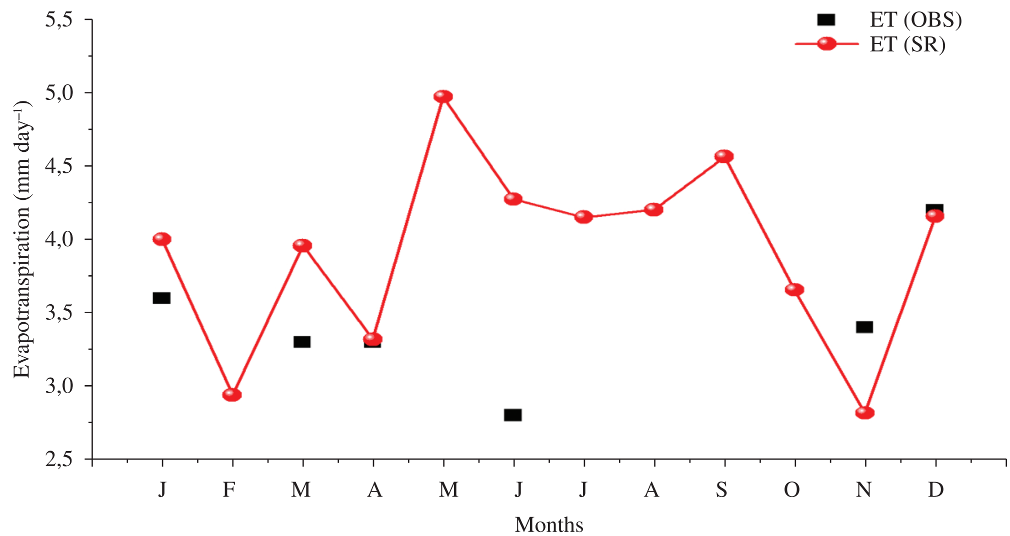

Figure 3. Months Variability of observed Evapotranspiration (black dots) and estimated ET by SEBAL (red line) in Caxiuanã - PA, during 2008.

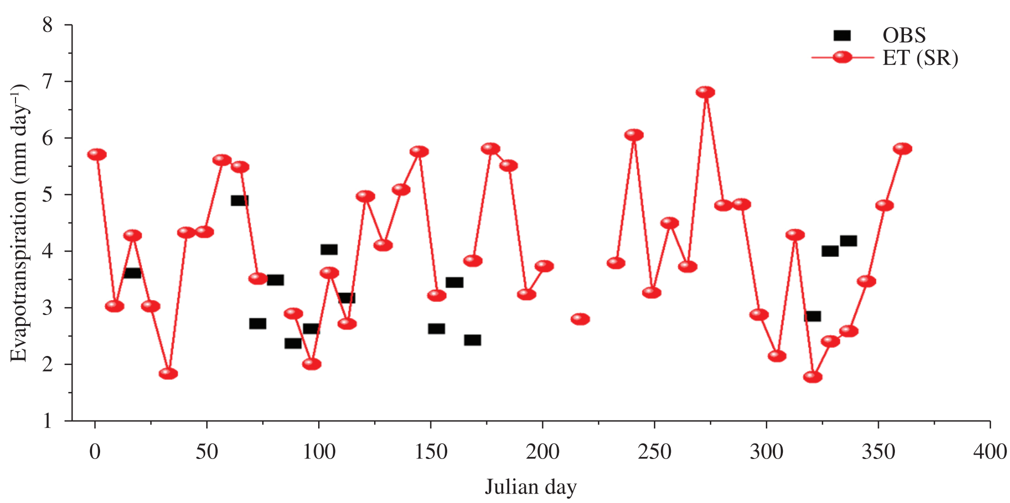

Figure 4. Daily variability of Observed ET (black dots) and estimated ET by SEBAL (red line) in Caxiuanã - PA, during 2008.

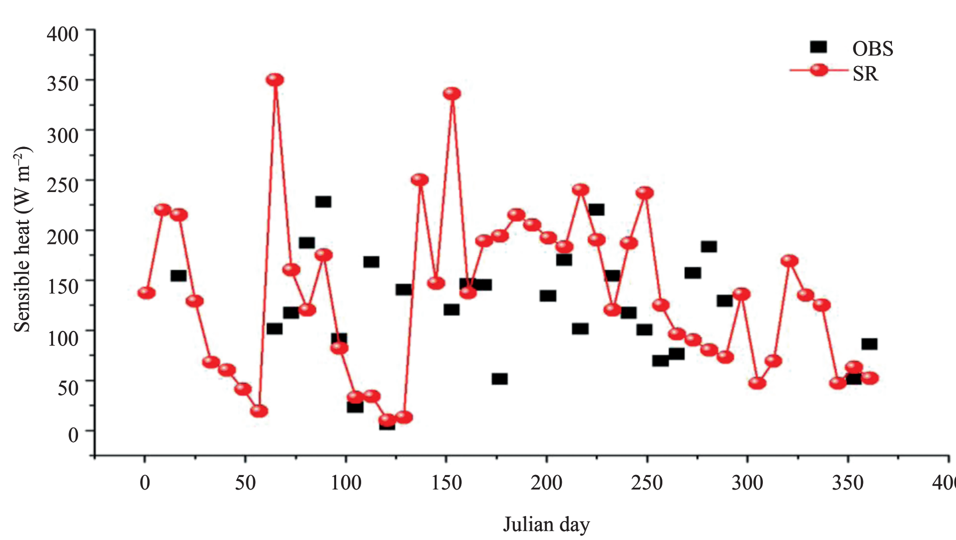

Figure 5. Daily pattern of observed sensible heat flux (black dots) and estimated by SEBAL (red line) in Caxiuanã during 2008. These fluxes are related to the time of satellite overpass Acqua/MODIS at 1:30 PM local time.

of the dry season is influenced more by the amount of soil moisture stored in the antecedent rainy season than by rain events that occurred during the dry season. In addition, during the dry season, when the total rainfall is lower in relation to the rainy season and, the moisture storage of soil available for root absorption may be sufficient to maintain the ET rate equal to or even greater than in the rainy season, as already shown by Shuttleworth (1988), Nepstad et al. (1994), Malhi et al. (2002), Sommer et al. (2002), Souza Filho et al. (2005), Negrón Juárez et al. (2007) and Von Randow et al. (2011). This suggests that in the dry season, transpiration is the main source for the regional ET, which is linked to the primary forest

According to Li and Fu (2004) and Fu and Li (2004) that maintenance plays a central role in determining the onset of the subsequent rainy season that will happen. Thus, a better understanding of the controls of ET during the dry season is important for predicting the timing and variability of the beginning of the rainy season.

Some results of the Anglo-Brazilian Amazonian Climate Observation Study (ABRACOS) (GASH et al., 1998) and Leeds (LBA, 1996; AVISSAR; DIAS; NOBRE, 2002; KELLER et al., 2004; BETTS; SILVA DIAS, 2010) have a better understanding of these controls, on the seasonal and interannual scales. Therefore, the estimate of ET in these scales is essential in determining on seasonal and interannual climate variability of Amazon region.

That daily estimated ET was overestimated in the rainy season, especially during the months of February and March, and in February showed a decrease of 1,9 mm d^{-1}, and underestimated in the driest months, with a minimum 1,7 mm d^{-1} in November. The observed and estimated results show that ET maintained a daily average pattern of 3,5 mm d^{-1} throughout the years, consistent value with the literature for the region (SOUSA et al., 2007; SOUZA FILHO et al., 2005).

Some studies suggest that the restoration of soil moisture during the months of the rainy season normally provides enough water to keep the ET in its first dry season, softening the impact of rainfall deficits during this period with low water availability (NEGRÓN JUÁREZ et al., 2007). Thus, if the deficit of rainfall during the rainy season is very large, it will result in a reduced storage in soil moisture reservoir, which may indicate a possible impact of low rainfall in the dry season subsequent. In addition, Hodnett et al. (1996) showed that this is true when observed, in a forest in the southern Amazonia, the soil profile below 2 m was not fully loaded during the rainy season of 1992/93, which was anomalously under the climatology.

The patterns of daily variability of estimated and observed H are very similar between them. The differences between the observed values and the estimated values by SEBAL are significantly small, especially in the rainy season. The fact that the cloudiness is smaller in the months of dry season favors greater accuracy in the estimation of sensible heat flux generated by SEBAL, since optical and thermal data obtained by remote sensing feature limitations caused principally by cloud cover. This confirms the high sensitivity of this algorithm for the determination and analysis of patterns of many environmental variables.

4 Conclusions

SEBAL proved to be effective in spatialization of the variability of evapotranspiration and sensible heat flux to a region of native forest, mainly in the dry season. This shows that, if applied to temporal and spatial data, the technique can be routinely used, becoming an essential tool in the monitoring of atmospheric and water needs.

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