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ENERGY AND MASS TRANSFER PARAMETERS IN A BRAZILIAN SEMI-ARID ECOSYSTEM UNDER DIFFERENT THERMOHYDROLOGICAL CONDITIONS

ANTÔNIO HERIBERTO DE CASTRO TEIXEIRA, RICARDO GUIMARÃES ANDRADE, JANICE FREITAS LEIVAS

Embrapa Satellite Monitoring, Campinas, São Paulo, Brazil

heriberto.teixeira@embrapa.br, ricardo.andrade@embrapa.br, janice.leivas@embrapa.br

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ABSTRACT

In the Brazilian semi-arid region, the natural vegetation ("Caatinga") has been replaced by irrigated agriculture, emphasising the importance for quantification of the energy and mass exchanges. Eddy covariance and micro-climatic measurements in this natural ecosystem, were analysed for two years under different thermohydrological conditions. Sensible heat flux (H) accounted for 49 and 64% of the net radiation (R_n), respectively, during the wetter and the drier conditions of 2004 and 2005. The corresponding fractions of R_n partitioned as latent heat flux (LE) were 40% and 25%. Evapotranspiration (ET) in 2004, with 693 mm, represented 96% of precipitation (P), while in 2005 (399 mm), it was 18% higher than P, which evidenced the use of the remaining soil moisture from the previous wetter year. All the soil-water-vegetation-atmosphere transfer parameters were influenced by the rainfall amounts. However, the surface resistance (r_s) was the most strongly affected by the soil moisture status, dropping with increases of the ratio of ET to reference evapotranspiration (ET_0). On the other hand, the highest r_s values were related to increases in both vapour pressure deficit (D_e) and aerodynamic temperature (T_0). The current research aimed to quantify the energy and mass exchange between the "Caatinga" and the lower atmosphere, testing in which circumstances the biophysical controlling parameters can be reasonably predicted from agrometeorological data, throughout parameterizations, to incorporate in large-scale models.
Keywords: energy balance; roughness parameters; modelling; "Caatinga".

RESUMO: PARÂMETROS DE TRANSFERÊNCIA DE ENERGIA E MASSA EM ECOSSISTEMA DO SEMIÁRIDO BRASILEIRO SOB DIFERENTES CONDIÇÕES TERMO HIDROLÓGICAS
Na região semiárida brasileira, a vegetação natural (Caatinga) tem sido substituída pela agricultura irrigada, enfatizando a importância da quantificação das trocas de massa e de energia. Medições microclimáticas e das correlações turbulentas no ecossistema Caatinga, foram analisadas para dois anos, envolvendo diferentes condições termo hidrológicas. O fluxo de calor sensível (H) representou 49 e 64% do saldo de radiação (R_n), respectivamente durante as condições mais úmidas e mais secas de 2004 e 2005. As frações correspondentes de R_n para o fluxo de calor latente (LE) foram de 40% e 25%. A evapotranspiração (ET) em 2004, com 693 mm, representou 96% da precipitação (P), enquanto que em 2005 (399 mm), foi 18% maior que P, evidenciando o uso da umidade do solo remanescente do ano anterior mais úmido. Todos os parâmetros de transferência das relações solo-água-vegetação-atmosfera analisados foram influenciados pela quantidade de chuvas. Entretanto, a resistência da superfície (r_s) foi o mais fortemente afetado pelas condições de umidade do solo, sendo reduzida com o aumento da razão da ET para a evapotranspiração de referência (ET_0). Por outro lado, os valores mais elevados de r_s foram relacionados com elevações em ambos, do déficit de pressão do vapor (D_e) e da temperatura aerodinâmica (T_0). A pesquisa corrente objetivou a quantificação das trocas de energia e massa entre a Caatinga e a baixa atmosfera, testando em que circunstâncias os parâmetros biofísicos de controle deste processo podem ser estimados razoavelmente com parametrizações através de dados agrometeorológicos, para incorporação em modelos de larga escala.
Palavras-chaves: balanço de energia; parâmetros de rugosidade; modelagem; Caatinga.

1. INTRODUCTION

In arid and semi-arid regions, actual evapotranspiration (ET) from vegetated surfaces dominates the water fluxes, which accounts for more than 90% of rainfall (Wang et al., 2004, Huxman et al., 2005, Sun et al., 2010). However, climate and land use changes in these environments will affect the large-scale energy and water balances due to alterations in species composition, vegetation cover and soil moisture (Wu and Archer, 2005; Zhang and Schilling, 2006, Lu et al., 2011), bringing the importance for quantification of the energy balance components. These components can be quantified by analysing the available energy, the gradients of air temperature or/and air humidity, and the aerodynamic and surface resistance (Gash and Shuttleworth, 2007).

Energy balance methods can be applied at specific sites by using field measurements, but it becomes increasingly important to assess the surface fluxes on large scales (Timouk et al., 2009). They are used for solving practical questions relating to environmental sciences such as hydrology, meteorology and agronomy. In meteorology, they allow to model land-surface-atmosphere interactions, leading to weather forecasts that are more reliable to detect effects of climate and land use changes on rainfall, which in turn influence desertification (Oyama and Nobre, 2004).

Eddy covariance (EC) systems, became a standard field method, despite the general problem of the lack of energy balance closure (Lu et al., 2011; Zhang et al., 2012; Kessomkiat et al., 2013). An additional difficult is the use of point measurements, which provide flux values for specific sites (Tanaka et al., 2008), because they may not be representative of the entire area of interest (Teixeira et al., 2014). However, meteorology demands reliable field data, serving as a ground truth for large-scale models, being important to improve the parameterizations, including the exchanges of momentum, energy and water vapour between the vegetated surface and the atmosphere (Anderson et al., 2012; Teixeira et al., 2014).

According to Mulligan (2004), to model the exchange processes between the vegetation and the atmosphere in semi-arid regions, it is indispensable to consider the different effects that may occur during wet periods and those that involve long water stress. The soil water state determines these processes largely (Xue et al., 2004). It has been shown that meso-scale moisture heterogeneity greatly influences the atmospheric boundary layer and thermodynamics, meso-scale circulations, and conversion triggering and intensity (LeMone et al., 2007).

Modelling studies have suggested that surface heterogeneity potentially has an effect on rainfall in the tropics (Avissar et al., 2004). The feedback between climate and land use changes and the variability of the surface radiation and energy balances in semi-arid regions, is still poorly understood. Several studies on the turbulent transports above and within crop canopies have been done in irrigated crops (e.g. Kounouhéwa et al., 2013; Teixeira et al., 2014); however, fewer ones have examined these processes within the Brazilian natural ecosystems under different thermohydrological conditions (e.g. Hayashi et al, 2002; Silans and Silva, 2007).

More insights are needed into the considerable influence of natural ecosystems on circulation at different spatial and temporal scales. Previous studies in Brazilian semi-arid region have used field measurements in irrigated crops and natural vegetation to calibrate and validate remote sensing methods based on the Penman-Monteith equation (Teixeira, 2010). However, the data set for "Caatinga", comprising different thermohydrological conditions, has not been in-depth explored.

Even the "Caatinga" ecosystem being heterogeneous both vertically and horizontally, it has an expressive potential for development of rural productivity activities, despite the low amounts of precipitation in the Brazilian semi-arid region (Costa et al., 2009). Oyama and Nobre (2004) demonstrated, however, through global circulation models that changes in this natural ecosystem have caused desertification, demanding more study about the effect of these changes on the energy and water balances.

In "Caatinga" ecosystem, the dry period is characterized by senescent vegetation, with some of the species losing their leaves in the dry season while others storing water in special organs. However, as soon as the rainy season starts, the plants develop rapidly, with the water consumption sometimes being higher than that for the surrounded introduced irrigated crops. This dynamic depend on the thermohydrological conditions for a specific year, which affects phenology and biomass production.

The feedback between the weather conditions and the variability of the surface energy balance in the "Caatinga" ecosystem is still poorly understood, despite that its seasonal dynamics and diurnal variations are known to play a major role in the water cycle on large scales. Surface albedo changes with moisture and vegetation conditions directly affect the the energy partition and then precipitation (Kounouhéwa et al., 2013). There is a need to understand and quantify these processes, which control the surface fluxes, as well to evaluate land surface models.

The main objective of the current research is to gain a better understanding of the dynamic of the energy and mass exchanges between "Caatinga" and the lower atmosphere. The energy balance was analysed on daily, four-month and annual periods by using micrometeorological and EC data set for two years comprising different thermohydrological conditions. A second research objective is to test in which circumstances the biophysical controlling parameters can be reasonably predicted from agrometeorological data, throughout parameterizations aiming the use of large-scale models applicable to the Brazilian semi-arid region. Variations of the energy fluxes are described from observation data for a unusual wetter year of 2004 and for the year 2005 with precipitation amounts bellow the long-term average.

2. MATERIALS AND METHODS

2.1 Study site description

The study site was a natural vegetation called “Caatinga”, with the flux tower located at the municipality of Petrolina (9º03' S; 40º19' W; elevation 375 m), Pernambuco (PE) State, in the semi-arid region of Northeast Brazil (Figure 1).

According to Teixeira (2009), in the Brazilian semi-arid region, disturbed currents from the South, North, East and West influence the climatology. Excluding the places of high altitude, all areas present long-term annual air temperatures (T_a) larger than 24 °C. The average maximum is 33 °C and the average minimum is 19 °C. The warmest months are October and November when the sun is near the zenith position with low cloud cover and the coldest ones are June and July at the winter solstice in the South hemisphere.

The thermal homogeneity strongly contrasts with the spatial and temporal heterogeneity of the rainfall regime. Most precipitation fall during the first four months of the year, accounting for 68% of the annual precipitation, which presents a long-term (50 years) value of 570 mm yr^{-1}. The sandy soil is classified as Latossoil Red-Yellow with low retention capacity, with the groundwater depth around 2.5 m.

2.2 Vegetation type and dataset

The geographic domain of “Caatinga” occupies an area of around 750,000 km^2, which corresponds to 54% of the Brazilian Northeast and 11% of the country (Alves et al., 2008). This type of semi-arid natural ecosystem is defined as bushes that possess small leaves or thorns. The dry period is characterized by senescent vegetation, however, as soon as the rainy season starts, the plants rapidly turn green. It is a mixture of different species and the more frequent ones are *Caesalpinia microphylla* Mart., *Manihot pseudoglaziovii* Pax et. K Hoffman, *Croton conduplicatus* Kunth and *Sapium lanceolatum*. Some of them lose their leaves in the dry season and others store water. The plants are adapted to tolerate water stress, under environmental constraints, which increases rainfall use efficiency (Teixeira, 2009).

Data sets from an Eddy Covariance (EC) system together with other microclimate measurements during 2004 and 2005 were used, involving different rainfall conditions (720 mm yr^{-1} and 340 mm yr^{-1}, respectively). Simultaneously, the reference evapotranspiration (ET_0) (Allen et al. 1998) was acquired from an automatic agro-meteorological station (9º08' S; 40º18' W; elevation 375 m) (see Figure 1). Although, the station being around 9 km from the experimental site, the study region is very flat and the ET_0 data is referred to a hypothetical grassed reference surface.

The mean height (h_v) of the “Caatinga” mixed species was 8.0 m, with the EC sensors installed 11 m above the ground surface providing a fetch higher than 200 m in all directions. The EC system consisted of a three-axis sonic anemometer (Model

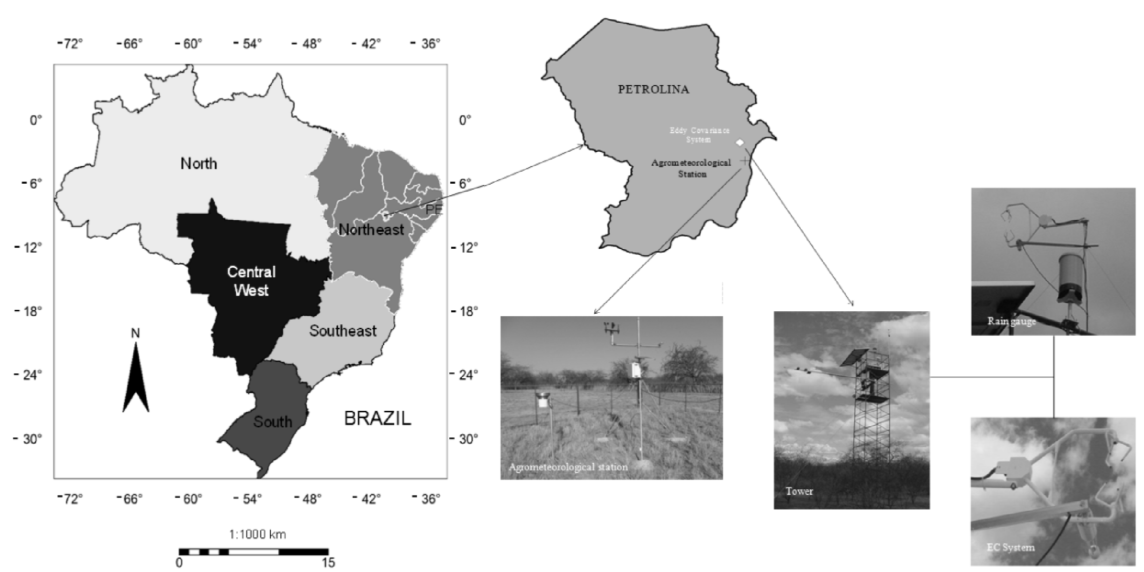

Figure 1 - Location of the study region at Petrolina municipality, Pernambuco (PE) State, Northeast Brazil. Highlights are given for the eddy covariance (EC) system in “Caatinga” and the agrometeorological station close to the experimental area.

CSAT3, Campbell Scientific, Logan, UT) to determine the sensible heat flux (H) and a fast response infrared CH_2/H_2O gas analyser (LI7500-Licor, Nebraska – USA) to acquire the latent heat flux (LE). The sensors were programmed with a sampling at a high frequency of 16 Hz. Corrections to LE due to sensible and latent heat fluxes (Webb et al., 1980), frequency losses (Moore, 1986) and coordinate rotation (McMillen, 1988) were applied by using software developed by van Dijk et al. (2004).

All components of short and long wave radiation were measured with pyranometers and pyrgeometers facing up and down (Kipp & Zonen, Delft, The Netherlands). Net radiation (R_n) was acquired by the difference of all incident and outgoing energy fluxes. The soil heat flux (G) was measured with one flux plate (model HFT3-L, REBS, Radiation and Energy Balance Systems, Seattle, WA), placed 2 cm below the soil surface. Although measuring G at only one place in "Caatinga" being not accurate, its value for 24 hours is close to zero. On the other hand, the main objective of the current research was to study the seasonal dynamics of daily energy partition under different thermohydrological conditions, with less interest in the short-time scale components.

Precipitation was quantified in the experimental area, with a tipping bucket rain gauge (model TE525-L, Campbell Scientific, Logan, UT, USA) close to the EC sensors. Microclimate measurements of air temperature (T_a) and relative humidity (RH) were taken above the vegetation with a probe from Vaisala (model HMP 45C-L, Helsinki, Finland) at the same height as the radiation sensors.

2.3 Theory

Latent (LE) and sensible (H) heat fluxes were calculated, respectively, by the following equations:

$$LE = \lambda \overline{w'\rho_v'} \quad (1)$$

$$H = \rho_a c_p \overline{w'T_a'} \quad (2)$$

where LE and H are in W m^{-2}; λ is the vaporization latent heat (J kg^{-1}); ρ_a is the air density (kg m^{-3}); c_p is the air specific heat at constant pressure (J $kg^{-1}K^{-1}$); and w', ρ_v', T_a' are respectively the instantaneous deviation of vertical wind speed, water vapour density and air temperature in relation to their mean values (respectively m s^{-1}, kg m^{-3}, °C). The bars indicate averages (Stull, 1988).

Missing and unrealistic EC-based LE data from the gas analyser during the rainy and low turbulence periods were filled by the relationship between (H + LE) and the available energy (R_n + G) (Teixeira and Bastiaanssen, 2012).

The Penman-Monteith equation was developed to predict LE from vegetated surfaces (Allen et al., 1998)

$$LE = \frac{\Delta(R_n - G) + \rho_a c_p \dfrac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)} \quad (3)$$

where R_n and G are in W m^{-2}, Δ is the slope of the saturated vapour pressure curve (kPa $^oC^{-1}$); e_s and e_a are respectively the actual and saturation vapour pressure of the air (kPa); γ is the psychometric constant (kPa $^o C^{-1}$); r_s and r_a are respectively the surface and aerodynamic resistances (s m^{-1}).

To estimate r_s (s m^{-1}), microclimatic data on T_a and RH were used together with R_n, LE and G, inverting Equation 3 (Teixeira, 2009). For r_a (s m^{-1}), the following equation was applied:

$$r_a = \frac{\ln\left[\dfrac{z-d}{z_{0h}}\right] - \psi_h}{k u_*} \quad (4)$$

where z_{0h} is the roughness length governing transfer of heat and vapour (m); k is the von Karman's constant (0.41); u_* is the friction velocity (m s^{-1}); z is the wind measurement height (m); d is the displacement height (m); Ψ_h is the stability correction due to buoyancy; and L is the Obukhov length.

Following the standard work of Allen et al. (1998), we assumed z_{0h} as being 10% of the roughness length for momentum (z_{0m}), with z_{0m} calculated by:

$$z_{0m} = \frac{z-d}{\exp\left[\dfrac{k\,u}{u_*} + \psi_m\left(\dfrac{z-d}{L}\right)\right]} \quad (5)$$

where Ψ_m is the stability correction due for momentum; and u is the horizontal wind speed from the sonic anemometer (m s^{-1}).

As "Caatinga" species have different heights, making it difficult to formulate a suitable formulation for d, we used the relationships d = 0.66h_v (Allen et al., 1998), being h_v the mean height of the vegetation. Ratios of d to the height of the vegetation (h_v) were usually reported to lie in the range of 0.6 (Garrat, 1978).

The EC data could be used to acquire u_* directly:

$$u_* = \overline{u'w'} \quad (6)$$

where u' is the instantaneous deviation of horizontal wind speed (m s^{-1}) in relation to their mean values (Stull, 1988).

The universal functions suggested by Businger et al. (1971) and the integrated stability functions of temperature (Ψ_h) and momentum (Ψ_m) were applied.

For unstable situations:

$$\psi_h\left(\frac{z-d}{L}\right) = 2\ln\left(\frac{1+x^2}{2}\right)$$

with

$$x = \left(1 - 16\frac{z-d}{L}\right)^{\frac{1}{4}} \quad (7)$$

$$\psi_m\left(\frac{z-d}{L}\right) = 2\ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right)$$

$$-2\arctan(x) + \frac{\pi}{2} \quad (8)$$

For stable situations:

$$\psi_h\left(\frac{z-d}{L}\right) = \psi_m\left(\frac{z-d}{L}\right) = -5\frac{z-d}{L} \quad (9)$$

The Obukhov length (L) was calculated by:

$$L = -\frac{\rho_a\ c_p\ u_*^3\ T_a}{k\ g\ H} \quad (10)$$

where g is the gravitational constant (9.81 m s^{-2}).

The aerodynamic surface temperature (T_0) was derived by using microclimatic data on H, T_a, and r_a (Smith et al., 1989).

$$T_0 = \frac{H\ r_a}{\rho_a\ c_p} + T_a \quad (11)$$

3. RESULTS AND DISCUSSION

3.1 Weather drivers

Figure 2 shows the monthly average weather variables in the agro-meteorological station, during the years 2004 and 2005.

Considering both years, R_G was lower from May to July, with a monthly mean value of 15.0 MJ m^{-2} d^{-1}, and higher from October to December, averaging 21.0 MJ m^{-2} d^{-1} (Figure 2a). T_a followed R_G along the years , however with a time lag of one month, with the largest thermal conditions from October to December, when there was a peak of 28.9 °C (Figure 2b). The T_a minimum values occurred between June and August, averaging 23.9 and 23.7 °C in July of 2004 and 2005, respectively. The seasonal trend for RH is shown in Figure 2c. The highest and the lowest values occurred respectively during the rainy season from January to May (averages of 74% and 71% for the years 2004 and 2005, respectively) and the driest period from September to November (corresponding average values of 52% and 50%). As an opposite behaviour of RH, the lowest u values were during the rainiest period (February to April), with mean values of 1.4 m s^{-1} and 1.6 m s^{-1}, respectively for the years 2004 and 2005,

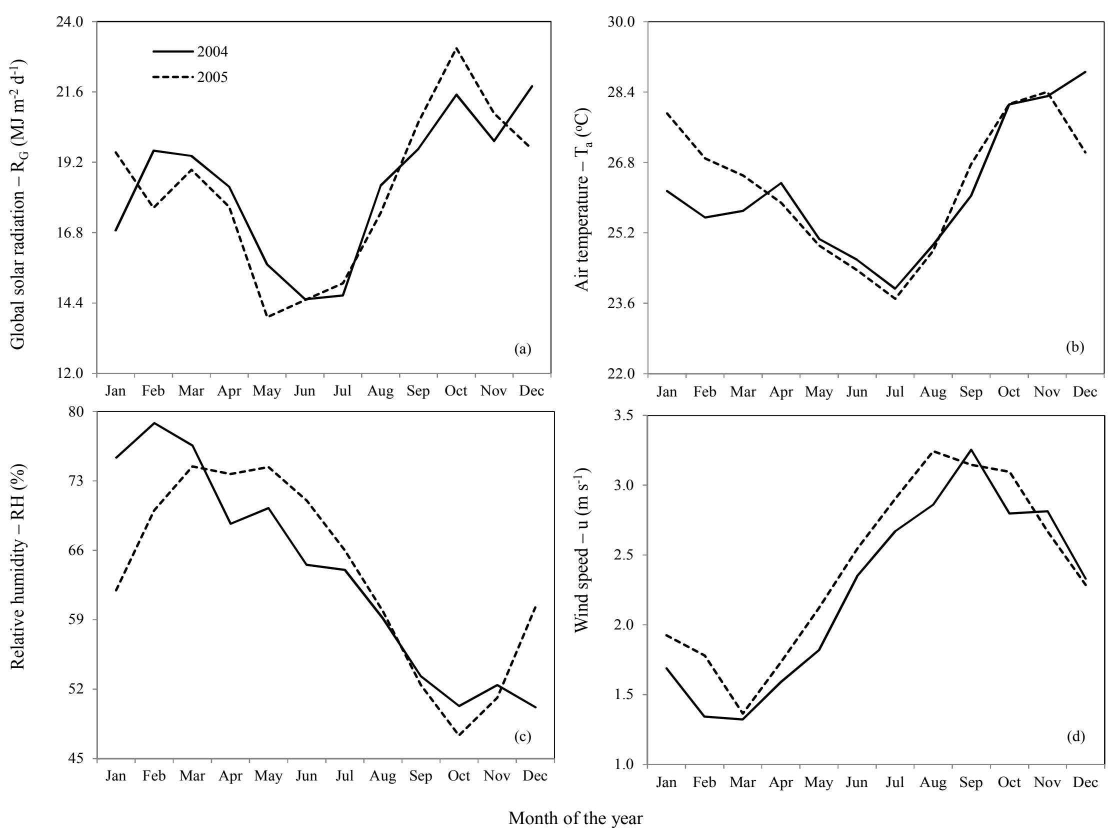

Figure 2 - Monthly average values of weather variables during the years 2004 and 2005: (a) Global solar radiation – R_G; (b) Mean air temperature – T_a; (c) Relative humidity – RH, and (d) Wind speed at 3 m above the ground – u.

while the highest ones were under the driest conditions, around 3.0 m s^{-1} in both years (Figure 2d).

3.2 Energy balance

Figure 3 presents the daily relations between R_n and R_G for each four-month period of the years 2004 and 2005.

There were consistent relationships between R_n and R_G, with the slopes of all equations ranging between 0.49 and 0.59, similar to those obtained by Hughes et al. (2001) for a temperate salt marsh in Australia. Stanhill et al. (2006) reported values of R_n/R_G around 0.50 for nine different associations of natural vegetation and two agricultural surfaces. Considering both years of the current study, the variation in R_G explained around 90% of that for R_n, evidencing that the daily available energy for "Caatinga" can be accurately estimated from pyranometers under any thermohydrological conditions. However, during the rainy season, R_n represented 60% of R_G, while outside this period, this fraction dropped to 50%. The high correlations between R_n and R_G are relevant because nowadays, the spatial variation of R_G across vast areas can be well described from satellite images.

Data quality from the EC system was verified by analysing the energy balance closure. The turbulent energy fluxes (LE + H) and the available energy (R_n - G) were compared for the whole period of measurements (2004-2005) on a daily time-scale (Figure 4).

Since the main objective of this research is for better understanding the dynamics of the seasonal energy balance in "Caatinga", there was no interest in studying hourly closures. Yet, storage components (soil, air column) were not included, but at daily time-scale analyses, the errors due to the absence of these components may be neglected.

The daily closure was 89%, with a Root Mean Square Error (RMSE) of 0.9 MJ m^{-2} d^{-1}, confirming the good quality of the dataset. A closure error of 10 to 30 % is frequent with EC measurements. Gu et al. (2008), Lu et al. (2011) and Zhang et al. (2012) also reported available energy (R_n - G) exceeding measured fluxes (LE + H) in natural vegetation. Results from 22 flux sites indicated a mean imbalance in the order of 20% (Wilson et al., 2002).

The lack of energy balance closure can be associated with measurement errors in R_n and G, however EC systems have their own sources of error (Twine et al., 2000). In addition, this lack can also be due to sampling errors related to different footprints, neglected energy sinks, loss of low and/or high frequency contributions to the turbulent heat flux and advection of scalars (Paw U et al., 2000).

The four-month and annual averaged values for the energy balance components in "Caatinga", along the years 2004 and 2005, are given in Table 1.

One can see clear seasonal variations in the energy partition, according to the thermohydrological conditions. H,

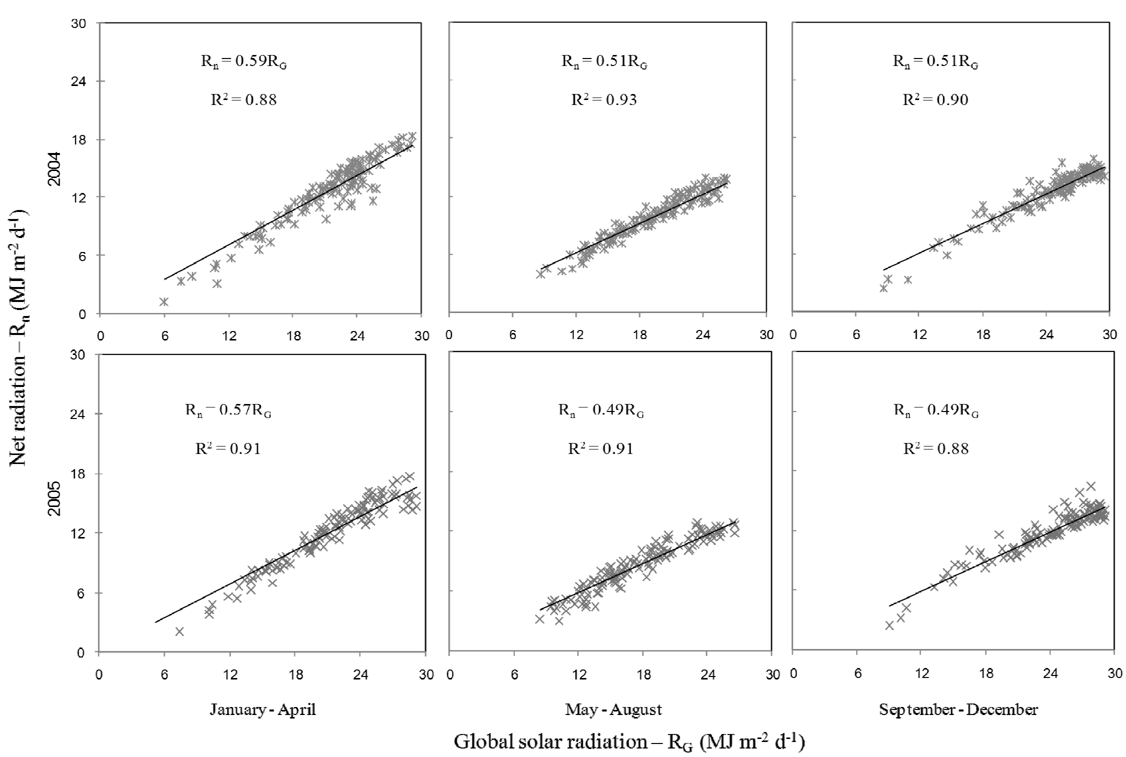

Figure 3 - Relations between the daily values of net radiation (R_n) and incident global solar radiation (R_G) in natural vegetation ("Caatinga") for each four-month periods of the years 2004 and 2005.

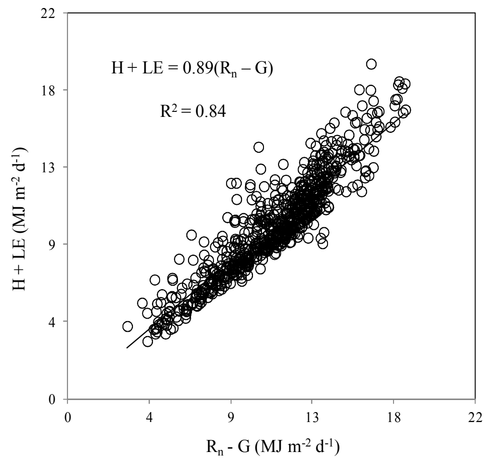

Figure 4 - Relationship between the turbulent energy fluxes (LE + H) and the available energy (R_n - G) from the energy balance measurements. LE – Latent heat flux; H – Sensible heat flux; R_n – Net radiation; and G – Soil heat flux.

in average, accounted for 49 and 64 % of R_n in 2004 and 2005, respectively. During the rainiest period from January to April, these fractions were 20% and 55%. The highest H/R_n values occurred from September to December, with an average of 74% for both years. The annual partitions of R_n as LE were 40 % and 25 % with the maximums of 77 and 45% occurring in the first four-month periods of the years 2004 and 2005, respectively. The available energy used as G on a daily time-scale may be neglected, being close to 0% for all thermohydrological conditions.

The LE range corresponded to daily ET rates between 4.0 and 0.3 mm d^{-1}, respectively, with the highest and lowest values, occurring during the first and third four-month periods of the years 2004 and 2005. Considering the annual amounts, ET for the first year with 687 mm represented 95% of P, while in the second one, with total ET of 403 mm, it was 19% more than the total rainfall amount. ET higher than P means that the remaining soil moisture from the previous year contributed to the water fluxes.

Lu et al. (2011) found the ratio ET/P varying from 0.78 to 1.50 for disturbed and undisturbed ecosystems in the semi-arid Inner Mongolia, the higher limit being attributed to ground water access from the root zones. ET rates of 207 mm yr^{-1} in a desert steppe Mongolia reported by Zhang et al. (2012) and of 266 to 319 mm yr^{-1} for grassland in California by Ryu et al. (2008), are lower than those for the Brazilian "Caatinga" species. However, ET for 2005 in the current study is inside the range of 341 to 426 mm yr^{-1} found by Gu et al. (2008) in a Qinghai-Tibetan alpine meadow grassland.

Figure 5 presents the daily relations of LE and H with R_n, for each four-month period of the years 2004 and 2005.

The largest fraction of R_n was transformed into LE from January to April; however, both, their relations and correlations, were different according to the amount of P in the different years. While in 2004 LE represented 77% of R_n, with the regression equation explaining 67% of the cases, in 2005 these numbers were 46% and 33%. From May to December, LE/R_n declined progressively. After April, LE variations could not be explained by changes in R_n, with the R^2 close to zero. Zhang et al. (2012) found variations in R_n explaining around 57% of those for LE from April to September in a desert steppe of Mongolia. However, the rainfall regime in Mongolia is more stable than that for the Brazilian semi-arid conditions, where R^2 of this magnitude occurred only during the unusual rainy season of 2004.

The H/R_n ratio is also dependent on P, but in an inverse way, when comparing with LE/R_n. From January to April in 2004, one can see much smaller H/R_n values, when compared with the same period in 2005. After the first four-month periods, H/R_n increased continuously, but from May to August, because of the higher remaining soil moisture in 2004, lower values are verified, when compared with those for 2005.

The difficulties of modelling the energy fluxes in the Brazilian semi-arid natural vegetation rely on the poor correlations of LE and H with R_n in some periods of the year. During the first four months, there were good relations of LE and

Table 1 - Four-month and annual average values for the energy balance components in "Caatinga", during the years 2004 and 2005: net radiation (R_n), sensible heat flux (H); latent heat flux (LE) and soil heat flux (G).

Period/ Year	R_n (MJ m^{-2} d^{-1})	H (MJ m^{-2} d^{-1})	LE (MJ m^{-2} d^{-1})	G (MJ m^{-2} d^{-1})
2004				
Jan-Apr	12.6	2.5	9.7	-0.3
May-Aug	9.8	5.4	3.0	0.0
Sep-Dec	12.4	9.2	1.3	0.4
Year	11.6	5.7	4.6	0.0
2005				
Jan-Apr	11.9	6.5	5.4	-0.2
May-Aug	8.6	5.4	2.0	0.0
Sep-Dec	11.9	8.8	0.7	0.3
Year	10.8	6.9	2.7	0.0

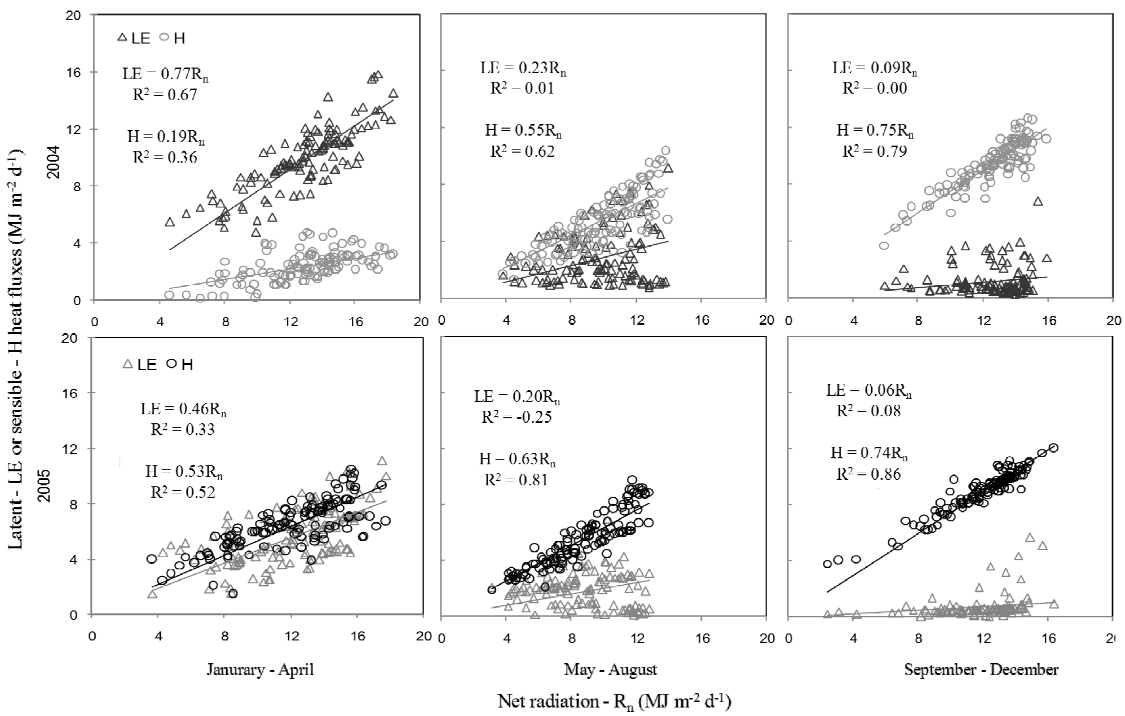

Figure 5 - Daily relations between latent (LE) and sensible (H) heat fluxes with net radiation (R_n) in "Caatinga" for each four-month periods of the years 2004 and 2005.

R_n, when the soil was wet enough. Then, ET from "Caatinga" is primarily determined by patterns of P. According to Yuan et al. (2010), annual ET rates will approach annual P in semi-arid environments, which is in agreement with other natural ecosystems (Wang et al., 2004; Ryou et al., 2008; Zhang et al., 2012).

3.3 Soil-Water-Vegetation-Atmosphere relations

In well-irrigated crops, values of ET/ET_0 (Well known as crop coefficient – K_c) can be used for estimating the water requirements at different spatial scales (Teixeira, 2009). This ratio is related to soil moisture conditions, and in natural vegetation, it can be used to characterize the moisture status in the root zones (Lu et al., 2011). In the current study, curves of the ET/ET_0 average ten-day periods, along the years 2004 and 2005, were constructed together with the corresponding P totals over the "Caatinga" for the same time-scale (Figure 6).

A strong ET/ET_0 dependence on rainfall conditions is observed, with the highest values occurring during the rainy season (January-April), and those for 2005 are 40% lower than those for 2004. During the driest periods of both years, ET/ET_0 was close to zero. Another increase happened in November, at the start of the next rainy season. The mean ET/ET_0 values were 0.47 and 0.31 with peaks of 1.19 and 0.95 for the years 2004 and 2005, respectively.

Zhang et al. (2012), who studied a temperate desert steppe in Inner Mongolia, China, found seasonal variations of ET/ET_0 with mean daily values from 0.16 to 0.75, lower than those of the current study. However, Lu et al. (2011), in the same Chinese region, presented values higher than 1.00 for six different ecosystems. Sumner and Jacobs (2005) reported an ET/ET_0 range between 0.47 and 0.92 in a non-irrigated pasture site in Florida, USA, similar to values during the rainy period for the Brazilian "Caatinga" species.

Zhou and Zhou (2009) concluded that air temperature, air humidity and the available energy were the most important variables for the ET/ET_0 variations in a reed marsh in the northeast of China. In the current study, the most explanatory factor for the highest values of this ratio was the concentration of precipitations during the first semester of the year. The strong ET/ET_0 dependence on the amount of rains is consistent with results in other semi-arid regions (Yamanaka et al., 2007; Lu et al., 2011).

It can be concluded that parameterizations will strongly depend on the soil moisture conditions. Zhang et al. (2012) confirmed this limitation in a desert steppe ecosystem in Mongolia, where the magnitude and frequency of ET were difficult to simulate during rainfall events. On the other hand, the ET/ET_0 values in natural ecosystems will also depend on stomatal regulation and plant adaptation to water stress (Mata-Gonzáles et al., 2005).

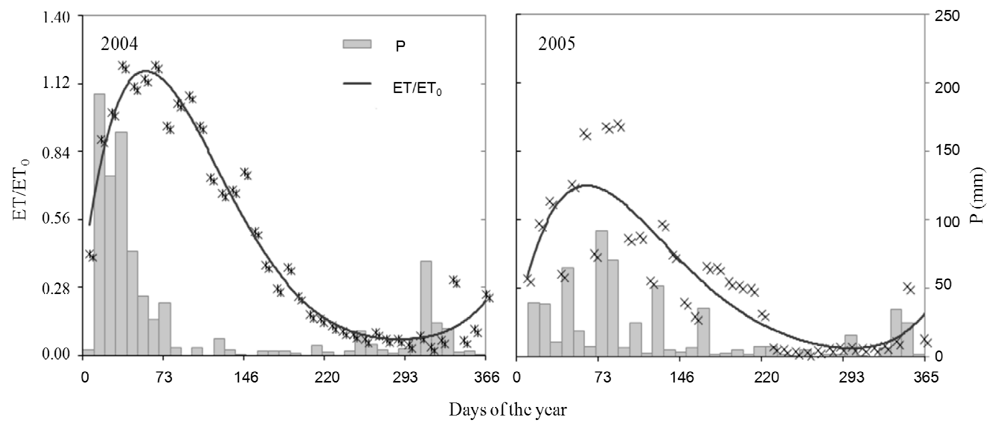

Figure 6 - Seasonal variation of the ten-day period averaged values for the ratio of actual (ET) to reference (ET_0) evapotranspiration in "Caatinga" during the years 2004 and 2005 together with totals of precipitation (P). The smoothed lines indicate the polynomial trends of ET/ET_0 values along the years.

In mixed vegetation, plant structures exert drag effects on the wind, producing turbulent eddies which are largely responsible for the vertical mixing of mass across the biosphere-atmosphere interface (Thomas and Foken, 2007). Our ability to predict surface-layer mass and energy fluxes at any time and spatial scales with accuracy, therefore, depends on the effectiveness of the parameterization of these effects (Mahrt, 2010).

The four-month and annual averages of the key vegetation parameters related to water and energy fluxes in "Caatinga", for the years 2004 and 2005, are shown in Table 2.

Due to several tall and aerodynamically rough canopy architectures, the mixed species from "Caatinga" presented high u_* values, however without differences between the drier and the wetter years, both with annual average values of 0.39 m s^{-1}. In 2004, the z_{0m} values were 30% larger than those for 2005, because during the first year, the natural vegetation generates much turbulent movements above the canopies, because of high rain amounts contributing to plant development. According to Harman (2012), z_{0m} is dependent on soil moisture and vegetation conditions.

The highest r_a coincided with the lowest r_s during the rainiest four-month periods of both years. The relatively low r_a, around 40 s m^{-1}, can be directly ascribed to the tall natural species. The both larger D_e and r_s in 2005 when compared to 2004, during the first four-month periods, are also consequences of soil moisture differences between the years. The higher u in 2005 did not contribute for increasing the ET rates in relation to 2004, because most of the time in 2005, the soil was drier.

Among the difficulties of using Equation 3, especially on large scales, are the r_a and r_s estimations (Jia, 2004). A more in-depth physical explanation of "Caatinga" energy and water fluxes can be obtained if these resistances are analysed. The average r_s from January to April 2005 was four times of that for 2004, as soil moisture constraints and high water vapour pressure deficit (D_e) induced much the stomata closure in 2005 (Mata-Gonzáles et al., 2005). The larger r_s from September to December in both years are due to the increasing atmospheric demand together with lower rainfall amounts.

The most influenced vegetation parameter by the thermohydrological conditions was r_s. Figure 7 shows its relation with other parameters, which also depend more or less on these conditions.

On the one hand, there was not a clear relationship between r_s and surface albedo (α_0). On the other hand, r_s dropped exponentially with increases on ET/ET_0, and rose with increments on T_0 and D_e. The highest correlation was obtained with ET/ET_0, followed by D_e and T_0. Testi et al. (2004), who studied an olive orchard in Spain also reported increases in r_s with rising D_e values. Rana et al. (2005) confirm the dependence of r_s on D_e, but according to these authors, the energy available to the vegetation also plays a role.

4. CONCLUSIONS

From the energy balance parameterizations in "Caatinga", it is concluded that net radiation can be estimated from the global solar radiation data with good accuracy, under any thermohydrological conditions. This is highly relevant because nowadays the spatial variation of solar radiation across vast areas can be acquired from satellites, which aids in the description of the available energy in this Brazilian natural ecosystem.

The sensible heat flux was in general in excess of the latent heat flux, except under the rainiest conditions. During the driest periods, the highest portion of the available energy is used to heat the air at the vicinities of the natural canopies. The difficulties for modelling the energy partition reside on the estimation of the energy fluxes as function of the net radiation,

Table 2 - Four-month and annual averages for the key vegetation parameters for "Caatinga", during the years 2004 and 2005: friction velocity (u_*); roughness length for momentum (z_{0m}); aerodynamic (r_a) and surface (r_s) resistances; vapour pressure deficit (D_e); and horizontal wind speed above the canopies (u)**.**

Period/ Year	u_* (m s^{-1})	z_{0m} (m)	r_a (s m^{-1})	r_s (s m^{-1})	D_e (kPa)	u (m s^{-1})
2004						
Jan-Apr	0.31	0.53	50	205	1.1	2.0
May-Aug	0.42	0.39	34	1134	1.3	3.0
Sep-Dec	0.44	0.36	36	3279	2.1	3.2
Year	0.39	0.43	40	1542	1.5	2.8
2005						
Jan-Apr	0.32	0.35	50	865	1.4	2.2
May-Aug	0.43	0.31	35	1710	1.2	3.2
Sep-Dec	0.44	0.31	38	4431	2.0	3.2
Year	0.39	0.33	41	2332	1.5	2.9

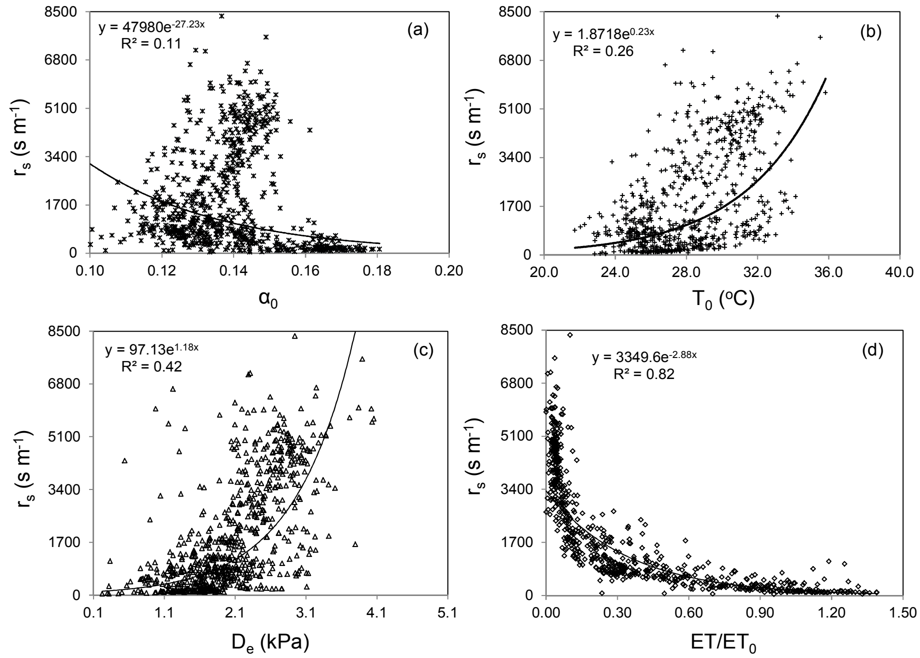

Figure 7 - Relationships between surface resistance (r_s) and other soil-water-vegetation-atmosphere related parameters. (a) with surface albedo (α_0); (b) with aerodynamic surface temperature (T_0); (c) with vapour pressure deficit (D_e); and (d) with the ratio of actual (ET) to reference (ET_0) evapotranspiration.

as these fractions will strongly depend on the soil moisture conditions, which in turn are variable along and among the years.

The use of the ratio of actual to reference evapotranspiration has been done efficiently in irrigated crops for water requirements determination, however, in the Brazilian natural vegetation it is also strong dependent on the amounts of precipitation. Indeed, the most explanatory factor for its highest values was the concentration of unusual rains in the first semester of 2004.

During the wetter year 2004, the natural vegetation generates much turbulent movement above the canopies, due to much rain amounts, which promoted larger vegetative development of the "Caatinga" species. The relatively low aerodynamic resistance (see Table 2) could be directly ascribed to the tall natural species, while the surface resistance values were affected by the soil moisture constraints and high water vapour pressure deficit, both inducing stomata closure. This resistance dropped exponentially with the ratio of actual to reference evapotranspiration, while increased with rising aerodynamic surface temperature and vapour pressure deficit.

The results of the current research are useful for understanding the dynamics of the natural vegetation in the Brazilian semi-arid conditions, which has experienced climate and land use changes with consequent signals of desertification processes. However, parameterizations of the energy and water balance components are strongly depend on the soil moisture conditions, which in turn are very variable along the years.

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