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Energy balance closure and footprint analysis using Eddy Covariance measurements in Eastern Burkina Faso, West Africa

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Abstract

The quality and the representativeness of the first long-term Eddy Covariance measurements in the savanna zone of West Africa were investigated using the energy balance closure and the footprint analysis. The quality and representativeness of the first long-term Eddy Covariance measurements over the West African savanna were investigated using the energy balance closure and the footprint analysis. The analysis covered four contrasting periods such as the complete dry season (January to March 2004), the dry to wet transition period (April to May 2004), the rainy season (June to September 2004) and the wet to dry transition period (October to November 2004).

The results show that the overall energy balance closure can be considered as satisfactory over the whole dataset. The regression fit between ($Rn-G$) and ($H+\lambda E$) was significant ($P<0.05$) with a coefficient of determination (r^2) of 0.80 and a slope of 0.88, while the intercept was 25 W/m^2. The energy balance closure was affected by rain during the rainy season (r^2=0.69), and by sampling problems during the transition periods (R^2 were 0.80 and 0.86, respectively).

The footprint analysis shows that the fetch ranged between 20 m (daytime) and 800 m (nighttime). This range showed that the fetch was adequate and fluxes sampled were representative, especially during the rainy season when the vegetal cover was dominated by crops and grasses with scale length of a few meters. During the dry season when the surface is free from crops and grasses, the measurements were also representative as about 60% of the trees around the station were contributing to the measured fluxes. However, during the transition periods some sampling problems appeared, less than 30% of the trees were contributing to the measured fluxes. The relevance of the dominant wind direction in the representativeness of the measurements was also discussed.

1 Introduction

The equation representing the energy balance of the earth's surface is a fundamental component of all models of land-surface/atmosphere interaction (Culf et al., 1997). The energy balance stipulates that the available energy at the surface (different between net radiation and ground heat flux) is equal to the sum of sensible heat and latent heat flux. When the components of the energy balance are measured separately, perfect balance is seldom obtained, but can be approached reasonably if the measurements have been well conducted. Therefore, micrometeorological researchers always use the energy balance closure to test for the reliability and the quality of their measurements. Dataset with energy balance closure within 10% is often considered reliable (Culf et al., 1997).

The review of the literature reveals that a Russian expedition in the seventies and the eighties was the first to report the problem of energy balance enclosure. In these studies, the energy balance was up to 80% (Elagina et al., 1978, 1973; Orlenko and Legotina, 1973; Tsvang et al., 1987). Wilson and Baldocchi (2000) obtained a similar result over temperate deciduous forest. Recently, some better results were found. For example, Shutteworth et al. (1984) reported 7% over tropical forest, Jarvis et al. (1997) found 3% over boreal black forest and Finch and Harding (1998) recorded 5% over pasture. Similarly, Aubinet et al. (2000) presented some energy balance closure of the EUROFLUX forest site as the plot of ($R_n - G$) versus ($H + \lambda E$). Good regression fits were obtained with the slope varying from 0.99 in the best case to 0.77 in the worst. In West Africa, this issue has not found much attention because of the scarcity of micrometeorological studies. An exception is the energy balance closure pattern-woodland and fallowed vegetation during HAPEX-Sahel project in Niger (Kabat et al., 1997) and more recently by Schttemeyer (2005) in central and Northern Ghana. They also found satisfactory closure. In the light of these studies, it appears that a good energy balance closure depends on the instruments used, climate (wind turbulence), measurement techniques and especially vegetation types.

The representativeness is also an important focus of the reliability and the quality of the micrometeorological measurements. This representativeness is often determined by analyzing the sensor footprint or source area (Ghash, 1985; Lloyd, 1994; Baldocchi, 1997; Schimid, 2002). However, researchers do not pay much attention to the positioning of the measurement station with respect to the dominant wind direction, which can have a significant effect on the representativeness of the measurements. In most of the cases, the location of the station is appreciated with respect to the aspect of the environment, the best one being a flat terrain free of tall trees and hills. As the eddy covariance (EC) technique consists of a point measurement of an average flux over a given area (Culf et al., 1997), if the objective of the study is to investigate the surfaces fluxes over a particular vegetation cover, special attention should be paid to covering a higher number of trees, so that the measured fluxes are representative of such vegetation. This becomes more relevant in the savanna regions, especially on farm land, as vegetation consists of very sparse trees. At the same time, two major wind regimes characterize the savanna region of West Africa such as the Harmattan wind (during the dry season) from the north-east and the monsoonal wind (during the rainy season) from the south. In order to obtain representative surface flux samples over a terrain in such region, the station should be installed such that the fetch area covers the higher number of trees within the dominant wind direction. This aspect is seldom taken into account in the micrometeorological studies. Therefore, the present research conducted within the framework of the GLOWA-Volta (van de Giesen et al., 2002) and VinVal projects, is aimed at contributing to the energy balance closure issue over the savanna vegetation, especially over *Vitellaria paradoxa* (sheanut tree) and *Sorghum vulgare* (sorghum). In addition, the relevance of the dominant wind direction in the representation and the quality of the flux measurement is discussed. The study covers four contrasting periods: the dry season (January to March 2004), the transition period between the dry and the rainy season (April to May 2004), the rainy season (June to September 2004) and the drying period (mid-September to November 2004). The results can be useful and representative of the savanna zone of West

Africa, because sheanut trees dominate the vegetation cover and sorghum is common crop grown widely.

The study covers four contrasting periods such as the complete dry season (From January to March 2004), the transition period between the dry and the rainy season (From April to May 2004), the rainy season (From June to September 2004) and the drying period (From mi-September to November 2004). The result could be useful and representative of the savanna zone of West Africa because sheanut tree dominates of the vegetation cover, while sorghum is grown everywhere.

1.1 Materials and methods

All climatic variables used in the analysis, except net radiation (R_n) and ground heat flux (G), were directly measured hourly with an Eddy Covariance (EC) station at 10 m height or processed from the EC raw data. The station was provided with a Krypton Hygrometer (model KH2O, Campbell Scientific, UK) for the measurement of air humidity, while wind speed (u), wind direction (*Dir*) and air temperature (T_a) were measured with a triaxial sonic anemometer (Gill Instruments Ltd., UK). Sensible heat flux (H) and latent heat flux (λE) were processed from the raw data with ALTEDDY software (Elbers, 2002). The variables u, *Dir*, and T_a were also measured at 2 m height above ground surface with an automatic weather station.

1.2 Trial site

The site was located in eastern Burkina Faso (11°07′ N; 0°33′ E). Agricultural production was intensive. The site is characterized by the Sudan climate and vegetation, and the rainfall pattern is monomodal. The main soil type is Lexisoils. The EC station was installed on farm land (average slope of 2‰) surrounded (during the dry season) by sheanut trees with an average height of 8 m. The average distance between the trees was 15 m, and density was about 17 trees/ha. During the rainy season, crops and grasses grow and alter the roughness length for momentum over time. Crop density

was about 4 plants/m^2. Figure 1 shows the location of the study area and gives an impression of the vegetation cover during the rainy and dry seasons.

1.3 Energy balance closure

The energy balance closure is usually tested by comparing the sum of sensible heat and latent heat flux ($H+\lambda E$) and the difference between net radiation and ground heat flux (R_n-G). R_n and G were estimated with commonly used equations available in the literature.

1.3.1 Estimation of net radiation

The energy budget equation was used to estimate R_n and is expressed as follows:

$$R_n = R_s - R_{su} + R_{Ld} - R_{Lu} \tag{1}$$

or

$$R_n = (1-\alpha) \times R_s + R_{Ld} - R_{Lu} \tag{2}$$

where α is the surface albedo [–], R_s is incoming shortwave radiation [W m^{-2}], R_{Ld} is downward long wave radiation and R_{Lu} is upward long wave radiation [W m^{-2}].

The surface albedo was measured every three weeks over bare soil from January to May 2004 and over the sorghum crop from June to September 2004 with a pyranometer (model: SP LITE, Kipp & Zonen, Delft, the Netherlands).

According to Idso and Jackson (1967), R_{Ld} and R_{Lu} are expressed as follow:

$$R_{Ld} = \varepsilon_a (1-c)\,\sigma T_a^4 + c\sigma T_a^4 + ck \tag{3}$$

and

$$R_{Lu} = (1-\varepsilon_s)\left[\varepsilon_a (1-c)\,\sigma T_a^4 + c\sigma T_a^4 + ck\right] + \varepsilon_s \sigma T_s^4 \tag{4}$$

where the first term in Eq. (3) represents the radiation from the clear sky as a function of the emission of the clear sky (ε_a), cloud cover (c), air temperature (T_a) in Kelvin and the Stefan-Boltzmann constant (σ=5.67×10^{-8}W m^{-2} K^{-4}). The second term is an estimate of radiation from clouds as a function of the absolute air temperature assuming that the emission is equal to unity. The third term is the product of the fractional cloud cover and an empirical correction factor (k) to adjust for the difference between air temperature and cloud base temperature. In Eq. (4), the first term is an estimate of the downward long wave radiation being reflected upward from the surface. The factor ε_s is the emission of the surface for long wave radiation. The second term of Eq. (4) is the long wave radiation emitted upward by the surface at the surface temperature. Combining Eq. (3) and Eq. (4), the following equation was obtained:

$$R_{Ld} - R_{Lu} = \varepsilon_s \left[\varepsilon_a (1-c)\sigma T_a^4 + c\sigma T_a^4 - \sigma T_s^4\right] + \varepsilon_c ck \quad (5)$$

According to Dong et al. (1992), Eq. (5) could be simplified by eliminating the term $\varepsilon_s ck$ and good estimation of $R_{Ld}-R_{Lu}$ can be obtained with the following equation:

$$R_{Ld} - R_{Lu} = 0.89\varepsilon_s \left[\varepsilon_a (1-c)\sigma T_a^4 + c\sigma T_a^4 - \sigma T_s^4\right] \quad (6)$$

The coefficient 0.89 is an empirical adjustment factor that eliminate $\varepsilon_s ck$.

According to Llasat and Snyder (1998), Eq. (6) holds only for daytime when the solar altitude (h) is greater than 10°. This condition is fulfilled here, since the daytime measurements were used in the analysis.

The clear sky emissivity (ε_a) was estimated with the equation proposed by Swinbank (1963) as follows:

$$\varepsilon_a = 0.92 \times 10^{-5} T_a^2 \quad (7)$$

The cloud fraction (c) was estimated with the equation proposed by Kasten and Czeplak (1980) as follows:

$$\frac{R_s}{R_a} = \left(1 - 0.75c^{3.4}\right) \quad (8)$$

where R_a is the clear sky irradiance [W m^{-2}] and is expressed as follows:

$$R_a = \left(0.79 - \frac{3.75}{h}\right) I \quad (9)$$

where I is the extraterrestrial radiation [W m^{-2}] estimated based on Allen (1999).

The sun altitude was estimated (Llasat and Snyder, 1998) as:

$$h = \arcsin(I/1367) \quad (10)$$

For h>10° and combining Eq. (9) and Eq. (10), the following equation was obtained:

$$c = 1.088 \left(1 - \frac{R_s}{R_a}\right)^{0.294} \quad (11)$$

1.3.2 Estimation of ground heat flux

There are several methods to determine ground heat flux (G). A review of literature reveals that G can be directly measured with heat plates buried at a certain depth in the soil, normally at a few centimeters below the surface (Oke, 1987). Analytical solutions are also available when the surface temperature varies sinusoidally (Carslaw and Jaeger, 1986). These analytical solutions are temperature-gradient and soil-calorimetric methods, which require soil surface temperature (Brutsaert, 1982). Here, the analytical solution based on temperature gradient was used. It describes heat conduction into the soil as follows:

$$\frac{\partial T}{\partial t} = \alpha_T \cdot \frac{\partial^2 T}{\partial z^2} \quad (12)$$

and soil heat flux is:

$$Q = -\alpha_T \cdot C \cdot \frac{\partial T}{\partial z_s} \quad (13)$$

where T is temperature [C] in the soil at depth z_s [m] and time t [s], α_T is the thermal diffusivity [$m^2\,s^{-1}$] equal to the ratio of the thermal conductivity over the volumetric heat capacity (C) [$J\,K^{-1}\,m^{-3}$].

When the time and depth increment (Δt) and (Δz_s) are sufficiently small, the solution of Eq. (12) for $T_{t+\Delta t,z_s}$ is expressed as follows (Anlauf et al., 1987):

$$T_{t+\Delta t,z_s} = \alpha_T \cdot \Delta t/\Delta z_s^2 \cdot \left(T_{t,z_s+\Delta z_s} - 2T_{t,z_s} + T_{t,z_s+\Delta z_s}\right) + T_{t,z_s} \quad (14)$$

Equations (13) and (14) were programmed in MATLAB based on the similar approach of HEATREG proposed by Anlauf et al. (1987). The initial temperature in the soil layers was set as soil surface temperature, which was calculated by extrapolating the air temperature at 2 m and 10 m above the soil surface. The time and depth increment (Δt) and (Δz_s) were set at 1 h and 10 cm, respectively.

1.4 Footprint analysis

The footprint was calculated based on Schuepp et al. (1990) as follows:

$$f(x) = \frac{1}{Q_0}\frac{dQ}{dx} = \frac{2X_m}{x^2}\phi_m \exp\left[\frac{-2X_m}{x}\phi_m\right] \quad (15)$$

where the left-hand side represents the flux footprint, x is the distance upwind from the point of measurement [m]. X_m is the distance upwind at which the flux footprint is a maximum [m], and ϕ_m is a momentum stability correction function. Following Dyer (1974), ϕ_m is expressed as:

$$\phi_m = \left[1 - 16\frac{z}{L}\right]^{-0.25} \quad (16)$$

z is the measurement height, L is the Monin-Obukhov length [m]. The ratio z/L was directly measured with the EC station.

$$X_m = \frac{Uz}{u^*2k} \quad (17)$$

where k is Von Karman coefficient (0.41). X_m was also directly measured and was set as the distance of 80% integration flux [m].

In order to show that the measured fluxes are representative over the investigated terrain, we roughly represented the fetches on the plan and the major trees with MATLAB. The coordinate X and Y of the wind source (corresponding to the upwind distance from the station) were calculated as follows:

$$X = X_m \times \cos(\mathrm{Dir}) + \mathrm{Lat} \quad (18)$$

$$Y = X_m \times \sin(\mathrm{Dir}) + \mathrm{Long} \quad (19)$$

where Dir is the wind direction in radian; Lat and Long are the latitude and the longitude of the EC station in UTM, respectively. Trees within 2 km radius around the station were located with a GPS (Etrex summit). The analysis was made for nighttime (unstable condition) and daytime (near-stable condition) measurements.

2 Results and discussions

The energy balance closure was first presented for the whole dataset (from January to November 2004) and the anomalies was detected and analyzed by presenting the closure over particular periods such as the complete dry period (from January to March), the dry to wet transition period (from April to May), the heavy and permanent rain period (from June to September), the wet to dry transition period (from mid-September to November). The representativeness of the measurement for the periods is discussed through the footprint analysis afterward.

2.1 Energy balance closure

The closure over the whole dataset (Fig. 2) was satisfactory but showed very scattered points around the 1:1 line with a coefficient of determination of 0.82. The slope and the intercept of the regression fit between ($Rn-G$) and ($H+\lambda E$) was 0.90 and 25 W/m^2, respectively. We first suspected a bad estimation of Rn and G as the cause of the scattering but the good distribution of the point around the 1:1 line pointed out the inability of the EC station to accurately measured H and λE during some particular times and periods. However, the estimation of Rn and G could also account for big part of the observed scattered feature because the relative bias errors were sometime greater than 50%, especially during the night, the early morning and days with rain. In fact, when Rn and G are measured with adequate devices, the uncertainties related to their measurement are 5% and 30%, respectively (Culf et al., 1997). When we analyzed the dataset according to the subdivision previously mentioned, one can notice a clear decrease of the goodness of the energy balance closure and the coefficient of determination from the complete dry to the rainy period and the trend reverses as soon as we enter in the wet to dry period (Fig. 2). The correlation coefficient was 0.91, 0.80, 0.68 and 0.86 according to the analyzed periods, respectively. Therefore, the cause of the scattered feature of the points observed on the whole data is more likely related to the sensitivity of the measurement device to rain. The high concentration of dust in the air could also be one of the reasons of our observations. In fact, Krypton Hygrometer was used to measure the air humidity, which is very sensitive to the dirty tubing (Leuning and Judd) and to rain droplets obscuring the optical path during rain (Culf et al., 1997; Moors, 1999). The malfunctioning of the Krypton hygrometer during and after the rain can last as long as the lens does not dry out. This is confirmed by Fig. 3, which compare the closure over DOY 168 with a total rain of 9.2 mm (Fig. 3b) and DOY 169 (Fig. 3a) without rain. We obtained poor correlation between ($Rn-G$) and ($H+\lambda E$) during DOY 168 (R^2=0.53), whereas it was very satisfactory during DOY 170 (R^2=0.97). The sensitivity of the Krypton hygrometer to dirty tubing and to rain is one of the big concerns about its use. These concerns can be even more pronounced in the savanna region where the air is constantly dusty during the dry season, and during the rainy season the rain is always preceded by violent dusty winds. As proposed by Moors (1997), the sampling tube has to be changed or cleaned regularly, which where not practically possible during this research because of the location of the station. In fact, the station was

maintained every three weeks and during the rainy season several rain events could happen between consecutive maintenance. The measured available energy ($H+\lambda E$) was also found to underestimate the estimated available energy ($Rn-G$) as mentioned by most of the authors in the literature (Brotzge and Crawford, 2003; Dugas et al., 1991; Goulden et al., 1998; Moore, 1976; Twine et al., 2000). The known causes of the underestimation are the distortion of the flow by the sonic anemometer (Wyngaard, 1988), water vapor fluctuation (Shuttleworth et al., 1988) and the experiment design, especially the measurement height, which determines the sensor footprint (Culf et al., 1997), the atmospheric condition, the non-homogeneous of the terrain over which the measurement is carried out (Foken and Wichura, 1996). However, the last cause would not be important in our trial site because of the vegetation was homogenous and the terrain flat with a slope of about 2%. Figure 3b also reveals an asymmetry in the diurnal energy balance closure. The measurements during the afternoon were smaller and more accurate than the ones during the early morning. Similar phenomenon was also observed during days with rain. This could be related to dew formation (for day without rain) and to rain (for day with rain) on the lens of the Krypton hygrometer. Therefore, before the lens dries out, all measurements of latent flux are overestimated. However, the asymmetry observed over the daytime measurements could also be related to the estimation of ground heat flux as the asymmetry of the incoming and outgoing radiation was taken into account by the changing every hour the average radiation at the soil surface. Energy balance closure based on the in-situ measurements of all components of the energy balance could be necessary for comparison with our observation.

2.2 Footprint analysis

The analysis of the effective fetch measured by the station showed that the maximum ranged between 20 to 800 m, which represents 2 to 80% of the theoretical fetch with measurement height of 10 m. The higher values were generally observed during the night and early morning where the atmosphere is very close to the stability, while the minimum values were observed around noon when the atmosphere is unstable. Figure 5 illustrates this observation for two contrasting hours selected in DOY 31 and in DOY 179 and for two contrasting periods (dry season and rainy season). During both periods, the footprint was similar, but with a higher peak during the rainy season. A peaked footprint exists with major contributing areas up to 100 m during the daytime. The result is similar to those obtained by Kabat et al. (1997) in the fallow vegetation and patterned woodland in Niger during the HAPEX-Sahel project. As the station was placed on a farm land, the fetch could be considered as representative during the rainy season because of the scale length of crops and grasses, which is a few meters. During that period, all soil, crops and grasses as well as trees were contributing to the measured fluxes. However, the representativeness could be problematic during the dry season and the transition periods as the major contributor to the measured fluxes was sheanut tree because of the absence of crops, grasses and the dryness of soil surface. The scale length of vegetation-bare soil was higher and ranged between 50 m and 100 m. Therefore, under unstable condition (daytime) where efficient latent heat fluxes are measured, some sampling problem may exist as the fetch was not more than 50 m. In such situation, most of the trees may not contribute to the measurement and could raise the problem of representativeness over the terrain.

When we represent roughly the fetch and the trees (Fig. 6) on the plan, we observed that just a maximum of 10 trees was contributing to the measured fluxes over an area of about 1 ha and mainly in the North-West from January to March. The 10 trees are in the high concentration of the fetches around the station corresponding to the daytime measurements (dark part of Fig. 6a). In fact, more than 50% of the winds were coming from the North-West and the remains were shared between the other directions. During the transition periods (Fig. 6b and d), just 2 and 5 trees were contributing to the measured fluxes, respectively. During both periods, winds were coming from the South-East and trees were not dense in that direction. Comparing the covered tree density and the average tree density on the terrain (17 tree/ha), one could say that the measured fluxes were representative for the dry season because a higher number (59%) of trees were contributing to it. This could be one of the explanations of the

relative good energy balance closure we observation from January to March. In contrast, during the transition periods, just 12% and 29% of the trees were contributing in the measured fluxes and could also partially explain the decrease of the correlation in those periods in addition to the rain and dust. These observations could be used in the positioning and the choice of the adequate height of the station to increase the representativeness of the measurements. For instance, before installing the station, one could first find out about the dominant wind direction for the period the intensive measurement is going to be carried out. Secondly, the station should be installed in such way that a maximum fetch is kept in the area we want to investigate. In the present case, one would have increased the representativeness of the measured fluxes during the problematic periods by installing the station in such way that higher number of trees contributes from the South-East. This probability would have been also achieved by increase the height of the station in order to increase the fetch, especially during the transition periods.

The installation of the station according to the dominant wind direction could imply the shifting of the station from site to site. However, this displacement could be limited to twice in the savanna zone of West Africa as there are just two dominant wind regimes.

3 Conclusion

The study clearly shows that Eddy Covariance technique performed very well on farm land in the savanna zone and the data collected are reliable and representative. However, the sensitivity of the system to rain and dust could have significant effect on the reliability of the measurement. During the rainy season, the measurements of most of the days with rain were excluded from the analysis because they did not satisfy the energy balance closure requirement, which may hinder a real evaluation of the dynamics of surface fluxes during that period. The study also pointed out an asymmetric effect on the energy balance closure on diurnal basis. This seems to reduce the measurement accuracy during the morning. Attention should be given to this issue in future because the reality of this asymmetry can not be substantiated since net radiation and ground heat flux were estimated.

Finally, the study reveals that the location of the station with regards to the dominant wind direction is very important and can have significant effect on the representativeness of the measurements. Therefore, this aspect should be added to the traditional criteria of selection of the best location when installing the eddy covariance system, especially over the savanna vegetation where trees are scattered.

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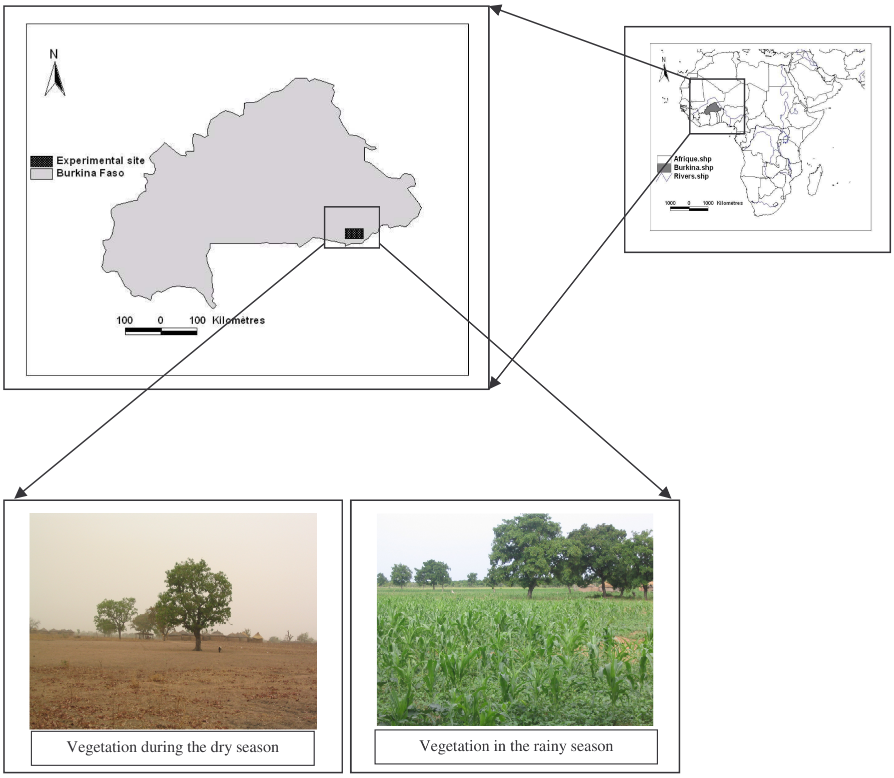

Fig. 1. Location of the experimental site.

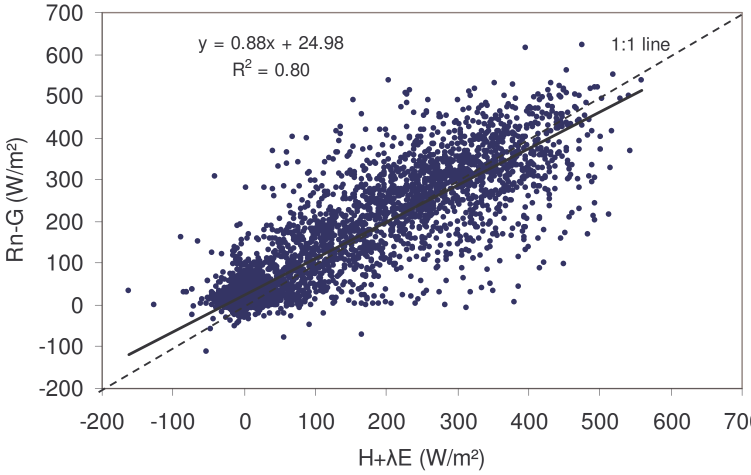

Fig. 2. Energy balance closure for the whole dataset (from January to November 2004).

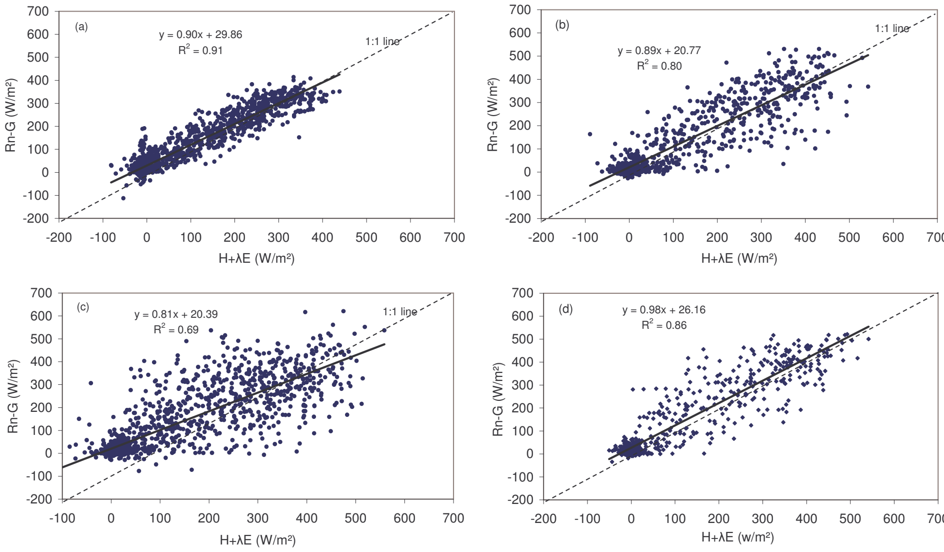

Fig. 3. Energy balance closure over different periods: **(a)** dry season (January to April), **(b)** transition period between dry and rainy season (April to May), **(c)** rainy season (June to September) and **(d)** drying period (October to November).

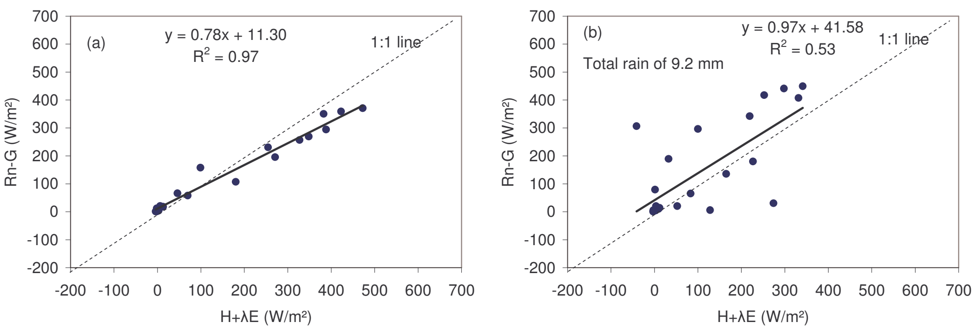

Fig. 4. Energy balance closure for two selected days during the rainy season: **(a)** DOY 170 without rain and **(b)** DOY 168 with a total rainy of 9.2 mm.

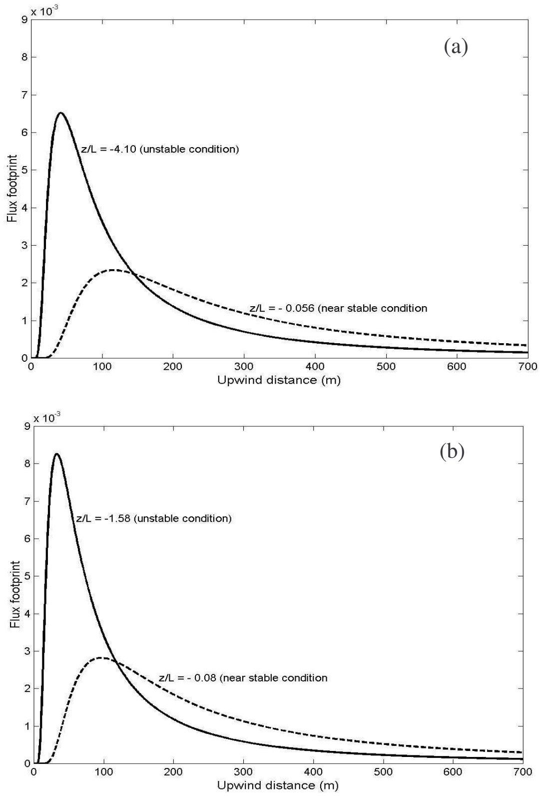

Fig. 5. Footprint representation for two selected days in the dry season and rainy season: **(a)**: DOY 31 (dry season) at 13:00 (unstable condition) and at 08:00 (near stable condition) **(b)**: DOY 179 (rainy season) at 12:00 (unstable condition) and 08:00 (near stable condition).

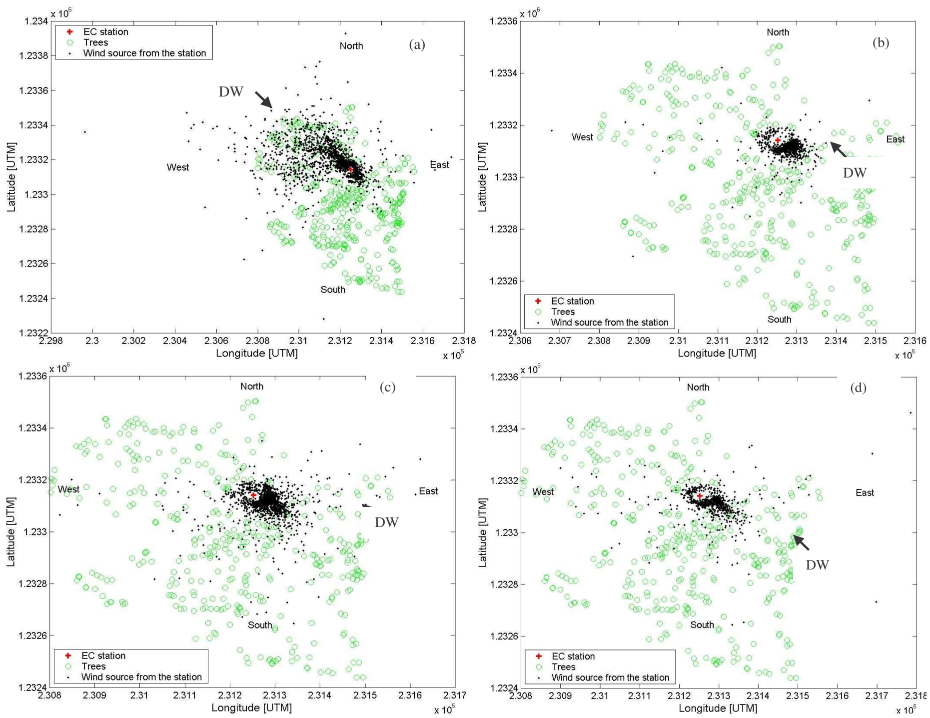

Fig. 6. Spatial representation of the fetch overlapped on the major trees around the EC station: DW is the dominant wind direction; **(a)**: dry season; **(b)** transition period; **(c)** rainy season; **(d)** drying period.