Revista Brasileira de Agrometeorologia, Piracicaba, v.15, n.3, p. 267-279, 2007
Recebido para publicação em 13/12/06. Aprovado em 30/11/07.

ISSN 0104-1347

Energy balance of a young drip-irrigated coffee crop in southeast Brazil: an analysis of errors and reliability of measurements by the Bowen ratio method

Balanço de energia de um cafezal em crescimento irrigado por gotejamento no sudeste do Brasil: uma análise de erros e da confiabilidade das medidas pelo método da razão de Bowen

Evandro Zanini Righi[1], Luiz Roberto Angelocci[2], Fábio Ricardo Marin[3]

Abstract: The energy balance of a young (one to two year-old), drip irrigated coffee crop in hedgerows configuration was determined using the energy balance-Bowen ratio (EBBR) method, during two periods in the wet season [October–Dezember/2002 (*P1*) and February–March/2003 (*P2*)] and two in the dry season [May–July/2003 (*P3*) and August–September/2003 (*P4*)], in Piracicaba, São Paulo State, Brazil. An analysis of errors affecting the estimates of latent and sensible heat fluxes was performed. Emphasis was given on determining the reliability of the assumption that $K_h=K_w$ in the EBBR method, in view of the possibility of occurrence of sensible heat advection (regional and or within-row) and on the effect of errors of measurements of the air temperature and vapor pressure through the use of thermocouple psychrometers. The psychrometric errors had a more prevalent effect in the dry periods when the humidity gradients were lower than during the humid periods, leading to a larger discarding of measurement during P3 and P4. In the wet periods, it was deduced that the assumption of $K_h=K_w$ did not introduce a large effect on the estimates of the heat fluxes, but during the dry periods this similarity could not be assumed as a function of advective fluxes. The soil surface water conditions were the main factor that determined the energy partitioning. The latent heat flux represented more than 80% of the available energy (R_n–G) in the wet season, decreasing to 78% in *P3* and 64% in *P4*, the dry periods. However, values obtained during P4 were affected by problems on management of the coffee crop. Weeds growing in the inter-rows affected the energy partitioning mostly during periods with low rainfall. The effect of coffee growth and the weeds on the latent heat flux was masked by the soil humidity inside each studied period. In the early dry period, the effect of inter-row weeds on the latent heat flux was important, because they could have extracted water from deep depths in the soil.

Keywords: measurements errors, advection, latent heat flux, sensible heat flux, psychrometry

Resumo: Determinou-se o balanço de energia de um cafezal em crescimento, entre um e dois anos após plantio, em Piracicaba, SP, cultivado em linhas de plantio adensado e irrigadas por gotejamento, utilizando-se o método do balanço de energia – razão de Bowen (BERB), durante dois períodos na estação úmida [outubro–dezembro/2002 (*P1*) e fevereiro–março/2003 (*P2*)] e dois na estação seca [maio–julho/2003 (*P3*) e agosto–setembro/2003 (*P4*)]. Foi feita uma análise de erros que podem ter afetado as estimativas dos fluxos de calor latente e de calor sensível. Analisou-se a possibilidade de se assumir a igualdade dos coeficientes de transporte turbulento para calor e vapor ($K_h=K_w$), além de serem estudados os efeitos dos erros das medidas dos perfis de temperatura e de pressão de vapor sobre o cafezal pelos psicrômetros de termopar usados, dois aspectos que afetam a confiabilidade das medidas do BERB. A importância dos erros desses sensores foi maior nos períodos secos, quando os gradientes de umidade foram menores do que nos períodos úmidos. Em conseqüência, descartou-se grande parte dos dias de medida nos períodos secos. Nos períodos úmidos, foi possível deduzir que a adoção da igualdade entre K_h e K_w não deve ter introduzido grande erro nas estimativas e que houve pouca evidência de ter ocorrido advecção de calor sensível, mas nos períodos secos houve evidência de advecção e de que a fuga dessa igualdade pode ter sido ponderável. A umidade da superfície do solo foi o principal fator determinante da partição da energia, tendo o fluxo de calor latente utilizado mais de 80% da energia disponível ($R_n – G$) nos períodos úmidos, diminuindo com a falta de chuvas para 78% em *P3* e 64% em *P4*. Devido a problemas ocorridos no manejo da área, o valor observado em *P4* deve ser tomado com cautela. O efeito da cobertura do solo das entrelinhas foi mais importante durante os períodos com poucas chuvas. O efeito tanto do crescimento dos cafeeiros como das plantas daninhas sobre o fluxo de calor latente foi mascarado pelo efeito da umidade do solo dentro de cada período analisado. No início do período seco, houve ponderável efeito da cobertura vegetal do solo das entrelinhas na evapotranspiração, provavelmente porque elas continuaram a transpirar bastante por extraírem água de camadas mais profundas do solo.

Palavras-chave: erros de medida, advecção, calor latente, calor sensível, psicrometria

---

[1] Dr. Professor, Centro de Ciências, Tecnologia e Produção, PUC-Paraná, Toledo.E-mail: ezrighi@yahoo.com.br

[2] Dr.,Professor Associado, Departamento de Ciências Exatas, Setor de Agrometeorologia, E.S.A. "Luiz de Queiroz"-SP, Pesquisador bolsista do CNPq. E-mail:lrangelo@esalq.usp.br

[3] Dr., EMBRAPA Informática Agropecuária, Campinas, SP, Brazil. E-mail: marin@cnptia.embrapa.br

Introduction

Coffea arabica originated from the rain forests of the Ethiopian highlands, where it grows as an under-storey plant. It is cultivated in equatorial regions in agroforestry systems, under shaded conditions. Studies have shown that shading is effective for frost protection in the Southern region of Brazil (CARAMORI et al., 1996) and that damages due to high temperatures can be avoided, but coffee plants continues to be cropped predominantly with plants exposed to full sunlight in Brazil. In the last two decades, Brazilian coffee plantations have expanded into regions where irrigation is required to achieve higher yield and grain quality, with increasing trends to use high-density plantations (3,000 to 10,0000 plants per ha).

The energy balance-Bowen ratio (EBBR) is one of the measurement methods used to determine the partitioning of available radiant energy into sensible heat and water vapor fluxes above the canopy, requiring simple instrumentation. However, caution must be taken when using this method in plantations with wide-rows spacing. This is the case of coffee plantations, where peculiar features concerning the energy and mass exchanges with the atmosphere occur (GUTIÉRREZ & MEINZER,1994). In a young coffee plantation with localized irrigation, as used in the experiment reported here, large heterogeneity of soil water availability, temperature and turbulence regimes can occur, affecting the heat fluxes. Also, there is a possibility that sensible heat generated by the inter-rows during dry periods contributes to the evapotranspiration of the rows plantation. The understanding of these micrometeorological features is of high relevance for eco-physiological studies and for assessing water requirements.

Furthermore, several sources of errors are present in the EBBR method, which must be quantified in order to allow for reliable estimates of latent and sensible heat fluxes. Some errors can be avoided through proper equipment installation, while others are inherent to the type of measurements and sensors. Representative measurements of net radiation require installation of the radiometer at an appropriate level above the vegetation. Determination of soil heat fluxes at the surface (G) is a challenge because normally there is a large horizontal variability of the thermal properties of the soil in a coffee plantation and the point measurements by heat flux plates require an adequate spatial sampling.

Caution is necessary when determining the Bowen ratio (β), for three main reasons. Firstly, it is calculated assuming similarity of the sensible and latent heat turbulent transport coefficients, which is valid only when advection of sensible heat and water vapor does not occur (VERMA et al., 1978; McNAUGHTON & LAUMBACH, 1998). Additionally to the large-scale regional advection, within-row advection can occur (ROSENBERG et al., 1983). Secondly, there are errors in the measurements of the vertical gradient, due to the response of the sensors in the field, especially under dry conditions (FUCHS & TANNER, 1970; ANGUS & WATTS, 1984). The third reason is that micrometeorological measurements of temperature and humidity must be performed within the atmospheric boundary layer adjusted to the surface, composed by the roughness and the inertial sub-layers (MONTEITH & UNSWORTH, 1990). Under limiting fetch conditions, the sensors must be installed inside the roughness sub-layer, where the turbulence by the vegetation elements causes distortion of wind, temperature, and humidity profiles (GARRAT, 1978).

Micrometeorological studies in coffee plantations are relatively scarce. In Hawaii (21°N), GUTIIERREZ & MEINZER (1994) carried out studies to determine latent heat fluxes in plantations of *Coffea arabica* L. of different ages, by the EBBR method. In Southeast Brazil, MARIN (2003) and MARIN et al. (2005) quantified evapotranspiration of the hedgerows and the inter-rows of an unshaded *Coffea arabica* plantation, using the EBBR method for determining the total crop water consumption and the stem heat balance method and modeling to determine the transpiration of coffee plants. In the same region of Brazil, PEZZOPANE (2005) carried out a micrometeorological study on two to three year-old coffee plants using the EBBR method, under unshaded coffee plants conditions and also with coffee plants intercropped with banana plants. KARASAWA et al. (2007) studied the energy balance and water use in the same coffee plantation described in the present paper, but at an older stand stage (three to four year-old plants).

In the studies reviewed, little is discussed about errors and reliability of the EBBR measurements in coffee plantations. In this paper we discuss the results of energy balance determinations with the use of the Bowen ratio in a young, wide-row spaced and drip irrigated coffee plantation in Southeast Brazil, focusing on the analysis of errors sources and the reliability of the measurements. The results of water use by the coffee crop will be focused in another paper.

Material and Methods

Site details and crop management

The measurements were performed in a coffee crop (*Coffea arabica L.* cv. Obatã IAC 1669-20) in a Red Nitosoil, at Piracicaba (22°42'30"S; 47°30'00"W; 546 m), São Paulo State, Brazil. The coffee crop had been planted in October 2001 and consisted of 0.2 to 0.3m tall plants at the time of this study, with 3.5 m-spaced rows and 0.90 m between plants, occupying a rectangular area of, approximately, 290 m by 100-120 m (Figure 1). The coffee field is bordered to the North by a large area of grass with a meteorological station, and a small airport to the Southeast with short vegetation between it and the plantation. Pasture and a 2.0 to 2.5 m tall coffee crop are to the East. To the Weast, there is a multi-crop field consortium composed of 10-12 m-tall rubber trees spaced 7.0 m X 3.0 m (total of 2800 trees) and five rows of coffee plants extending to inside the rubber tree area; in the same side, there is also an area with crop of 8 to 10 m-tall pijuayo plants. From February to March 2003, the southern border was covered with weed plants about 2 m-height.

A 0.9 to 1,5m-wide soil strip under the coffee plants was kept weed-free. However, weeds were always present in the inter-rows, being periodically mowed to a mean height of 0.15 to 0.20 once they reached 0.50 to 0.70 m-tall, in early October, November, December, February, mid-March and end of May. Details on the height of the inter-rows weed will be presented in the results section.

Soil water availability was kept at adequate levels during the experimental periods through irrigation with drippers spaced 0.9 m (one for each plant) and water supply rates of 2.5-2.8 l h^{-1} during a period of 12 h (30 to 34 L per plant) from the planting to March 2003. Afterwards, the irrigation duration turn was changed to 16 h (40 to 45 L per plant). RIGHI (2004) showed that the depletion of soil water below the value of field capacity did not surpass 30% from October 2001 until February 2003 and 35% from March to October, meaning that coffee plants were not subjected to water deficit according to the criteria of ALLEN et al.(1998).

Biometric measurements

In September and December 2002, February and September 2003, the number of leaves, plant height and crown diameter of 50 plants were determined. The mean leaf area was estimated by taking the mean value of the length (*l*) and width (*w*) of leaves of 10 branches. The leaf area was determined from the number *N* of leaves per plant, according to *w.l*.0.69.*N*, where the factor 0.69 was empirically determined by RIGHI (2004).

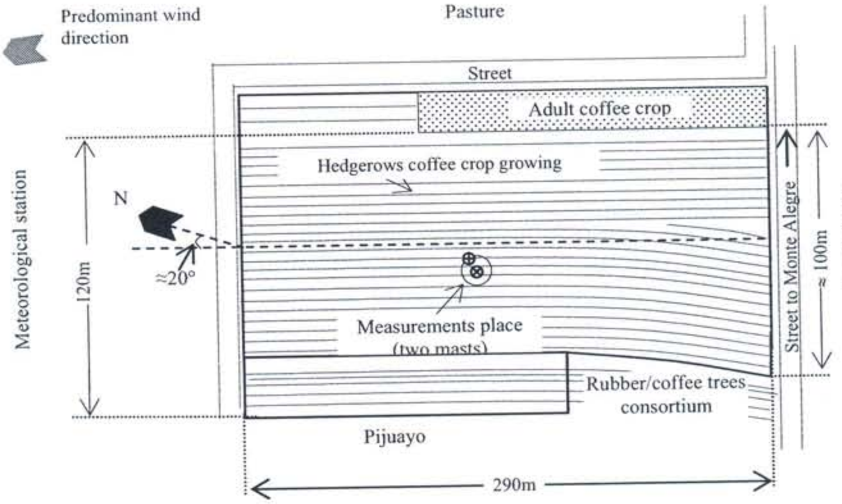

Figure 1. Diagram of the coffee crop and surrounding areas, with the location of the equipments and the masts M1 and M2 (⊕).

Micrometeorological measurements

Data were collected from October to December 2002 (period *P1*), from February to March 2003 (*P2*), both humid periods, from May to July (*P3*) and from August to September 2003 (*P4*), dry periods.

Considering that the predominant wind direction at the site is in the quadrant S-E (PEREIRA et al., 2002), the micrometeorological equipment was installed northwest to the center of the area, at approximately 170 m from the southern edge, about 60 m away from the adult coffee crop and about 40 m from the rubber trees (see Figure 1).

From October 2002 to June 2003 an iron mast (5.5 m height) was installed 0.90m from the center of a row of coffee plants, with the following instruments: a) six thermocouple psychrometers, built as proposed by MARIN et al. (2001), installed at six heights, which were adjusted according to growth of coffee plants (Table 1); b) one net radiometer Q*7.1 model (REBS Inc., Seattle, USA), at 3.5 m above the soil surface, with a supporting arm of 2.5 m length. In July 2003, a second mast was installed 15 m away from the first one, with psychrometers at the same levels as in mast 1, εξχεπτ for the upper one, which was placed between 4.72 m and 4.80 m. Periodically, a procedure of alternating the psychrometers of two adjacent heights was done, trying to minimize systematic errors of the sensors. The gauzes of the wet bulb thermocouples were replaced every four days, after cleaning them in boiling water to remove impurities.

Soil heat flux at the surface was measured with three heat flux plates HFT 3.1 model (REBS Inc., Seattle, USA), installed at a soil depth of 0.03 m, one installed in the projection of the coffee plant canopy, another between two coffee plants and the third installed in the center of an inter-row. The variability of the soil heat flux could be minimized if the sensors had been installed at a greater depth (eg. 0.8-0.10 m), but the installation at 0.03 m-depth minimizes the effect of soil heat storage (MASSMAN, 1992; MALEK, 1993). The mean values (*G*) were calculated by weighing the values proportionally to the soil area represented by each one measurement (RIGHI, 2004). It was assumed that the soil flux measured at the depth of 0.03 m is a good approximation of the value at the soil surface, because of the high thermal diffusivity of this type of soil, so that corrections to obtain G at the surface were assumed to be unnecessary (PASSERAT DE SILANS et al., 1997).

Data were sampled at 5 sec intervals by a CR-7 datalogger (Campbell Scientific Inc., Logan, USA), and averaged over a 15-min interval.

Values of LE were estimated by (PEREIRA et al., 1997):

$$\beta = \frac{H}{LE} = \frac{-\rho c_p K_h (\partial\theta/\partial z)}{-\rho L K_w (\partial q/\partial z)} \approx \gamma \frac{\Delta\theta}{\Delta e} \qquad (1)$$

$$LE = \frac{Rn - G}{1 + \beta} \qquad (2)$$

where β is the ratio of sensible (*H*) to latent heat (*LE*) fluxes measured over the vegetation ("Bowen ratio"); R_n is the net radiation; *G* is the soil heat flux; $\partial\theta/\partial z$ and $\partial e/\partial z$ are the vertical gradients of potential temperature and water vapor pressure of the air, respectively; *L* is the water vaporization heat; c_p is the specific heat of air; ρ is the air density; γ is the psychrometric coefficient, and are K_h and K_w the turbulent diffusion coefficients for sensible heat and water vapor, respectively.

Values of β were computed by a modified form of the Equation 1:

$$\beta = \left(\frac{s + \gamma}{\gamma} \frac{\Delta T_u}{\Delta\theta} - 1 \right)^{-1} \qquad (3)$$

where $\Delta\theta$ and ΔT_u, are the potential and wet bulb temperature differences, respectively, between two heights over the crop, *s* is the slope of saturation water vapor pressure curve as a function of air temperature, and γ given by $\gamma = A_p P$, where A_p is the psychrometric constant, assumed as 6.6 x 10^{-4} °C^{-1} (VISSCHER, 1995; SIMÕES-MOREIRA, 1999) and *P* is the atmospheric pressure.

Calculated LE values were integrated over 30 min-intervals.

Data quality controls

LE values were computed only when the following conditions were observed (PEREZ et al., 1999), with the vertical differences (Δe and $\Delta\theta$) taken as the upper minus the lower measurement heights :

$$\frac{\Delta e}{LE} = \frac{\Delta e + \gamma\Delta\theta}{Rn - G} < 0 \qquad (4)$$

and $\beta \leq (-1 - |\partial\beta|)$ or $\beta \geq (-1 + |\partial\beta|)$.

The absolute error of β was calculated as:

$$\delta\beta = \frac{\partial\Delta e - \gamma.\partial\Delta T_s}{\Delta e} \qquad (5)$$

Table 1. Heights (m) of the psychrometers (T_i) above the soil surface.

Period	T_1	T_2	T_3	T_4	T_5	T_6
04/10-17/12/02	0.24	1.04	1.96	2.88	3.80	4.72
31/01-13/03/03	0.24	1.04	1.96	2.88	3.80	4.72
13/03-23/03/03	0.68	1.28	1.99	2.91	3.83	4.75
27/05-02/07/03	0.68	1.27	1.98	2.93	3.87	4.80
02/05-08/07/03	0.71	1.29	2.00	2.93	3.85	4.78
08/07-22/07/03	0.71	1.29	2.00	2.93	3.85	4.78
20/08-18/09/03	0.72	1.29	2.01	2.95	3.86	4.78

where $\partial \Delta e$ was estimated from $\partial e/\partial T_u$ and $\partial e/\partial T_s$, considering all the errors additive, by (RIGHI, 2004):

$$\partial \Delta e = \left(\frac{4098 e_{su,z_i}}{(237{,}3 + T_{u,z_i})^2} + A_p P + \left| - \frac{4098 . e_{su,z_{i-1}}}{(237{,}3 + T_{u,z_{i-1}})^2} - A_p P \right| \right) \delta T_u + \\ + \left(\left| - A_p P \right| + A_p P \right) \delta T_s \qquad (6)$$

where e_{su,z_i} is the value of the saturation vapor pressure curve for T_u and the subscript z_i refers to the measurement height i. The values of δT_u and δT_s were assumed to be equivalent to the mean standard deviation of a sequence of 4 days of measurements at the end of the experiment, being the psychrometers installed at the same level in laboratory, with air temperature ranging from 20 °C to 29 °C and relative humidity from 33% to 59%. Errors can occur in opposite directions, so fixed values for $\partial \Delta T_s$ and $\partial \Delta T_u$ were adopted, i.e. $\partial \Delta T_s = 2\ \partial T_s$ and $\partial \Delta T_u = 2\ \partial T_u$.

When values of β were discarded by the criteria of PEREZ et al. (1999), the missing values of *LE* in that time interval were replaced by interpolation from the preceding and the subsequent values, but only when the period of missing data was equal to or less than two hours. When one or more periods greater than two hours showed inconsistent values, all data for the whole day were discarded from the analysis. Usually, inconsistent *LE* values were observed during night-time, when stable conditions of the atmosphere and small vertical gradients render significant the effect of the sensor errors. Considering that the nocturnal *LE* values are significantly small compared to the diurnal ones, daily values of LE were computed by summing up the values of the daytime period.

Results and Discussion

Evolution in vegetative cover

Growth parameters of coffee plants during the experimental periods, calculated from a relationship established with the number of days after transplanting (RIGHI, 2004), are shown in Table 2. A six-fold increase in leaf area, fourfold increase in number of leaves and twofold increase in crown diameter and in plants height were observed from the first to the last periods.

During the transplanting, an accident occurred with some of the seedlings, when their soil clods partially crumbled. These plants were still transplanted, because there were no others to replace them. However, a number of these plants failed to grow after the transplanting. Afterwards, with the availability of new young plants, a replanting was done, but this fact led to a great heterogeneity in crop growth, with a coefficient of variation of about 24% for plant height. For the crown diameter and the number of leaves, the coefficient of variation was even greater (40% and 60%, respectively).

The period from May to September 2003 was very dry, with daily thermal amplitudes higher than 20°C, which caused yellowing and fall of leaves, particularly after mid-September, but this is a common event for coffee plants in the region.

Table 2. Mean values of crown diameter (D_c), plant height (h), number of leaves (LN) per plant and leaf area (LA) of the coffee plantation.

Period	D_c	H	LN	LA
	m			m^2
04/10/02 – 10/11/02 (*P1*)	0.43	0.39	131	0.33
11/11/02 – 17/12/02 (*P1*)	0.49	0.44	195	0.53
31/01/03 – 23/03/03 (*P2*)	0.62	0.53	317	1.00
27/05/03 – 22/07/03 (*P3*)	0.80	0.66	450	1.66
20/08/03 – 18/09/03 (*P4*)	0.91	0.74	519	2.09

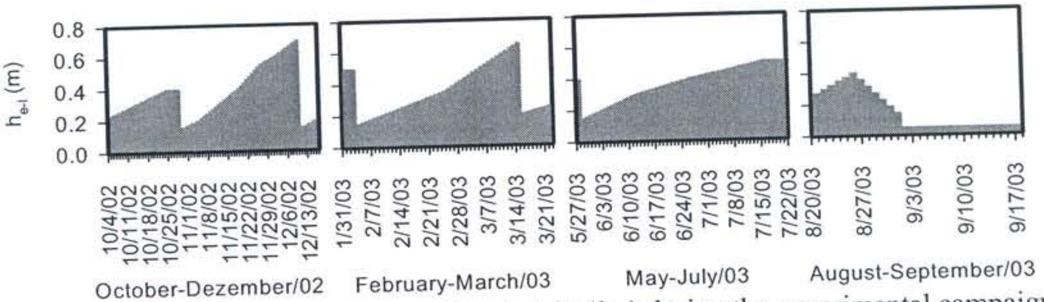

Figure 2. Time evolution of inter-rows vegetation height (h_{e-l}) during the experimental campaigns.

During the period *P4* weeds were present in about 50% of the experimental area, with the remaining area presenting bare soil. The fraction of inter-rows covered by weeds was 80 to 100%, with less than 20% of these vegetation being desiccated in *P1* and *P2* (about 40% desiccated in the first week after mowing). During *P3*, the percentage of the soil covered by weeds ranged from 70 to 100%, with 55% to 70% of desiccated weeds.

Analysis of errors and reliability of the micrometeorological measurements

The reliability of the estimates by the Bowen ratio method (BRM) depends on some assumptions, such as: a) the measurements of temperature and water vapor pressure are taken in the fully adjusted boundary layer; b) similarity of the coefficients for turbulent transport of heat and water vapor ($K_h/K_w = 1$), with the absence of heat advection; c) measurements of *Rn and G* representatives of the experimental area. Furthermore, errors arising from the measurements of the input variables, mainly those from the psychrometers, can critically affect the results. The following paragraphs are concerned with these aspects.

Measurements of *Rn* in the same plantation between September 2004 and October 2005, using two net-radiometers recently calibrated, one positioned over a coffee plant row, another on the inter-row, allowed us to infer that the measurement of this variable did not impose serious errors in the net radiation determination. The measurement of soil heat flux can be a serious source of error, as already explained, mainly when a small number of sensors is used. But, G averaged from 5 to 8% of Rn, except for 2002, when it averaged approximately to 15% of *Rn* during the daytime period, being G a small component of the energy balance.

Regarding the assumption that the measurements were taken in the fully adjusted boundary layer to the coffee crop, in a previous analysis RIGHI (2004) reported that the thickness η of this layer, estimated by the equation of MUNRO & OKE (1975), ranged from 2.71 m to 3.41 m when a fetch of 170 m in the predominant wind direction was adopted. The values of η for the smallest fetch (60 m), considered in the E direction (see Figure 1) varied from 1.34 m in 2002 to 1.70 m in 2003. These results suggest that the measurements were carried out within the adjusted boundary layer to the crop up to height 3 in 2002 and to height 4 in 2003, considering wind closely matched the direction of the largest dimension of the area, almost parallel to the coffee rows. When the wind blew crossing the hedgerows, only heights 1 and 2 were within the adjusted boundary layer (Table 1). However, according to

HEILMAN et al. (1989), under unstable atmosphere, a condition more frequent during daytime, and with the wind occurring from a rougher to a smoother surface, a ratio of 1:20 between η and the fetch length is acceptable when using β. By this approach, in this study η values ranged from about 3.0 m to 8.5 m, depending on the wind direction, suggesting that the psychrometric measurements done in heights from 1 to 4 probably were within the adjusted boundary layer.

Temperature and vapor pressure profiles are similar when the ratio $(\partial\theta/\partial z)/(\partial e/\partial z)$ is constant in the observed atmospheric layer (VERMA et al., 1978), being one of the requirements for the assumption $K_h/K_w = 1$. This situation, however, does not occur under conditions of sensible heat advection. The relationship between $(\theta_4 - \theta_1)/(\theta_3 - \theta_1)$ and $(e_4 - e_1)/(e_3 - e_1)$ in the period from 9:00 a.m. to 4:00 p.m. in days without rainfall and with the gradients physically acceptable, according to the criteria of PEREZ et al. (1999), can be seen in Figure 3. This daytime period was chosen because in it it occur the larger rates of sensible heat and vapor flux. In the humid periods (*P1* and *P2*), the scatter of data around the 1:1 line was smaller than in the dry period (May to September 2003), suggesting the occurrence of advective fluxes during the dry period.

The deviation from the 1:1 line also can be a consequence of measurement errors, mainly those arising from the psychrometers. As described in Material and Methods, δT_u and δT_s were adopted as 0.06°C and 0.02°C, respectively. Simulations showed that these values should lead to a deviation of up to ± 0.3 from the line 1:1, corresponding to a variation from 0.7 to 1.3 in the ratio

$$I = \left[(\theta_4 - \theta_1)/(\theta_3 - \theta_1)\right] / \left[(e_4 - e_1)/(e_3 - e_1)\right],$$

represented by dashed lines in Figure 3. During the humid periods, about 65% of data were within the range (0.7 to 1.3).

During the *P3* period, an analysis was performed considering only data of wind with directions between 40° and 100°, corresponding to a smaller fetch (60 m), a situation which imposes a more probable effect of advective fluxes and that could lead to a greater dispersion of data points around the 1:1 line. The greater scatter in this situation is confirmed in Figure 4a, when compared to data obtained for other wind directions (Figure 4b). During the period *P3*, about 41% of wind observations were in the directions ranging from 40° to 100°, with 30% of *I* values between 0.7 and 1.3. When wind direction not was from the 40° to 100° sector, data were more concentrated around the 1:1 line (Figure 4b), whereas when wind was from the East direction, the great majority of the points remained below the 1:1 line (Figure 4a), indicating a more critical situation in terms of profiles uniformity.

It is worth to remark on the errors and *I* values during the dry season. A simulation with data of air temperature and vapor pressure showed that closer to zero the vertical gradients values are, the further the unity the *I* values are (Figure 3, inset). A higher concentration of data points above the 1:1 line and out of the range from 0.7 to 1.3 was observed (Figure 3, dashed lines), especially during the dry periods *P3* and *P4*, when the air vapor pressure gradients were generally smaller than those during the humid periods (RIGHI, 2004).

Data of the period *P4* deserves a complementary analysis. From August 27th to 29th, and from September 3rd to 10th and on September 13th 2003, only data from mast M2 were used, because those obtained with mast M1 were rejected, following the criteria of PEREZ et al. (1999). Until September 1st, in about half of the crop area (to E - see Figure 1) the inter-rows were plowed and the soil surface became rougher, whereas the inter-rows of the other half remained totally covered by weed plants. The consequent increase of the horizontal heterogeneity of the surface properties could potentially explain the large scatter of the data observed in this period. Furthermore, during some days of this period (August 27th to September 20th) the gauzes of the wet junctions of the psychrometers on mast M1 were replaced; this coincided with changes between the incoherent and coherent profiles on this mast, the same occurring with mast M2 from August 22nd to 27th and after the replacement of the gauzes on September 12th.

In summary, in the humid period, the within-row advection of sensible heat due to the horizontal heterogeneity of the surface properties and regional heat advection apparently did not represent a serious problem and the assumption of the similarity of K_h and K_w was acceptable. During the dry period there was evidence of sensible heat advection, contributing to the increase of data scatter in Figures 3 and 4. But, a large part of the scatter was also a consequence of the errors in the psychrometers. However, it is difficult to assess the degree of error associated with deviation on the assumption of the similarity of K_h and K_w in the dry periods.

If the measurements under conditions of temperature inversion profiles are not taken into account and if the data analysis are performed using heights 3 or 4 as the upper levels of measurement, then the use of the data from heights 3 and 1 does not imply significant errors (if assumed similarity of K_w and K_h). So, $z_{p,3}$ was assumed as the most adequate upper height to the calculation of energy fluxes. After the end of the measurements, RIGHI (2004) verified that $z_{p,1}$ was often lower than the zero plane displacement (*d*), in the period from end-January to mid-March 2003, giving some uncertainty as for how representative the measurements taken in $z_{p,1}$ were. But, when $z_{p,2}$ was taken as the lower height for the computation, the results showed small differences with $z_{p,1}$ and the use of $z_{p,2}$ as the lower height resulted in an increase of the relative effect on the psychrometric errors, leading to discards of about 40% of the days with physically consistent measurement. In view of the previous discussion and considering the small differences of *LE* values estimated with data from the heights 3-1 and 4-1, when compared with those estimated with data from heigths 3-2 and 4-2, it was decided to use the heights 3 and 1 for estimating the fluxes.

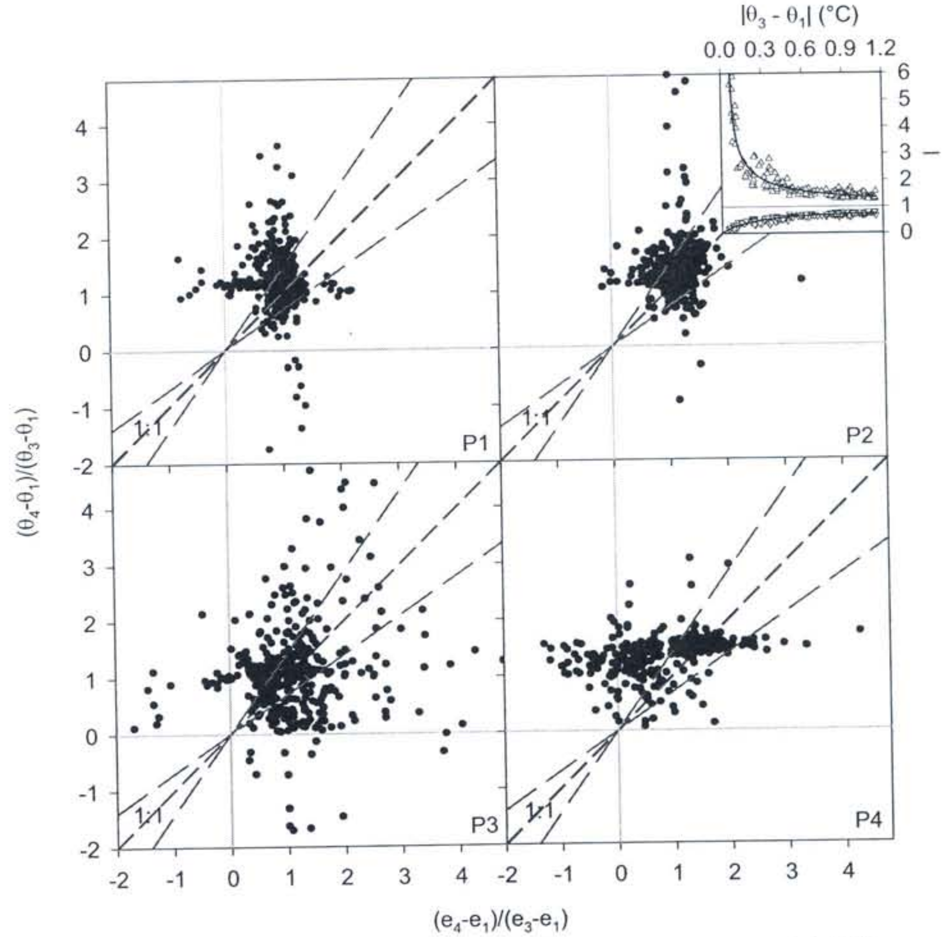

Figure 3. Relations between potential temperature (θ) and air vapor pressure (e) differences, expressed as the ratio of differences of the two variables at heights 4-1 and 3-1, during periods *P1* (October-December 2002), *P2* (January -March 2003), *P3* (May-July 2003) and *P4* (August -September 2003). Data from 9:00am to 04:00pm, with no rainfall. The inset panel in the upper right corner is a simulation of error effects on the ratio $I = [[(\theta_4 - \theta_1)/(\theta_3 - \theta_1)]/[(e_4 - e_1)/(e_3 - e_1)]$, as a function of vertical temperature difference simulated for the heights 3 and 1 ($\theta_3 - \theta_1$).

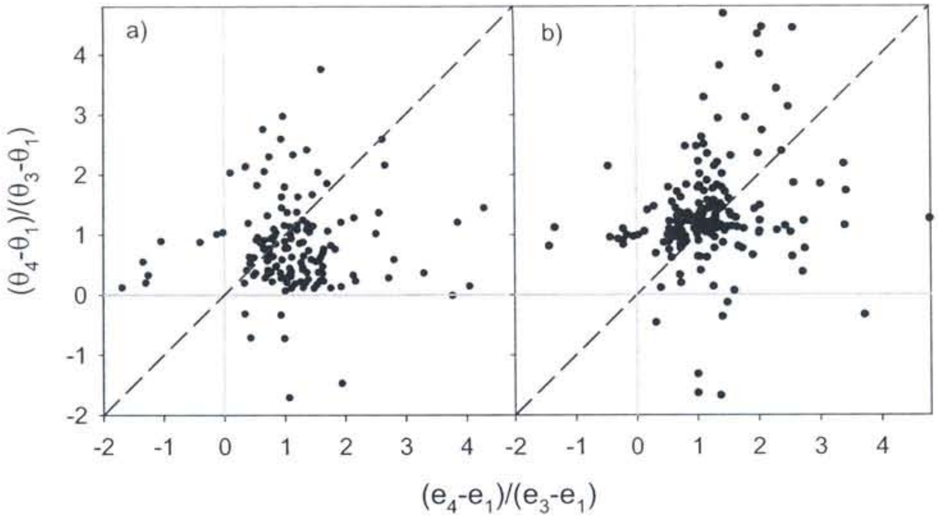

Figure 4. Relationship between the ratios of potential temperature (θ) and air vapor pressure (e) differences, at heights 4–1 and 3–1, during the period from mid-May to July 2003, with wind direction within the range 40° to 100° (a) and outside the range from 40° to 100° (b). Data from 9:00 am to 4:00 pm and no rainfall.

Energy balance

Assuming that the fraction of radiant energy used in photosynthesis and energy stored in the soil-plant system are negligible, the remaining available energy (R_n–G) is partitioned between *LE* and *H*. This partitioning depends on the soil water availability (PEREIRA et al., 1997), as can be verified by the values of β, which followed the seasonal regional water availability, with mean values of 0.14 ±0.06 in *P1*, 0.26 ±0.16 in *P2* (averaged in the period of 9:00 a.m. to 4:00 p.m.), 0.38 ±0.32 in *P3* and 0.71±0.34 in *P4* (averaged in the period of 9:00 a.m. to 3:00 p.m.).

The rainfall effect on β. can be seen in Figure 5, with noticeably increase with the progressive soil drying after a rain event, due to increases in *H* in the energy partitioning. In addition, a high variation in the energy partitioning in the dry periods (high values of standard deviation) is observed, probably due to measurement errors and to the advection effects. The high values of β in the lower levels of measurements in P4 can be ascribed to the lower values of air humidity (65%) in the period, in contrast with 79% in *P1*, 83% in *P2*, and 72% in *P3*.

LE corresponded to 88% and 81% of the available energy ($R_n - G$) in the periods P1 and P2, respectively, decreasing in the dry period to 78% (*P3*) and 64% (*P4*) (Figure 6). These values are larger than those observed by GUTIÉRREZ & MEINZER (1994) in Hawaii [$LE/R_n = 40\%$ or $LE/(R_n - G) \approx 53\%$] for a drip irrigated coffee plantation with leaf area index (LAI) of 1.4, rows spaced 3,6 m and plants spaced 0,7 m (about 25% more plants per area than in this study). It is necessary to consider that in Hawaii (21°N), the dry period coincides with the largest radiant energy availability, which provides a high thermal load. MARIN et al. (2005) verified that the environmental conditions of the coffee cropping regions of Hawaii and Brazil lead to a large vegetation-atmosphere coupling. It is possible that in the period of high energy levels in Hawaii, the great drying of the inter-rows and a pronounced stomatal control of the coffee plant transpiration explain the smaller relative use of available energy for evapotranspiration, even though *LAI* was twice as larger as than the maximum value observed in *P4*.

During the periods *P2* (February and March 2003) and *P3* (last week of May to third week of July), there was not significant difference in the partition of R_n–G between *LE* and *H*, with *LE* equivalent to 81% and 78% of the available energy in the two periods. The abnormally low rainfall in February (52 mm) compared to the historical mean value (183 mm) and the mowing of the weeds in early February, probably led to a reduction of the inter-row water vapor flux and of the value of $LE/(Rn$–$G)$ during *P2* when compared to *P1*, in spite of the twofold increase in leaf area of the coffee plants (Table 2).

The small difference of the partition of *Rn–G* in *P3*, when compared with *P2*, deserves a discussion. In *P3* there were three days of rainfall, totaling only 20 mm. The vegetation of the inter-rows showed some growth during this period (see Figure 3), but in 50-70% of the area it was observed desiccated vegetation. However, the active plants of the inter-rows perhaps contributed to LE by extracting water from deep soil depths. Also, it was observed that living weeds covered about 30% of the irrigated soil in the coffee plant rows and the increase of the coffee plants leaf area also contributed to the increase of the latent heat flux. Evapotranspiration of the coffee plant rows was measured by two load cell lysimeters, each one having a coffee plant and the daily transpiration was estimated by the measurement of sap flow using the stem heat balance method (RIGHI, 2004). Hence, it is possible to evaluate and discuss the values of the relative contribution of the coffee plants to the total latent heat of the canopy and, by difference, to infer the relative contribution of the inter-rows.

From November 2003 to February 2004 (*P1* and *P2*), the estimated percent contribution of the coffee rows to the latent heat of the canopy was practically constant (22%), from which less than 3% originated from coffee transpiration. But, in *P3* (May-July), the estimated relative contribution of the coffee rows to *LE* amounted to 30%, from which 18% was due to coffee plant transpiration. The estimated relative contribution of the inter-rows to the canopy *LE* in the period *P3* was large (70%), corresponding to a mean vapor water flux (evapotranspiration) of 1.8 mm d^{-1}, or 75% of the reference evapotranspiration estimated by the Penman-Monteith method, showing a certain level of soil water deficit, but still representing an important contribution to the canopy *LE*. Probably, a value smaller than 1.8 mm d^{-1} would be expected for the inter-row vegetation under some degree of drought, but it is difficult to draw a conclusion about the reliability of this value. It is necessary to consider the evidence of sensible heat flux advection, as previously discussed, and the increase of errors, as well as of uncertainties of measurements in the dry period. During the period *P4*, the environmental conditions were similar to those of the period *P3*, with a possible, but not confirmed, effect of sensible heat flux. Whatever the causes, the dry conditions and/or the bare soil of the inter-rows and/or the coffee plant stomatal regulation due to the high water vapor saturation deficit of air, they led to a smaller participation of *LE* in the partition of *Rn–G* in *P4*.

The relative values of *LE* in the partitioning of *Rn–G* were more dependent on the environmental variables and surface moisture than on the degree of inter-row soil cover during the periods of analysis. For the same experimental period, an effect of the inter-row soil cover was evident only after mowing on March 16th, during three days without rain, when a reduction of about 10% in the values was observed, compared to those of the previous week. For the rainy periods, it is difficult to draw a conclusion due to the high soil surface moisture and to the possible masking of the soil cover effect by the coffee growth. Evidently, this coffee plant growth contributed to higher values of LE/(Rn-G). But, as the coffee plant grows slowly, the effect was not clear, rendering the soil surface moisture effects more evident.

The error analysis, by considering $\delta T_u = 0.06\,°C$, $\delta T_s = 0.02\,°C$ and assuming a value of $\delta(R_n - G)/(R_n - G)$ of 0.04 proposed by ANGUS & WATTS (1984) showed that the mean values of the relative errors of estimating □*LE/LE* from 9:00 a.m. to 4:00 p.m. were below 10% in *P1* and in *P2*, while during some days of the dry period they almost reached 200%. The relative mean uncertainties were 8% in *P1*, 10% in *P2*, 38% in *P3* and 34% in *P4*. It is important to emphasize that the high relative errors were computed considering extreme cases, resulting in maxima possible uncertainties. Extreme cases did not occur at all times, so the true errors are probably lower than those cited above. Even though we did not quantify how much lower the errors were, it was assumed that they did not invalidate the fluxes estimate, although a certain caution must be used with values in the dry periods.

These results show that in this young coffee plantation, the soil moisture of the inter-row was the most important variable affecting the energy partitioning. The climatic conditions of Southeast Brazil and relatively high roughness of the surface lead to a large degree of coupling between atmosphere and the surface (MARIN et al., 2005), mainly under conditions of large crop spacing, as in the present coffee crop, where rows spacing varied between 8*h* and 4*h*, being *h* the crop height. The inter-rows have an important role on the fluxes, because they represent the largest area (more than 75% in this case) of the surface coverage. When the coffee plants grow and the hedgerows cover most of the soil surface, the rows vegetation probably become more coupled to the atmosphere due to the increase in their roughness, decreasing the coupling of the inter-rows, and the physiological and geometrical conditions of the coffee plants, as well as the planting geometry, become determinant factors of the energy partitioning. In a similar way, GUTIÉRREZ & MEINZER (1994) observed that when *LAI* of coffee rows increased, the importance of *H* and the contribution of the inter-rows to *LE* was lower.

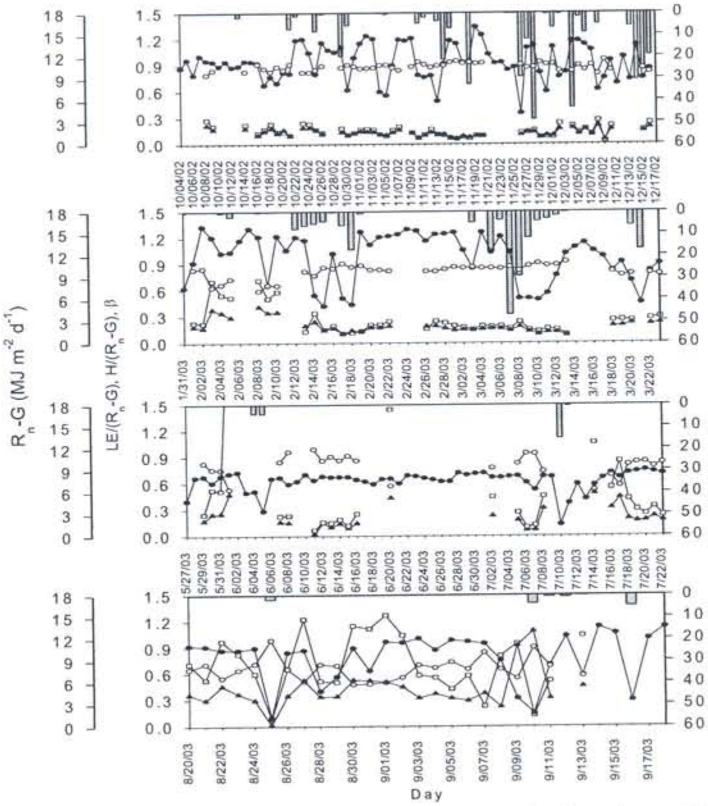

Figure 5. Daily values of the available energy for water vapor and sensible heat fluxes (R_n–G, —●—), ratios *LE*/(R_n–G) (—o—) and *H*/(R_n–G) (—▲—), precipitation (P_r, ■) and the Bowen ratio (β, —□—). Values of (R_n–G), *LE* and *H* correspond to accumulated values from 6:00 a.m. to 6:30 p.m. for *P1* (October 4 to December 16 2002) and *P2* (January 1 to March 23 2003) and from 6:00 a.m. to 6:00 p.m for *P3* (May 22 to July 22 2003) and *P4* (August 20 to September 18 2003); β data corresponding to mean values from 9:00 a.m. to 4:00 p.m. in *P1* and *P2*, and from 9:00 a.m. to 3:00 p.m. in *P3* and *P4*.

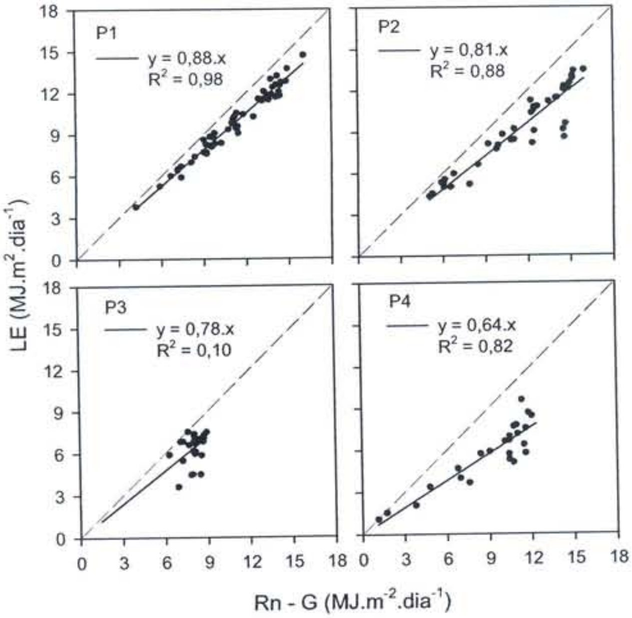

Figure 6. Relations between latent heat flux estimate (*LE*) between heights 3 and 1 and the diurnal available radiant energy (R_n-G) on the periods *P1* (October-mid December 2002), *P2* (February-March 2003), *P3* (May 27th – July 22th 2003) and *P4* (August 20th – September 18th 2003).

Conclusions

Data analysis, considering the errors associated with the measurements of the profiles of dry and wet bulb temperatures, allows to infer that in the wet periods the horizontal heterogeneity of the surface properties and the advection of sensible heat flux were not a serious problem, while during the dry periods there was some evidence of advective flux of sensible heat, especially when the wind direction corresponded to the smaller fetches. However, it was not possible to quantify this effect on the equality $K_h = K_w$ and on the fluxes estimates. Nevertheless, the data analysis suggests that the sensible heat advection did not invalidate the results, but that care must be taken in interpreting the those from the dry periods. Also, a large effect of the sensor errors was verified, which was the main cause of low quality data observed in the dry periods, resulting in uncertainties of the estimate in energy partition.

The values of $LE/(Rn\text{-}G)$ depended more from soil moisture, especially that of the inter-rows, and from the environmental variables than from the degree of soil cover. The young coffee plants covered a small part of the soil surface in all periods, so that soil moisture of the inter-rows was the determinant factor in the energy partitioning. The effect of coffee growth and of the inter-row weeds on the energy partitioning were masked by the inter-row soil moisture for each period studied. In the wet period, latent heat flux represented more than 80% of the available radiant energy ($R_n - G$), decreasing to about 64% in the dry period.

In the wet periods, the energy partitioning was close to values observed for crops covering the whole soil, because of the high evapotranspiration of the inter-rows. Otherwise, under dry conditions, $LE/(Rn - G)$ was lower because the drip irrigation wets only part of the soil surface in the hedgerows, in despite of the importance of inter-rows early in the dry period, when the weeds would take water from deeper depths in the soil.

Acknowledgements

To Dr. Claudia Wagner-Riddle and to Dr. Nereu August Streck for reviewing the manuscript, to Fundação de Amparo à Pesquisa do Estado de São Paulo – FAPESP, to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – CAPES and to Conselho Nacional de Desenvolvimento Científico e Tecnológico-CNPq, Brazil, for the financial support.

References

ALLEN, R.G.; PEREIRA, L.S.; RAES, D.; SMITH, M. **Crop evapotranspiration: guidelines for computing crop water requirements**. Rome: FAO, 1998. 300p. (FAO Irrigation and Drainage Paper, 56).

ANGUS, D. E.; WATTS, P. J. Evapotranspiration – how good is the Bowen ratio method?. **Agricultural and Water Management**, Amsterdam, v.8, p.133-150, 1984.

FUCHS, M.; TANNER, C.B Error analysis of Bowen ratios measured by differential psichrometry. **Agricultural Meteorology**, Amsterdam, v.7, p.329-334, 1970.

GARRATT, J.R. Flux profile above tall vegetation. **Quarterly Journal of the Royal Meteorological Society,** London, v.104, p.199-211, 1978.

GUTIÉRREZ, M.V.; MEINZER, F. C. Energy balance and latent heat flux partitioning in coffee hedgerows at different stages of canopy development. **Agricultural and Forest Meteorology**, Amsterdam, v.68, p.173-186, 1994.

HEILMAN, J. L.; BRITTIN, C. L.; NEALE, C. M. U. Fetch requirements for Bowen ratio measurements of latent and sensible heat fluxes. **Agricultural and Forest Meteorology**, Amsterdam, v.44, p.261-273, 1989.

KARASAWA, S.; ANGELOCCI, L.R.; MARIN, F.R. Evapotranspiração de cafezal irrigado por gotejamento e sua relação com a evapotranspiração de referência. **Revista Brasileira de Agrometeorologia,** Piracicaba,v.15, p. 001-013, 2007.

MARIN, F. R. **Evapotranspiração e transpiração máxima em cafezal adensado**. Piracicaba, 2003. 118p. Tese (Doutorado) – Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo, 2003.

MARIN, F. R.; ANGELOCCI, L. R.; COELHO FILHO, M.A.; VILLA NOVA, N.A. Construção e avaliação de psicrômetro aspirado de termopar. **Scientia Agrícola**, Piracicaba, v.58, n.4, p.839-844, 2001.

MARIN, F. R.; ANGELOCCI, L. R; RIGHI, E. Z.; SENTELHAS, P. C. Evapotranspiration and irrigation requirements of a coffee plantation in Southern Brazil. **Experimental Agriculture**, v.41, n.2, p.1-11, 2005.

MASSMAN, W. J. Correcting errors associated with soil heat flux measurements and estimating soil thermals properties from soil temperature and heat flux plate data. **Agricultural and Forest Meteorology**, Amsterdam, v.59, n. 3-4, p.249-266, 1992.

MALEK, E. Rapid changes of the surface soil heat flux and its effects on the estimation of evapotranspiration. **Journal of Hydrology**, Amsterdam, v.142, n.1, p.89-97, 1993.

McNAUGHTON, K. G.; LAUBACH, J. Unsteadiness as a cause of non-equality of eddy diffusivities for heat and vapour at the vase of an advective inversion. **Boundary-Layer Meteorology**, Amsterdam, v.88, p.479-504, 1998.

MONTEITH, J,L.; UNSWORTH, M.H. **Principles of Environmental Physics**, London: Edward Arnold, 1990. 291p.

MUNRO, D. S.; OKE, T. R. Aerodynamic boundary-layer adjustment over a crop in neutral stability. **Boundary-Layer Meteorology**, Amsterdam, v.9, p.53-61, 1975.

PASSERAT DE SILANS, A.; MONTENY, B. A.; LHOMME, J. P. The correction of soil heat flux measurements to derive an accurate surface energy balance by the Bowen ratio method. **Journal of Hydrology**, Amsterdam,.v.188-189, p.453-465, 1997.

PEREIRA, A. R.; ANGELOCCI, L. R.; SENTELHAS, P. C. **Agrometeorologia: Fundamentos e Aplicações**. Guaíba: Editora Agropecuária, 2002. 478p.

PEREIRA, A.R.; VILLA NOVA, N.A.; SEDIYAMA, G.C. **Evapo(transpi)ração**. Piracicaba: FEALQ, 1997. 183p.

PEREZ, P. J.; CASTELLVI, F.; IBAÑEZ, M.; ROSELL, J. I. Assessment of reliability of Bowen ratio method for partitioning fluxes. **Agricultural and Forest Meteorology**, Amsterdam, v.97, n. 3, p.141-150, 1999.

PEZZOPANE, J.R.M. **Avaliações micrometeorológicas, fenológicas e agronômicas em café arábica cultivado a pleno sol e consorciado com banana 'Prata Anã'**. Piracicaba, 2004. 136p. Tese (Doutorado) – Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo, 2004.

RIGHI, E.Z. **Balanço de energia e evapotranspiração de cafezal adensado em crescimento sob irrigação localizada e sua partição nos renques e nas entrelinhas**. Piracicaba, 2004. 168p. Tese (Doutorado) – Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo, 2004.

ROSENBERG, N.J.; BLAD, B.L.; VERMA, S.B. **Microclimate: the Biological Environment.** New York: John Wiley & Sons.1983. 495 p.

SIMÕES-MOREIRA, J. R. A thermodynamic formulation of the psychrometer constant, **Measurement Science & Technology**, Bristol, v.10, p.302-311, 1999.

VERMA, S. B.; ROSENBERG, N. J.; BLAD, B. L. Turbulent exchange coefficients for sensible heat and water vapor under advective conditions. **Journal of Applied Meteorology**, Oxford, v.17, p.330-338, 1978.

VISSCHER, G.J.W. Standard psychrometers: a matter of (p) references. **Measurement Science & Technology,** Bristol, v.6, p.1451-1461, 1995.