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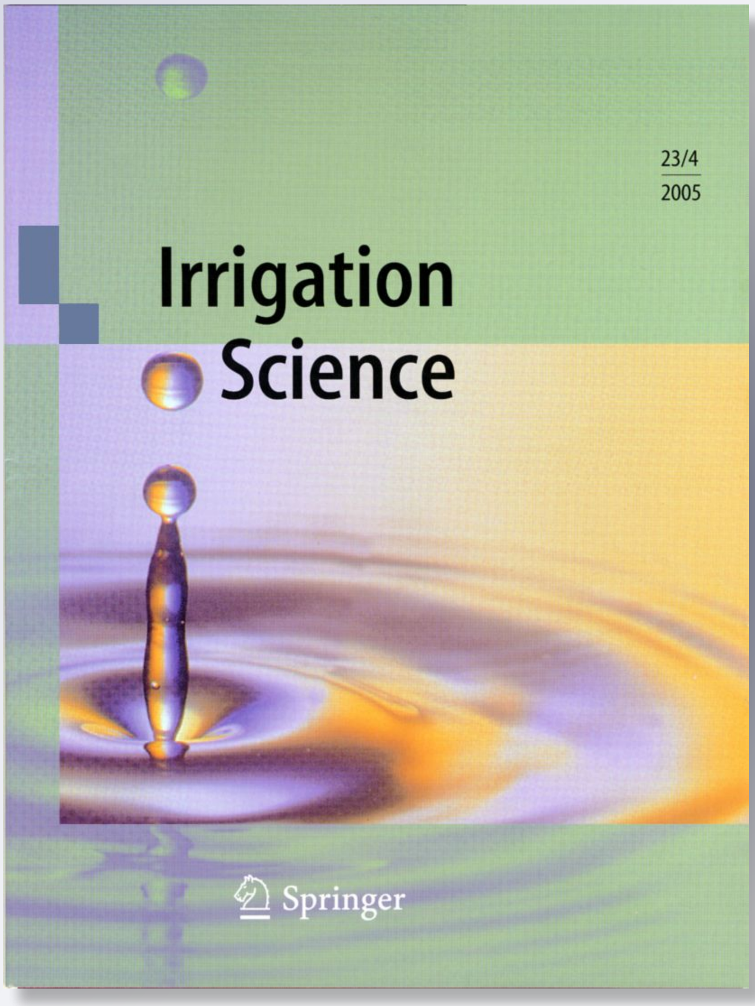

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ORIGINAL PAPER

Five methods to interpret field measurements of energy fluxes over a micro-sprinkler-irrigated mango orchard

A. H. de C. Teixeira · W. G. M. Bastiaanssen

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Abstract Energy balance measurements were carried out in a mango orchard during two growing seasons in the semi-arid region of Brazil. The actual evapotranspiration (ET) was acquired by eddy correlation (EC) and Bowen ratio energy balance (BR) techniques. The daily energy balance closure in the EC measurements showed an average gap of 12%, with a root mean square error (RMSE) of 1.7 MJ m^{-2} d^{-1}. Three different correction procedures were tested for closing the energy balance from the EC system: (1) the surface energy balance residual method (RES), (2) the Bowen ratio determined from the EC fluxes, the combination approach (EC_BR), and (3) a new regression energy balance closure technique (REG). All closing energy balance methods presented good correlation with the direct EC measurements, but the trends were not similar. The latent heat fluxes estimated by the BR method—λE_{BR}—were higher than those from the direct EC measurements—λE_{EC}. When using the RES method, the half-hour λE_{EC} measurements represented around 88% of the λE_{RES} values, as the uncertainties of net radiation—R_n—and soil heat fluxes—G—are propagated into the RES method. The latent heat flux derived from the combination approach—λE_{EC_BR}—also brings these uncertainties, being the agreements comparable with those for RES method. It was therefore concluded that a single correction method for EC measurements considering only the latent and sensible heat fluxes does not exist. A new way to solve the lack of energy balance closure from EC techniques was tested by means of a curve fitting, the REG method. Considering the REG corrections applied to the energy balance components involving all periods of the day and the average conditions of the two growing seasons, half-hour values of λE_{EC} were overmeasured by 18%, H_{EC} was undermeasured by 17%, and G values required a correction of 466%. The REG method appeared promising because it considers different weights for all energy balance components in the optimization process. Taking the REG results for the drier second growing season as a reference, it was concluded that seasonal ET values by the other methods in mango orchard ranged from 7 to 28% higher, showing that turbulent flux measurements lack accuracy for executing on-farm water-saving programmes and calibrating transient soil water flow models.

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Introduction

Actual evapotranspiration (ET) from irrigated crops is receiving renewed attention because of the increasing competition of crop water use with other sectors. Reduction in ET in irrigation systems is thought to be a viable solution for achieving water savings in overexploited river basins (Bastiaanssen et al. 2008; Teixeira 2009). Deficit irrigation experiments saves water, enhances stream flow and does not necessarily affect crop production (Fereres and Soriana 2007).

The highest yield levels per unit of water use (kg m^{-3}) are obtained at mild water stress conditions, and to establish these conditions, it is first necessary to know actual and potential ET. Modelling of ET processes is therefore getting new impetus; hydrological, soil physical and remote sensing models are used to determine optimum levels of water use (Bastiaanssen et al. 2007). All these advanced models require careful calibration and validation with field data (e.g. Ahmad et al. 2002; Droogers et al. 2010). Standardized and simplified methods for crop ET computations such as described in FAO 56 (Allen et al. 1998) require experiments over extend periods of time. Many of them have shown accurate results in a wide range of agricultural situations. However, their application to sparse crops like orchards is generally more difficult than for uniform field crops.

In the widely recognized energy balance non-closure problem in eddy correlation (EC) systems, few intercomparisons have focused on the role of data-processing schemes between EC measurements and the forcing closure methods in irrigated orchards. Some research in different kind of vegetation has shown that differences are reduced if the components of the energy balance are averaged over longer time periods (Dugas et al. 1991; Unland et al. 1996; Spano et al. 2000; Beringer and Tapper 2000; Olejnik et al. 2001; Azevedo et al. 2003; van Dijk et al. 2004a, b; Ortega-Farias et al. 2007; Simmons et al. 2007). However, all components of the simplified energy balance equation have their own source of errors, being important to apply a method where the additional corrections for net radiation (R_n) and soil heat flux (G) are included when considering short timescale (Allen 2008).

Traditionally, ET has been measured with lysimetery (Doorenbos and Pruitt 1977; Wright 1982; Jensen et al. 1990; Allen et al. 1998). For orchards, the size of the trees and the need to sample a representative area means that lysimeters are not practical. Due to large rooting depths, the ET measurements in trees are very difficult to be made with weighing lysimeters and soil water balance. There are considerable uncertainties related to the measurements of the soil depth affected by root water uptake, percolation, runoff and capillarity rise (Teixeira et al. 2008a). According to Rana et al. (2005), the use of the soil water balance to determine ET is not ideal, especially in the case of sparse crops and in regions subjected to semi-arid climates. In some occasions, transpiration can be measured directly with the heat pulse velocity-sap flow technique, which has been applied in vineyards (e.g. Yunusa et al. 2004) and olive groves (e.g. Testi et al. 2006). This method together with soil evaporation measurements may give good results, but in orchards, it is affected by individual tree variability and the upscaling from trees to a stand or block is problematic.

During the twenty-first century, lysimeters have been replaced by several micro-meteorological techniques for ET calculations, being the use of EC systems the most common (Wilson et al. 2002), which directly measure the latent (λE) and sensible (H) heat fluxes. Examples of their applications in agricultural and natural ecosystems are published by Oliver and Sene (1992), Sene (1994), Trambouze et al. (1998), Ohta et al. (2001), Cleverly et al. (2002), Wilson et al. (2002), Humphreys et al. (2003), Lund and Soegaard (2003), Prueger et al. (2004), Vilalobos et al. (2004), Testi et al. (2004), Simmons et al. (2007), Hiyama et al. (2007), Teixeira et al. (2008a, b). According to all these EC results, the energy balance is usually not closed, which poses a serious problem for achieving progresses in the general knowledge of crop ET variability.

The lack of the energy balance closure in EC systems can be related to malfunctions of the sensors during rainfall conditions; instrumental maintenance; neglected energy sinks; heat storage in the top soil; loss of low and/or high frequency contributions to the turbulent heat fluxes; advection of scalars; different correction algorithms used to process the data; flux divergence in the boundary layer; non-uniform footprint; non-representative sensing of R_n and G; proper average times; and when neglecting of the energy stored in the tree canopies for accounting for the available energy partitioning (Paw et al. 2000; Baldocchi et al. 2001; Scott et al. 2003a, b; Papale et al. 2006; Wolf et al. 2008; Castellvi et al. 2008). Yet, after applying algorithms for general corrections to λE_{EC} and H_{EC}, energy balance closure errors still remain in the other energy balance components (Allen 2008).

The Bowen ratio (BR) method forces the energy balance closure and requires cheaper instruments than EC systems. BR measurements are very useful when λE and H cannot be measured directly. Examples of applications of BR method are found in Heilman et al. (1996), Ahmad et al. (2002), Inman-Bamber and McGlinchey (2003), Lee et al. (2004), Teixeira et al. (Teixeira et al. 2007, 2008b), and Savage et al. (2009). Other advantage of the BR method over EC measurements is its ease of use, as the simple theoretical basis requires relatively modest instruments. The BR fluxes are obtained, however, from indirect measurements, and the high degree of turbulent mixing over sparse crops promotes small temperature and humidity gradients demanding high measurements resolution and accuracy. Another important disadvantage is that the uncertainties of R_n and G measurements are propagated into the BR method.

The assumption of the similarity for the diffusion coefficients for heat (K_h) and vapour (K_v) is implicitly imbedded in the BR technology. An earlier study from Denmead and McIlroy (1970) showed that the assumption of $K_h = K_v$ is acceptable for neutral to moderately unstable conditions over smooth surfaces; however, Verma et al. (1978) reported data evidencing $K_h > K_v$ for stable conditions. At night or under advective conditions, the negative values for Bowen ratio promote large relative error in the energy fluxes resulting in inaccuracies of ET values. In addition, the BR technique is not suitable for dry areas, and the simplified energy balance equation, frequently used, states that R_n is redistributed over H_{BR}, λE_{BR} and G, considering only vertical fluxes, ignoring the net rate at which energy is being transferred horizontally by advection and the heat stored or released in the canopies. These terms can be significant near the edges of tall trees, mainly in irrigated crops in semi-arid regions (Teixeira 2009).

According to Tanaka et al. (2008), estimation errors in energy balance components due to fetch problem or footprint discrepancy have been reduced with the advances in diagnostic procedures and technology. The measurements are usually done at one location that must be sufficiently downwind of any significant changes in the surface characteristics to allow development of the internal boundary layer to a depth greater than the top measurement height and to smooth out the effect of local surface heterogeneity. More essential sources of error might be the large-scale atmosphere mixing due to the night-time flux drainage and the daytime turbulent organized structure, although night-time drainage being less important because of the small input of R_n. During the night, as the air temperature and vapour pressure gradients are small, it is expected that larger errors occur when using BR systems than for daytime periods.

Alternative ways to force the energy balance closure in EC measurements have been studied in this paper with additional measurements of R_n and G: the residual (RES); the combination (EC_BR); and the regression (REG) methods. In the case of RES method, λE is obtained as a residual in the energy balance equation after measuring directly H (Simmons et al. 2007; Castellvi et al. 2008). The advantage of the RES method is that λE_{RES} can be obtained without expensive instrumentation for water vapour measurements, such as the application of the surface renewal method (Castellvi et al. 2008). By using the EC_BR method, after the EC measurements of λE and H, the first energy flux is recomputed by the Bowen ratio of the fluxes (Twine et al. 2000; Chehbouni et al. 2006). The REG method—to our knowledge first introduced by Allen (2008)—is based on a regression equation between R_n and the other energy balance terms providing weighting for each energy balance component.

One EC and one BR systems were set up to measure the energy fluxes in a micro-sprinkler-irrigated mango orchard in the Brazilian North-east. Growing of irrigated fruit crops in the semi-arid conditions of this region is important for the livelihoods of rural communities where water resources are strained. This paper compares five different energy balance interpretation and measurements, and the overall accuracy of the measured and estimated ET fluxes is investigated for different rainfall conditions. The performances of EC and BR techniques are evaluated, and the reasons for the lack of energy balance closure in the EC system and adjustments are discussed. The effects of forcing the latent and sensible heat fluxes from the EC system to match the available energy are examined. It is demonstrated that ET fluxes from the different methods and measurements are associated with considerable uncertainty.

Materials and methods

Measurement site and orchard conditions

A field measurement campaign was carried out from 2003 to 2005 in a mango orchard located in the semi-arid region of the Pernambuco State, Brazil, in Petrolina city (09°22′S, 40°34′W). The area at 370 m above the sea level has an average value for the total annual precipitation (P) and pan evaporation of 570 and 2,700 mm, respectively, at a mean air temperature (T_a) of 26.5°C. The warmest month is November (average T_a of 28.2°C) when the sun is in the zenith position at low cloud cover conditions. The coldest month is July (average T_a of 24.2°C) at winter solstice in the southern hemisphere. Despite the relatively small thermal annual amplitude, due to the proximity of the equator, the increase in T_a together with higher levels of global solar radiation (R_G) during the hottest periods of the year affects crop ET. The annual thermal homogeneity strongly contrasts with the spatial and temporal heterogeneity of the rainfall regime. The rainy period is concentrated from January to April, representing 68% of the annual amount, with water deficits in the climatic water balance along the year (Teixeira 2009).

The mango cultivar is *Tommy Atkins*, 18 years old in 2003, with the trees spaced in a regular square pattern of 10 m × 10 m. The trees presented an average height of 5.5 m, a mean leaf area index (LAI) of 5.6 and were pruned to a pyramidal and erect canopy, over an area of 11.92 ha bordered on all sides by other mango crops with similar height that matches fetch requirements. The mango trees undergone vegetative growth between November and January, followed by branch maturation from January to May, flowering from May to July, with fruit initiation between June and July. Fruit growth occurred from July to August, maturing during August and September being harvested between September and October. The sandy soil is classified as Latossoil Red-Yellow with low water retention capacity, with the groundwater depth approximately 2.5 m, and the farm is located 5,500 m away from the banks of the São Francisco River (Teixeira et al. 2008a).

The orchard was daily micro-sprinkler-irrigated with one in-line micro-sprinkler between two trees on the ground and a discharge rate of 44 l h^{-1}, which wetted 70% of the soil surface. The irrigation water requirements were calculated based on reference evapotranspiration and crop coefficients yielding to seasonal totals of 675 and 1,195 mm (1.7 and 3.2 mm d^{-1}) during the first and second growing seasons, respectively. The differences in water applications were due to different rainfall amounts for the growing seasons. The study comprised two growing seasons including the previous post-harvest stage. The duration of the first period was 390 days, from 01 October 2003 (Day 274) to 24 October 2004 (Day 298). The measurements continued into a second period of 370 days, from 25 November 2004 (Day 299) to 29 November 2005 (Day 302).

Orchard energy balance

The sensors were installed at the centre of the study plot. All energy balance components were measured. Both EC and BR systems were used simultaneously (Fig. 1).

The EC system used determines the sensible (H_{EC}) and latent (λE_{EC}) heat fluxes by a three-axis sonic anemometer (Model CSAT3, Campbell Scientific, Logan, UT, USA) and a krypton hygrometer (Model KH20, Campbell Scientific, Logan, UT, USA), respectively, both connected to a datalogger (model CR10X, Campbell Scientific, Logan, UT, USA). The EC sensors were installed at a height of 8.5 m from the ground above the crowns of a row of trees, with a horizontal separation of 0.15 m and a sampling frequency of 16 Hz. The fluxes were computed for 30 min periods and later summed to give daily totals.

For the BR method, the gradients of air temperature and vapour pressure were calculated using wet and dry

Fig. 1 Energy balance measurement systems in mango orchard, Petrolina-PE, Brazil

thermocouples of copper/constantan at 1.0 and 3.0 m above the canopy positioned to the predominant south-west wind directions (Fig. 1). R_n was acquired with one net radiometer (model NR-Lite, Kipp & Zonnen, Delft, The Netherlands) above a row of trees at a height of 7.5 m. Previous experiments with fruit crops have shown that no big differences arise by using one sensor or two above and between rows for determination of R_n in row crops (Teixeira et al. 2007). G was measured by two soil heat flux plates (model NR-Lite, Kipp & Zonnen, Delft, The Netherlands) at 2 cm soil depth and below the projected tree crown at 100 cm from the trunk. The plates were buried at the west and east sides of a row of trees, and the values of G were taken as the average of the two measurements, being not corrected for the heat storage above the plates. Heusinkveld et al. (2004) have shown that when the flux plates are close to the surface, corrections for heat storage are not necessary. Additional routine measurements of R_G, T_a, P, relative humidity (RH) and wind speed (u) were also done over grass by an agro-meteorological station located 500 m from the orchard.

R_n, G and T_a in the experimental plot were measured at each 5-s interval, and averages of 10 min were stored in a datalogger (model CR10X, Campbell Scientific, Logan, UT, USA) equipped with a multiplexer (model AM416, Campbell Scientific, Logan, UT).

The energy fluxes can be expressed by the simplified energy balance equation:

$$R_n - \lambda E - G - H = 0 \quad (1)$$

where all terms of Eq. 1 can be in W m^{-2} or MJ m^{-2} d^{-1} being either positive or negative. Positive R_n means energy flux to the surface and positive G, λE and H indicate fluxes of energy from the surface.

Using data from the EC system, the latent (λE_{EC}) and sensible (H_{EC}) heat fluxes were calculated, respectively, by the following equations:

$$\lambda E_{EC} = \lambda \overline{w' \rho'_v} \quad (2)$$

$$H_{EC} = \rho_a c_p \overline{w' T'_a} \quad (3)$$

where λE_{EC} and H_{EC} are in W m^{-2}, λ is the vaporization latent heat (J kg^{-1}), w' is the instantaneous deviation of vertical wind speed in relation to mean value (m s^{-1}), ρ_v' is the instantaneous deviation of water vapour density in relation to the mean value (kg m^{-3}), 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 T_a' is the instantaneous deviation of air temperature in relation to mean value (°C). The quantities $\overline{w' T'_a}$ and $\overline{w' \rho'_v}$ are the covariances between the vertical wind speed and air temperature and the vertical wind speed and water vapour density, respectively. The bars indicate averages (Stull 1998).

A number of corrections to EC data have been proposed in literature. For this research, the ECPack from Wageningen University was applied (van Dijk et al. 2004a, b), which includes the following corrections:

1. Coordinate rotation of the 3D sonic wind speed vectors. Covariance is rotated to a natural coordinate system to partially consider the assumption that the measurements represent the flux perpendicular to the surface out of a nominal control volume defined at its top by the sensor and neglecting horizontal divergence so that the system becomes one-dimensional. The planar fit method is applied by the software (Wilczak et al. 2001).
2. Corrections due to density variations introduced by fluctuations of temperature and moisture content of air in updrafts and downdrafts which create spurious fluxes when air is measured volumetrically (Webb et al. 1980).
3. Oxygen absorption. Krypton hygrometers are used to measure the water vapour content of the air by absorption of H_2O molecules in the ultraviolet spectrum. Due to the used wave length, there is a cross-sensitivity to O_2 molecules, which is corrected (Tanner et al. 1993).
4. Frequency losses. The turbulent flux density can be measured using eddy correlation, provided that fluctuations in the frequency range in which turbulent transport takes place are all sensed. In practice, this condition is hardly met due to a limited frequency response of the sensors and the data acquisition system; averaging over a path rather than taking a point value; separation between sensors for different quantities; and filtering applied. For each of these effects, a theoretical co-spectral transfer function is computed (Moore 1986).

The latent heat flux according to the BR method (λE_{BR}) was calculated as follows:

$$\lambda E_{BR} = \frac{R_n - G}{1 + \beta} \qquad (4)$$

The related sensible heat flux in the BR method (H_{BR}) was computed as:

$$H_{BR} = \frac{R_n - G}{1 + 1/\beta} \qquad (5)$$

where λE_{BR}, H_{BR}, R_n and G are in W m^{-2}, and assuming that the eddy diffusivities for heat (K_H) and water vapour (K_v) are equal, β, the Bowen ratio, can be expressed as:

$$\beta = \gamma\left(\frac{\Delta T}{\Delta e}\right) \qquad (6)$$

and γ is the psychometric constant (kPa °C^{-1}), ΔT (°C) the vertical temperature gradient measured by the dry thermocouples and Δe (kPa) is the vertical water vapour pressure gradient measured by the difference between dry and wet thermocouples over the height interval above the canopy surface.

In addition to these 'standard' measurements, two forcing energy balance closure methods were employed to estimate the latent heat flux from EC data: the residual (λE_{RES}) and the combination (λE_{EC_BR}) methods:

$$\lambda E_{RES} = R_n - H_{EC} - G \qquad (7)$$

$$\lambda E_{EC\_BR} = \frac{R_n - G}{1 + \beta_{EC}}; \quad \beta_{EC} = \frac{H_{EC}}{\lambda E_{EC}} \qquad (8)$$

where all energy fluxes are in W m^{-2}.

The daily actual evapotranspiration ET_{24} (mm d^{-1}) was obtained from the 24-h average latent heat flux λE_{24} (W m^{-2}), the latent heat of vaporization λ (J kg^{-1}) and the density of water ρ_w (kg m^{-3}), throughout the different methods:

$$ET_{24} = 8.64 \times 10^7 \frac{\lambda E_{24}}{\lambda \rho_w} \qquad (9)$$

Quality control for the energy balance data

The deviation of BR, RES and EC_BR results from direct EC measurements can be ascribed to inaccuracies in R_n and G data. In irrigated areas under semi-arid conditions, R_n is most likely to be accurate. G measurements can affect considerably the energy balance for short timescale but do not influence λE values in direct EC measurements.

Missing EC-based λE data from the krypton hygrometer and missing BR-based λE data from instrumental problems and small temperature gradients during the rainy periods were filled by the relationship between ($H_{EC} + \lambda E_{EC}$) and the available energy ($R_n + G$) for the lack of λE_{EC} measurements and by the relation of λE_{BR} with ($R_n + G$) to fill λE_{BR} data gaps (Teixeira et al. 2008a). Footprint models were not necessary because the energy fluxes at 8.5 m elevation were surrounded by more than 850 m of homogenously irrigated mango plantations in all directions (i.e. 1:100 rule applies), as the plot of 11.92 ha was in the centre of a big commercial farm with 140 ha of mango orchards and with a predominant south-east wind direction, there was an upwind fetch of about 1.5 km. After gap filling, the complete energy balances for the entire growing seasons could be derived.

Many research tried to explain and solve the problem of the lack of energy balance closure in EC systems. Wilson et al. (2002) summarized results from 22 flux sites of measurements and indicated a general lack at most of the sites, with a mean imbalance of about 20%. This problem was also reported by Twine et al. (2000), Paço et al. (2006) and Testi et al. (2006), which can be associated with inaccurate measurements of R_n and G, but not completely explained by these inaccuracies, because EC systems have their own sources of error (Twine et al. 2000). Following Allen (2008), the lack of the closure in EC data can be solved by using a simple regression method that accounts for all sources of errors, assuming that R_n is the most accurate energy balance component in the semi-arid conditions. This approach does not favour one particular method and contains less assumptions; it just creates a correction on the basis of the best fit of independently collected field data:

$$R_n = c_0 + c_1 G + c_2 \lambda E_{EC} + c_3 H_{EC} \quad (10)$$

Equation 10 (all components in W m^{-2}) was applied to half-hour EC data with specific coefficients for daytimes and night-times, being an attractive solution based on the best statistical agreements of all fluxes, which ensures the energy balance closure providing unequal weighting of different measurements, depending on the variable uncertainty of each energy flux term.

Results and discussion

Weather conditions

Figure 2 shows the daily averaged weather variables during the two growing seasons of the mango orchard studied. The routine data collected by an automatic agro-meteorological station include R_G, T_a and relative humidity (RH), and wind speed (u) above an irrigated grass surface for the reference evapotranspiration (ET_0) calculations.

The first growing season—GS1—with an average R_G of 21.8 MJ m^{-2} d^{-1}, presented higher atmospheric demand than the second one—GS2 (20.2 MJ m^{-2} d^{-1}). Although GS1 was wetter than GS2, R_G was larger outside the rainy period for the first growing season than for the second.

The mean 24 h T_a reached its maximum value from October to December at approximately 29.5°C. Minimum values occurred during June–July (around 22.5°C). The values for vapour pressure deficit (D) calculated for each half hour, and averaged for 24 h, presented the same temporal behaviour as T_a throughout the growing seasons.

Average values of u at 3 m above the grass field at the agro-meteorological station were highest from July to November (around 3.6 m s^{-1}) and lowest from January to April (around 0.8 m s^{-1}) for both growing seasons. The u values from the sonic anemometer over the mango orchard were 12% greater than over grass due to the aerodynamic properties of the tall mango trees.

Precipitation in the region is concentrated in the period from January to April with a long-term annual value of 570 mm. The year 2004 was, however, unusually wet. The accumulated rainfall from October 2003 to October 2004 was 887 mm, while from November 2004 to November 2005, it was only 380 mm.

Energy balance closure

The closure of the EC system measurements was analysed for the two growing seasons of the mango orchard at a daily timescale (Fig. 3). At this timescale analyses, the errors in G measurements due to the variation in soil

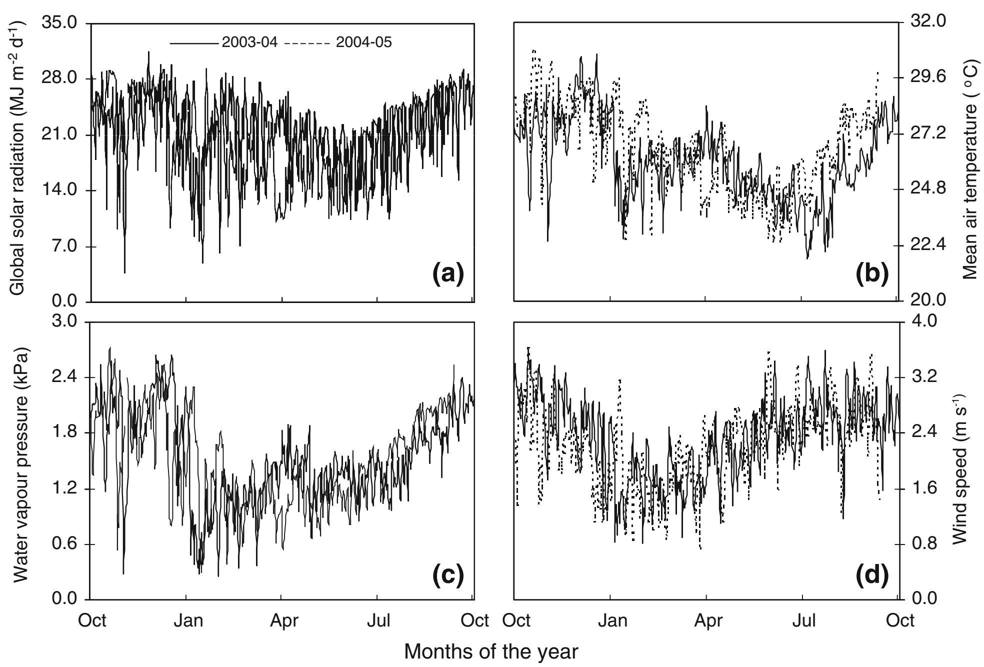

Fig. 2 Daily values of weather variables during the study period 2003 to 2005: **a** global solar radiation—R_G, **b** mean air temperature—T_a; **c** water vapour pressure—D, **d** wind speed—u

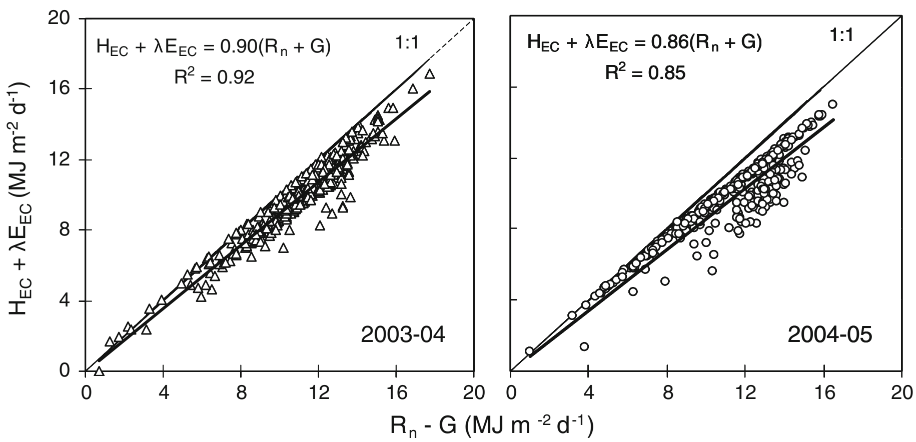

Fig. 3 Relationship between latent (λE_{EC}) plus sensible (H_{EC}) heat fluxes from the eddy correlation system and the available energy ($R_n - G$) at daily timescales (24 h): first growing season (2003–2004); second growing season (2004–2005)

moisture and shadows of the canopy are reduced. The ratio of turbulent energy fluxes to the available energy was 88% on average, with a root mean square error (RMSE) of 1.7 MJ m^{-2} d^{-1}, which is close to the lower limit of the range of 10–30% commonly found in the literature. As a first guess, either H_{EC} or λE_{EC} (or a combination of them) could not be so reliable, because the EC measurements reflect errors from the system itself, mainly caused by rain; however, uncertainties also arise on R_n and G measurements. Another aspect is that the energy storage in the canopies was not accounted in the available energy, which can be a source of error in mango tress which present large amount of branches and leaves. Depending on the time scales, the positive and negative values during days and nights of the energy fluxes can also influence these errors, making it important to analyse the effect of different methods of measurements and interpretation on these variations.

Comparison of methods and data quality

The sensible heat fluxes as obtained from the EC measurements and BR method were firstly compared. The relation for half-hour values involving all periods of the day during the two growing seasons of the mango orchard is shown in Fig. 4. The agreement was moderately good for both seasons, with general lower values for the BR method, but a considerable scatter is noticed. Lower scatter was observed in Fig. 3, and as a first guess, it is therefore likely that the BR measurements could be less reliable.

Considering both growing seasons, half-hour H_{EC} values were 25% higher than those for H_{BR}. An underestimation of H_{BR} could be ascribed to inaccuracies in R_n and/or G measurements, however, as the sonic anemometer is also not free of errors; an overmeasurement of H_{EC} could also be possible, mainly in conditions of high wind speed which by advection brings the hotter air from the dry areas at the vicinities of the mango orchards. On the other hand, the closure ratio, being 0.88 on average, can suggest that H_{EC} could be higher to meet the available energy, which reinforces a possible systematic underestimation in H_{BR} values, mainly for the first growing season due to more dense cloud cover and rainfall inducing lower temperature gradients. For the drier second growing season, it is evident that the scatter of the sensible heat fluxes from EC and BR systems' relation is larger for the higher values, which

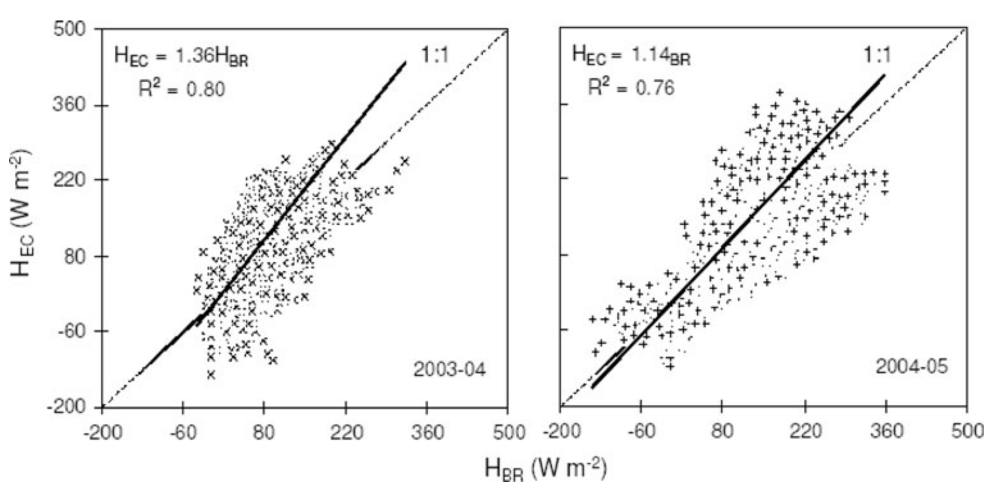

Fig. 4 Comparison between the values of sensible heat fluxes obtained by the eddy correlation system (H_{EC}) and those from the Bowen ratio method (*BR*): first growing season (2003–2004); second growing season (2004–2005)

occur during daytime periods. As different errors exist according to the time of the day, the diurnal behaviour was also analysed. Figure 5 shows the variation of H_{EC} and H_{BR} during different times of the day; half-hour averaged values over the first and the second growing seasons of the mango orchard were used.

Figure 5 confirms the highest differences between the two systems around midday. The accuracy of BR method increases with more developed gradients ΔT and Δe, which occurred during the drier and hotter conditions. During rainfall periods, ΔT is difficult to measure and β becomes more uncertain. While for the second growing season, the values of H_{BR} represented 73% of H_{EC}, in the first one, H_{BR} accounted for 63% of H_{EC}. The lower differences between methods occur between 07.00 and 09.00 h in the morning and 15.00–17.00 h in the afternoon, situations when the surface is, respectively, receiving and releasing solar energy. One reason for the less negative H_{BR} values during the night could be situations of $K_h > K_v$ for stable and advective conditions, making the assumption of similarity between these coefficients to deviate (Verma et al. 1978).

Figure 6 shows that the agreement of latent heat fluxes between EC measurements and BR method was more satisfactory than for sensible heat fluxes, even with an EC undermeasurement of 20% in relation to BR method. The BR values were higher than those for EC measurements due to the complementary relationship between H_{BR} and λE_{BR}, with the correlation between the two techniques ($R^2 = 0.95$) being substantially higher than for the sensible heat flux ($R^2 = 0.78$). Since both λE_{BR} and H_{BR} are based on β that close the energy balance, there is the possibility that H_{EC} could be overmeasured and λE_{EC} undermeasured. The high correlation between λE_{BR} and λE_{EC} suggests, however, that λE_{EC} is less wrong than H_{EC}, and it could possibly pinpoint that H_{EC} is one of the uncertain parameters. As for the sensible heat fluxes, different errors in the EC and BR systems for the latent heat flux measurements arise according to the time of the day, being evidenced by the largest distances from the line 1:1 for the higher values of the relation depicted in Fig. 6.

The diurnal behaviours of λE_{EC} and λE_{BR} are shown in Fig. 7. Half-hour averaged values over the first and the second growing seasons of the mango orchard were used. It is confirmed that λE_{EC} values agree very well with λE_{BR} values and that the largest differences occur during midday, when λE_{BR} is 35% greater than λE_{EC}. As the temperature and vapour pressure gradients used for β calculations (see Eq. 6) are most strongly developed during noon, this is somewhat unexpected as this parameter can be measured with more accuracy than during the early morning or late afternoon. An overestimation of λE_{BR} at noon could be in part a consequence of advective effects at this time of the day under well-irrigated conditions in a semi-arid region. As for the sensible heat fluxes, the lowest differences occurred between 07.00 and 09.00 h in the morning and 15.00–17.00 h in the afternoon. λE_{BR} was 24 and 22% higher than λE_{EC}, respectively, for the first and second growing seasons. Seasonal differences are mainly due to the fact that in the BR method, the closure of the energy balance is forced in addition to the assumption of the similarity between sensible and latent heat turbulent diffusion coefficients in the energy balance equations.

Dugas et al. (1991) comparing four BR systems and three EC systems in an irrigated wheat field in Arizona (USA) founded H_{EC} values being 82 and 69% of H_{BR}, during 2 days of measurements, respectively, while λE_{EC} values were 77 and 67% of λE_{BR}. The differences in their latent heat flux measurements were comparable with our results for the irrigated mango orchard, although the inverse situation occurred for the sensible heat flux values, supporting a possible overestimation of our H_{EC} measurements.

In the case of using the RES method for forcing the energy balance closure, the sensible heat fluxes were acquired with the sonic anemometer together with additional measurements of R_n and G. λE_{RES} was then obtained as a residual in the energy balance (see Eq. 7). Figure 8

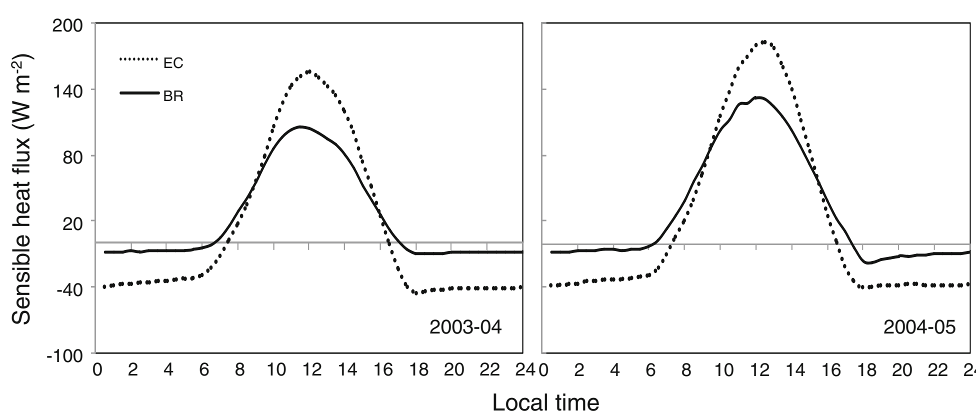

Fig. 5 Diurnal trend for the sensible heat flux during the first (2003–2004) and the second (2004–2005) growing seasons for the mango orchard. Averaged half-hour values for the eddy correlation (*EC*) and the Bowen ratio (*BR*) systems were used

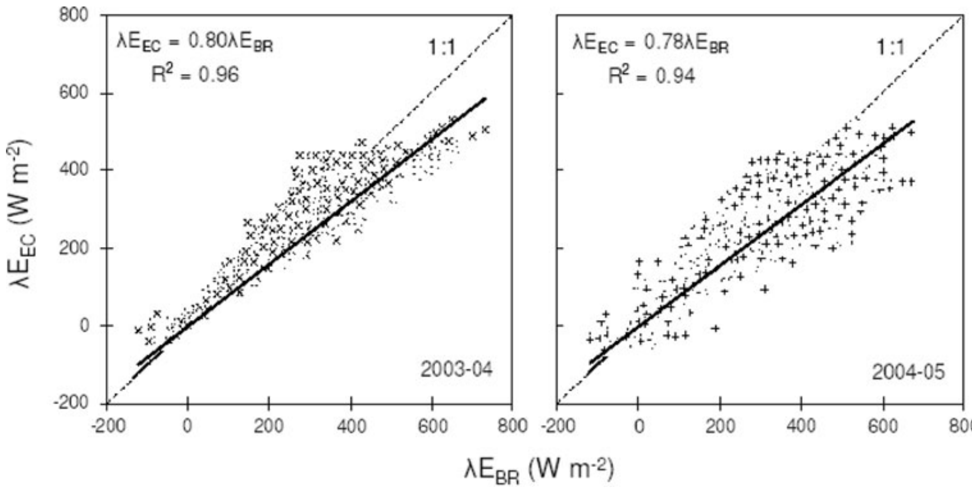

Fig. 6 Comparison between values of latent heat fluxes obtained by eddy correlation measurements (λE_{EC}) with those from Bowen ratio method (λE_{BR}): first growing season (2003–2004); second growing season (2004–2005). Half hourly values are depicted

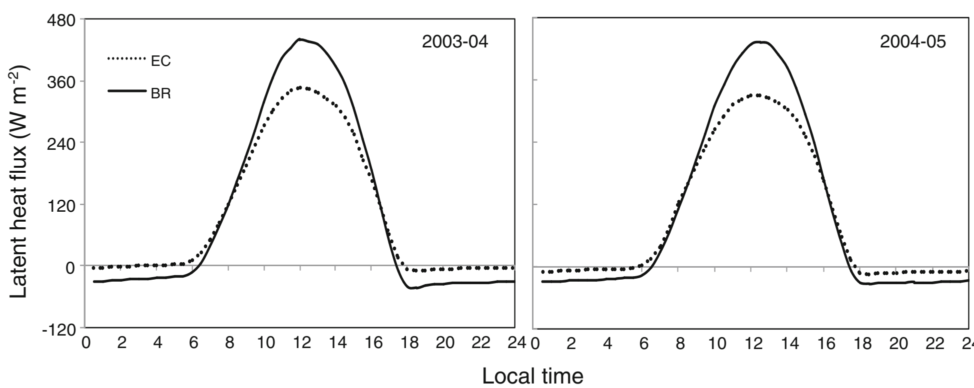

Fig. 7 Diurnal trend for the latent heat flux during the first (2003–2004) and the second (2004–2005) growing seasons for the mango orchard: Averaged half-hour values for the eddy correlation (*EC*) and the Bowen ratio (*BR*) measurements are depicted

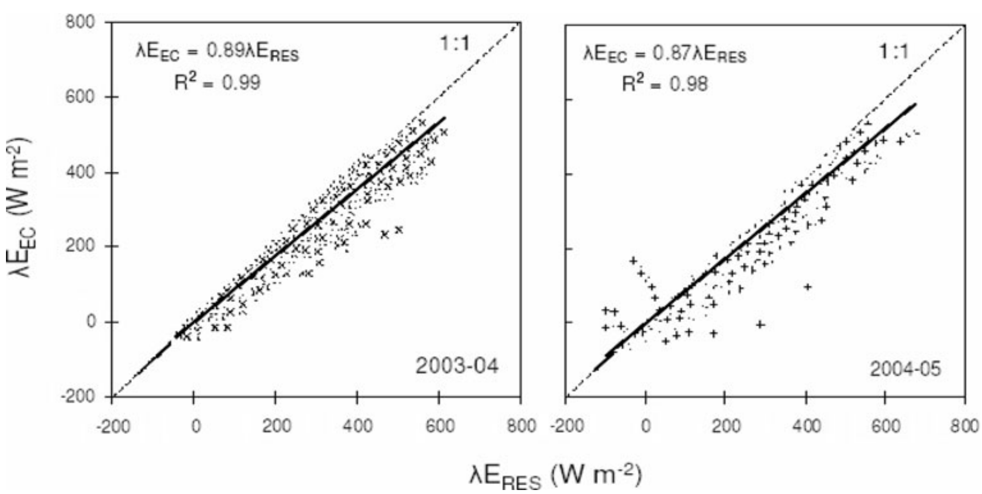

Fig. 8 Comparison between the values of latent heat fluxes obtained by the eddy correlation measurements (λE_{EC}) with those from residual method (λE_{RES}): first growing season (2003–2004); second growing season (2004–2005). Half hourly values are depicted

shows the results of the relationship for λE_{EC} and λE_{RES} values taking half hour measurements, which presented lower scatter than for BR method. In agreement with the lack of the energy balance closure in the EC system, the λE_{EC} represented around 88% of λE_{RES} which could be an indication of an overestimation of λE_{RES} or an undermeasurement of λE_{EC}. Whatever is right, this evidences the fact that both BR and RES methods, closing the energy balance, provide an uncertainty of more than 10% in the final ET measurements. Simmons et al. (2007), using EC measurements and the RES method over a flood-irrigated pecan orchard during two growing seasons in New Mexico, reported that for the daily values there was an undermeasurement of λE_{EC} within 8% for both growing seasons. In their study, the method presented fewer problems in *G* accuracy at short timescale, because if the surface is flooded, the spatial distribution of this energy balance component is more homogeneous.

Earlier and actual results for BR and RES methods are somewhat disappointing if these field values are to be used to validate soil water balance models or remote sensing algorithms. The uncertainties of R_n and G are propagated into both methods. Even G accounting only for 10–30% of R_n, the hole of G fluxes in the closure problem has been attempted for the surface energy balance in vegetated and not vegetated surfaces (Heilman et al. 1994; Heusinkveld et al. 2004). The advantage of using these methods is that λE_{BR} and λE_{RES} can be obtained without expensive instrumentation. An example of application of the RES method in a cheap way is by using the surface renewal method to measure the sensible heat flux (Castellvi et al. 2008).

The EC_BR combination approach applying the Eq. 8 was also compared with direct EC measurements. The method recomputes the latent heat fluxes from EC system by using the ratio $H_{EC}/\lambda E_{EC}$ and the measured available energy (Twine et al. 2000). Figure 9 shows the relation between the latent heat fluxes obtained by EC measurements and by the EC_BR method. The results of the λE_{EC_BR} and λE_{RES} are comparable. Chehbouni et al. (2006) also used this EC_BR method over irrigated wheat in the Yaqui Valley in Northwest Mexico. While the lack of energy balance closure could undermeasure λE_{EC}, it is believed that forcing the closure by this combination method (EC_BR), this undermeasurement should be corrected (e.g. Hoedjes et al. 2002). However, the EC_BR method again brings the uncertainties of R_n and G as the BR and RES methods, being not necessarily better, unless independent water balance estimates confirm this. In addition, the advantages of direct measurements of EC systems are incorporated into this combination method.

The methods discussed before have uncertainties in all measurements, and no overriding argument can be found for favouring a certain solution. A final method was applied to solve the lack of energy balance closure in the EC system and to assess the data quality, by means of a curve fitting involving all energy balance components (Allen 2008). Equation 10 was applied to half-hour periods by using: (1) all data, (2) daytime data only and (3) night-time data only. Systematic corrections were identified for the two growing seasons of the mango orchard (Table 1).

The regression coefficients (R^2) were highest for all data included, averaging 0.97 when used in association with an offset c_0, even though for night-time periods the R^2 being 0.65 for the second growing season. The high regression coefficients for all data included can be attributed to the large extremes and variations in the combined data set that strongly reduced the root mean square error (RMSE) in relation to the situations when only daytime or night-time data were used.

In both growing seasons, H_{EC} appeared to be undermeasured during the day and overmeasured during the night, which supports an underestimation of H_{BR} during daytime periods in Fig. 5. λE_{EC} was overmeasured during the daytime periods, which supports an overestimation of λE_{BR} in Fig. 7 for this time of the day. For the growing season of 2003–2004, the differences between the corrected and uncorrected values of latent and sensible heat fluxes were larger than those for the growing season of 2004–2005 as a result of the unusual rains during 2004 which affected both the sonic anemometer and the krypton hygrometer measurements. G was highly undermeasured during all periods of the day, although the correction coefficients were much higher for daytime periods. This was expected as the soil heat plates were buried near the irrigation system, because they could not be installed between the rows due to the path of machines. The very low measured G values are attributed to the high soil moisture levels near the micro-sprinklers and the shadowing effects of the mango trees during daytime periods promoting high thermal soil conductivity.

Taking all periods of the day and the average conditions for the two growing seasons, half-hourly λE_{EC} was

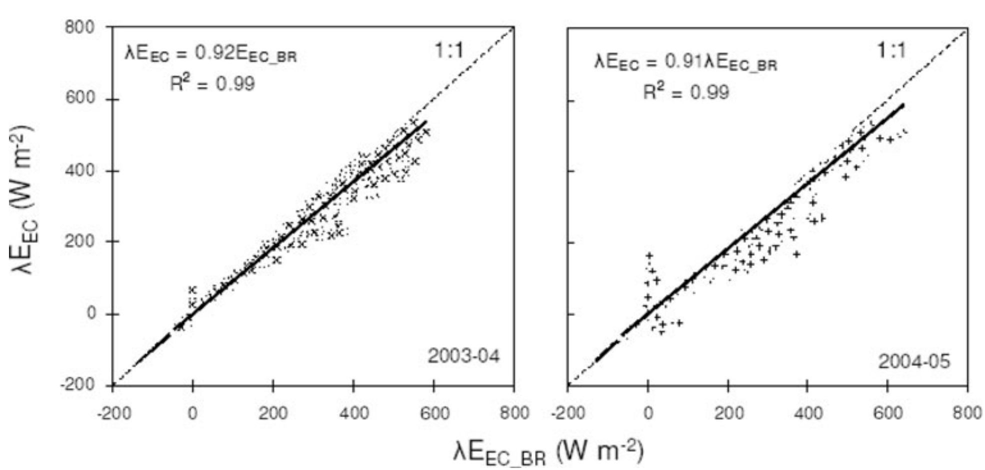

Fig. 9 Comparison between the latent heat fluxes obtained by the eddy correlation measurements (λE_{EC}) with those from the combination method (λE_{EC_BR}): first growing season—(2003–2004); second growing season (2004–2005). Half hourly values are depicted

Table 1 Energy balance regression coefficients for 30-min energy balance measurements over mango orchard at Petrolina-PE, Brazil, during the growing seasons of 2003–2004 and 2004–2005

Data	c_0 (W m^{-2})	c_1 (G)	c_2 (λE)	c_3 (H)	R^2	RMSE (W m^{-2})
2003–2004						
All	–	4.25	0.71	1.47	0.93	37.1
Daytime	–	5.01	0.64	1.48	0.86	53.6
Night-time	–	1.54	1.08	0.67	0.80	2.4
All	54.9	4.00	0.67	1.38	0.98	13.3
Daytime	76.9	6.54	0.54	1.25	0.90	69.4
Night-time	−11.8	1.22	0.86	0.53	0.81	2.1
2004–2005						
All	–	5.06	0.93	0.87	0.93	25.2
Daytime	–	5.21	0.73	1.40	0.91	36.0
Night-time	–	1.54	0.88	0.58	0.46	4.8
All	40.2	4.80	0.88	0.82	0.96	14.9
Daytime	61.4	4.58	0.64	1.23	0.93	35.1
Night-time	−17.4	1.05	0.60	0.40	0.65	3.7

overmeasured by 18%, H_{EC} was undermeasured by 17%, and G measurements required the biggest correction of 466%. Although the intercept c_0 for daytime periods was large (average of 69 W m^{-2}), a small improvement in R^2 was achieved with its use. The REG method was then applied to the energy balance components for the first and second growing seasons of the mango orchard at 30-min intervals with only the coefficients c_1, c_2 and c_3 from Table 1 for daytime and night-time separately.

As the biggest discrepancy was from G values, an analysis for the diurnal behaviour of this energy balance component is provided by using half-hour averaged values over the first (2003–2004) and the second (2004–2005) growing seasons of mango orchard (Fig. 10). It can be seen from Fig. 10 and Table 1 that both G values and corrections coefficients were lower for the rainier growing season than those for the drier one during the daytime periods. The reason is that the rain kept G more homogeneous with a higher thermal conductivity during the first growing season. Considering all periods of the day and both growing seasons, the averaged correction coefficient of 4.66 is too high because of the absence of measurements between rows, showing the importance of the REG method for short timescales, which considers all energy balance components to force the closure in situations of difficult reliable G measurements, as for sparse irrigated crops. The effect of the shadow of the trees is evident by the lower values around midday with midmorning and midafternoon peaks, mainly during the drier conditions of 2004–2005 (Heilman et al. 1994, 1996; Teixeira et al. 2007).

Despite the biggest correction for the half-hour G values in relation to the other energy balance components, the effect of these measurement errors in the available energy (AE $= R_n - G$) is low (Fig. 11). The small differences in AE are due to that G accounted only for a small portion of R_n (Heusinkveld et al. 2004). When taking daily values, which are considered for irrigation management, G tends to zero and the correction becomes irrelevant at this timescale. After applying the corrections for G, considering the coefficients for day- and night-times from Table 1 separately, the corrected values of AE represented 93% of the uncorrected ones. Hence, measurement errors in G were not the main reason for the lack in the daily energy balance closure of the EC system.

Seasonal variations of the averaged daily values of net radiation and latent heat fluxes from the different measurements and methods used during the two growing seasons of the mango orchard are portrayed in Table 2.

Although the seasonal behaviour of G is not shown in Table 2, the average values of the evaporative fractions (EF $= \lambda E$/AE) (Shuttleworth et al. 1989) ranged from 0.71 to 0.89, among the measurements and methods. The differences in EF between the methods were more modest than those for λE. The mean ΔEF was 0.17 for 2003–2004 and 0.14 for 2004–2005. The reason is the inclusion of AE in the definition of EF, which, according to the Fig. 11, presented small differences between the corrected and uncorrected values, mainly for periods of the day outside the noon time. During an earlier BR energy balance study

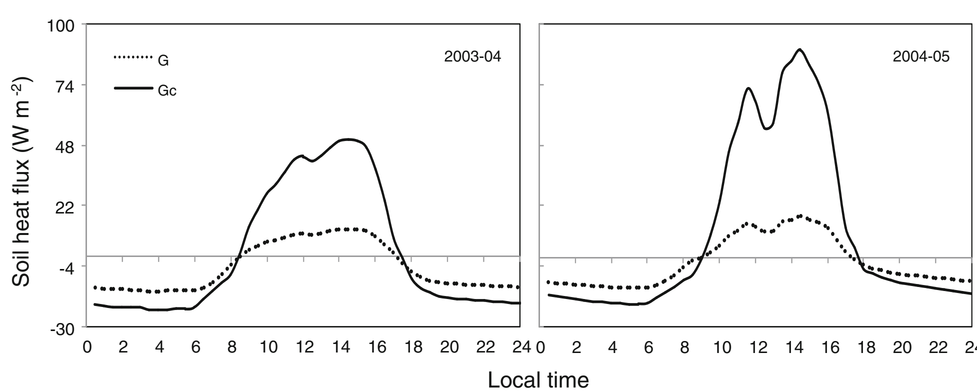

Fig. 10 Diurnal averages for measured (G) and corrected (Gc) soil heat fluxes, during the first (2003–2004) and the second (2004–2005) growing seasons for the mango orchard. Averaged half hour values are depicted

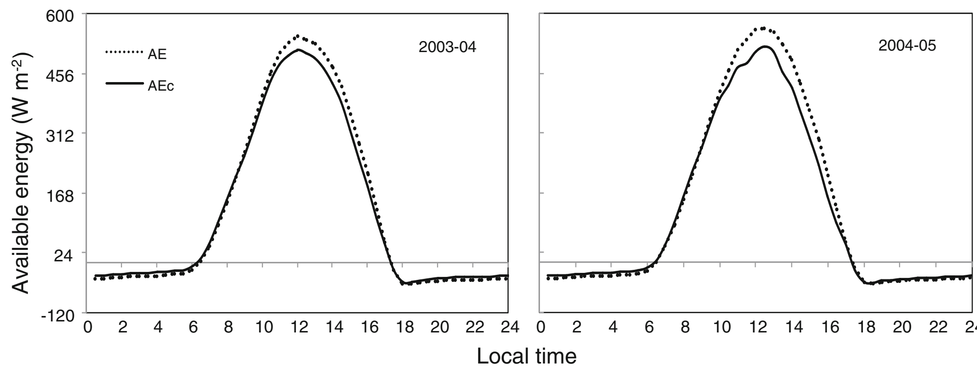

Fig. 11 Diurnal averages for the measured (*AE*) and corrected (*AEc*) available energy, during the first (2003–2004) and the second (2004–2005) growing seasons for the mango orchard. Averaged half hour values are depicted

Table 2 Daily averages of net radiation (R_n) and latent heat fluxes (λE) in a mango orchard, using different measurements and methods

Day/year	R_n (MJ m^{-2} d^{-1})	λE_{EC} (MJ m^{-2} d^{-1})	λE_{BR} (MJ m^{-2} d^{-1})	λE_{RES} (MJ m^{-2} d^{-1})	λE_{EC_BR} (MJ m^{-2} d^{-1})	λE_{REG} (MJ m^{-2} d^{-1})
2003–2004						
303/03	9.66	7.55	7.86	8.92	8.43	5.20
333/03	10.84	8.36	8.96	9.86	9.49	5.90
363/03	10.64	8.19	8.75	9.66	9.13	5.66
028/04	9.73	8.00	8.37	8.36	8.30	5.87
058/04	12.18	9.54	10.90	10.59	10.28	6.94
088/04	11.69	8.92	10.09	10.09	10.15	6.47
118/04	11.96	9.83	10.32	10.63	10.46	7.06
148/04	9.75	8.07	8.33	8.59	8.45	5.75
178/04	8.91	7.51	7.57	8.48	8.09	5.34
208/04	8.70	7.42	6.83	8.21	8.01	5.24
238/04	9.71	7.97	8.26	8.88	8.49	5.63
268/04	11.51	10.12	9.79	11.83	11.19	7.08
298/04	12.21	10.30	10.14	12.73	11.65	7.23
Mean	10.58	8.60	8.94	9.76	9.39	6.11
2004–2005						
327/04	12.47	8.82	9.44	11.92	10.61	8.33
354/04	12.17	8.42	7.87	11.06	10.17	7.95
016/05	11.67	7.76	8.11	9.41	8.71	7.31
044/05	12.13	8.73	9.20	9.78	9.37	8.18
072/05	11.87	8.49	9.15	9.60	9.10	7.94
100/05	12.41	8.74	10.04	9.88	9.43	8.18
128/05	9.04	7.36	7.28	8.08	8.11	6.89
156/05	8.78	7.29	7.15	7.96	7.85	6.83
184/05	8.43	7.16	7.11	7.79	7.67	6.71
212/05	10.03	7.85	7.61	9.23	8.40	7.30
240/05	10.62	7.93	8.34	8.94	8.56	7.45
268/05	12.04	8.45	9.74	9.58	9.14	7.94

Data were collected during the growing seasons of 2003–2004 and 2004–2005

* The subscripts EC, BR, REG, RES and EC_BR mean the eddy correlation, Bowen ratio, regression, residual and the combination of EC and BR methods, respectively

in a mango orchard close to our study site, the EF values were found to be 0.73 in August, 0.86 in September, 0.78 in October and 0.80 during November (Lopes et al. 2001), being inside the range of our actual study.

Figure 12 presents the seasonal behaviour of EF for all methods from 2003 to 2005, involving the two growing seasons of the mango orchard. In general, the EF values remained fairly constant with a standard deviation between

0.03 and 0.07, which is ascribed to a daily micro-sprinkler irrigation water supply. The rainy season concentrates from January to April, and during this period, farmers stop irrigation, thus causing a drop in EF during the maturing phase of the crop growth. The EC measurements were more sensitive than the BR estimates to detect such effects. During the drier second growing season (after the Day/Year 298/2004), the EF curve from the REG method in Fig. 12 became a good representation of the average EF values. It is also evident when comparing Figs. 2 and 12 that the lowest differences in energy partitioning between measurements and methods happened during the driest and coldest conditions of the second growing season (from Day/Year 120/2005 to 270/2005). Testi et al. (2004) studied the variation of EF in a young olive orchard under different water conditions and concluded that the values are influenced by soil moisture, which is also supported by Scott et al. (2003a, b) for irrigation systems in Mexico and Pakistan.

The accumulated ET for the five interpretation and measurements methods studied for the two growing seasons of the mango orchard is summarized in Fig. 13. It can be seen that the RES method produced the highest accumulated values in both growing seasons, followed by the EC_BR method, the BR method, the EC measurements and the REG method, with averages of 1,496 mm (RES), 1,419 mm (EC_BR), 1,362 mm (BR), 1,289 mm (EC) and 1,046 mm (REG), respectively, for the two growing seasons. The accumulated differences between methods and measurements increased progressively towards the harvest dates.

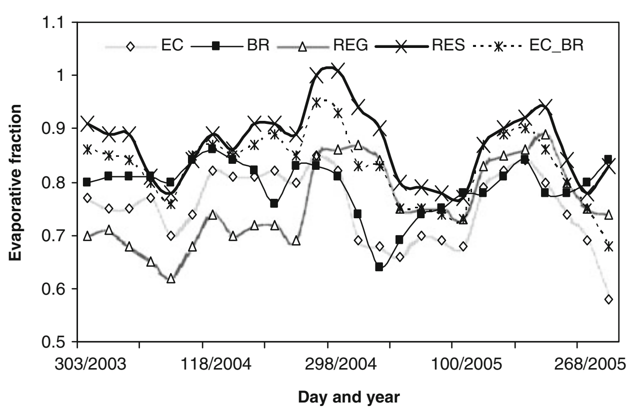

Fig. 12 Evaporative fraction (*EF*) determined by eddy correlation (*EC*) measurements; Bowen ratio (*BR*), regression (*REG*), residual (*RES*) and the combination (*EC_BR*) methods

Table 3 shows the seasonal ET for the five methods and measurements considering the growing seasons of the mango orchard of 2003–2004 (wetter conditions) and 2004–2005 (drier conditions) together with the differences in percentages taking the REG method as a reference.

Considering the higher confidence in the results of the second growing season, it was taken as a reference to analyse the differences in ET obtained from EC measurements and the other methods over large time periods. The REG method is a good choice because it forces a closed energy balance; maximally utilizes highly advanced eddy correlation systems; does not exclude any flux measurement from the optimization process; and adds variable weights to the energy fluxes, which seems acceptable because actual deviations of the fluxes from reality are not known. With these considerations, it is concluded that seasonal ET values obtained by direct EC measurements in mango orchard are around 7% higher than those from the REG method (Table 3). Hence, we believe that λE_{EC} is overestimating the true seasonal ET, despite that λE_{BR}, λE_{RES} and λE_{EC_BR} values were found to be even higher.

Conclusions

The energy balance components of a large commercial mango orchard were analysed at different timescales by applying five interpretation and correction methods. The basic measurements were from eddy correlation (EC) and

Fig. 13 Accumulated actual evapotranspiration of a mango orchard, at Petrolina (*PE*), Brazil, during the growing seasons of 2003–2004 and 2004–2005: eddy correlation technique (*EC*); Bowen ratio method (*BR*); regression method (*REG*); residual method (*RES*); and the combination method (*EC_BR*)

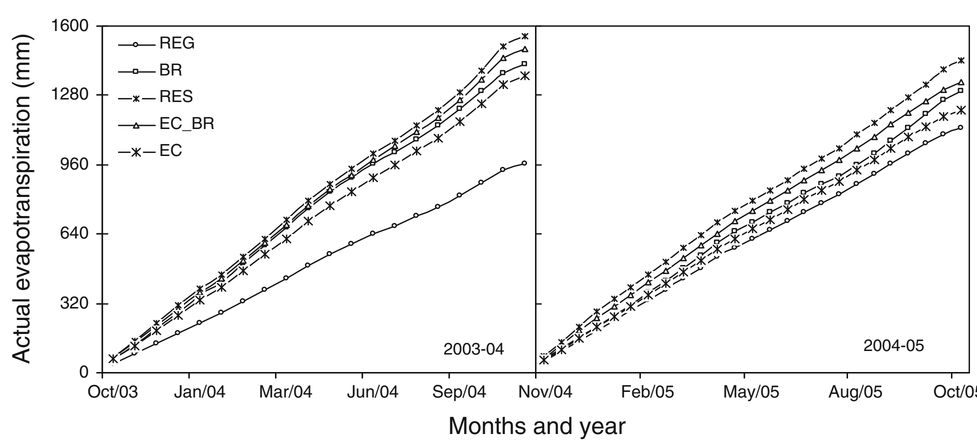

Table 3 Seasonal evapotranspiration (ET) of a mango orchard at Petrolina-PE, Brazil, interpreted from five methods and measurements during the growing seasons of 2003–2004 and 2004–2005

GS/ method	ET_{EC}	ET_{BR}	ET_{REG}	ET_{RES}	ET_{EC_BR}
2003–2004	1,368 mm	1,422 mm	965 mm	1,552 mm	1,495 mm
	142%	147%	100%	161%	155%
2004–2005	1,210 mm	1,302 mm	1,127 mm	1,440 mm	1,343 mm
	107%	116%	100%	128%	119%

GS growing season, *EC, BR* measurements from eddy correlation technique and Bowen ratio method, respectively, *REG, RES, EC_BR* regression, residual and the combination methods, respectively

Bowen ratio (BR) techniques. While EC systems are expensive, BR method is cheaper and the instrumental is easier to operate. The classical BR estimations showed 4 and 15% more seasonal ET compared to the measurements from the EC system for a wetter and a drier growing season, respectively.

The EC system in the irrigated mango orchard showed an energy balance closure gap of 12% at daily timescale. This is low compared to the international literature. Many explanations for this problem exist, and it is reasonable to conclude that the EC system cannot be used as a high reliable way to measure the latent heat flux in irrigated crops without adequate correction procedures. Evapotranspiration research should therefore develop appropriate interpretation and correction procedures. The current paper is a contribution in that respect, and much more research is needed covering different irrigated surfaces.

The four methods, Bowen ratio (BR), residual (RES), combination (EC_BR), and Bowen ratio (BR), showed a reasonable agreement with EC measurements, although the BR method was less sensitive to phenological changes throughout the mango-growing seasons compared to those which uses EC measurements. The simple multiple linear regression method appears to be very helpful in identifying the components of the energy balance that need adjustments to force the energy balance to close, mainly when the soil heat flux is difficult to measure accurately. It is a more elegant solution than the Bowen ratio of EC fluxes that implicitly assumes that sensible and latent heat fluxes measured with an EC system have the same level of confidence and do not consider the accuracy of the other energy balance terms.

Since there is no consensus in the literature on denoting one particular flux term as the source of error, we believe that the REG method is the most unbiased solution. Applying this last method for the drier season of the mango orchard as a reference, the regression coefficients were 0.93, 0.87 and 5.06 for latent, sensible and soil heat fluxes, respectively, considering all periods of the day. This suggests that the latent heat flux from the kripton hygrometer was measured with relatively more accuracy than the sensible heat flux from the sonic anemometer in conditions of low precipitation. While there were sound reasons to move away from lysimeters to turbulent flux measurement systems in the eighties and nineties, this study shows that the perfect method for direct field measurement of the latent heat flux does not exist yet. This should be understood by the irrigation, hydrological, soil physical, crop yield and remote sensing modelling community, because it implies that modelled data of evapotranspiration may be as appropriate as the measured ones for specific purposes.

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