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Assessment of reliability of Bowen ratio method for partitioning fluxes

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Abstract

The errors associated with the Bowen ratio-energy balance (BREB) method are analysed, to determine analytically the reliable values of the Bowen ratio (β) and of the latent and sensible heat fluxes. It is shown that, if advection is considered negligible, the BREB method is able to determine correctly the surface flux partitioning or the flux values when certain conditions, consistent with the flux-gradient relationship, are fulfilled. An analytical method to find the range of β around -1 that produce unacceptable flux calculations of latent and sensible heat is presented. It is based on an error analysis of the Bowen ratio and, rather than being fixed, this excluded region depends on the vapor pressure gradient measured in each averaging period and on the resolution limits of the sensors used.

Keywords: Bowen ratio; Energy balance; Latent heat flux; Vapor pressure gradient; Error analysis

1. Introduction

The partitioning of available energy between sensible and latent heat can usually be obtained by the Bowen ratio-energy balance (BREB) method, based on the flux-profile relationships for energy and mass exchange, to estimate evapotranspiration over vegetated or bare soil. However, in this method the accuracy of the calculated values of latent and sensible heat fluxes depends on the accuracy of the Bowen ratio (β), which in turn depends on the accuracy of the measurements. Consequently, there is a need to analyse the errors associated with this method to know how they may affect the results and to determine simple expressions for parameterizing when the BREB method gives consistent surface flux partitioning.

The errors introduced by the BREB method in the computed energy fluxes values have been already evaluated by several authors (Fuchs and Tanner, 1970; Sinclair et al., 1975; Angus and Watts, 1984; Bertela, 1989). In many other works in which the BREB method is used, to avoid serious errors in the estimation of the fluxes, the data within the instrumental errors of the Bowen ratio system are excluded. For example, the measurements of the gradients less than the resolution of the sensors. For the cases in which the β values are close to -1, some authors eliminate β values lower than -0.75, or values in the range $-1.3 < \beta < -0.7$ (Ortega-Farias et al., 1996; Unland et al., 1996). But that interval should depend on the measurement accuracy of the sensors used.

Since there is a large difference in the energy transfer process between day and night due to availability of energy and atmospheric stability, some authors only consider as reliable data some subsets of the measured gradients or only the averages calculated over the daytime period, excluding missing data corresponding to rainy days or other measurement problems (Ashktorab et al., 1989; Heilman and Brittin, 1989; Cellier et al.,

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1996; Kustas et al., 1996; Unland et al., 1996). However, the subsets of data to be excluded may depend on the climatic characteristics of the sampling site. Generally, in places with arid and semiarid climates and with very limited soil moisture, the vapor pressure gradients during daytime will be smaller and the temperature gradients larger than those of humid areas (Miller, 1977). Another problem occurs when for short periods of less than an hour no reliable data are available; then, missing values of energy fluxes must be interpolated from the preceding and subsequent values, with subsequent uncertainties introduced into the daily values of evapotranspiration.

The situations in which the BREB fails or causes inconsistent results have been analysed (Blad and Rosenberg, 1974; Ohmura, 1982; Angus and Watts, 1984; Bertela, 1989) as well as the relationship between measurement errors and energy fluxes errors (Fuchs and Tanner, 1970; Blad and Rosenberg, 1974; Sinclair et al., 1975). However, a clear procedure for rejecting the fluxes computed depending on the data collected has never been proposed. Hence, there is no practical and general set of criteria for selecting between reliable and unreliable β values, except over saturated surfaces (Philip, 1987; Andreas, 1989; Andreas and Cash, 1996).

For this reason, we decided to look for a practical answer to the problem of evaluating clearly when the BREB method works or fails to determine reliable and correct values of β and of latent (λE) and sensible (H) heat fluxes. The situations in which the method gives consistent surface flux partitioning and the actual uncertainty in β and in the estimations of λE and H, are presented. The results of the present method are based on data collected at four different sites, all of them in a zone with a semiarid climate but with different degrees of continentality. The campaigns were performed from 1991 to 1994 in northeastern Spain over plots of rye-grass (Castellvi et al., 1996).

2. Method

2.1. Description of the measurement technique

The partition of energy between sensible (H) and latent (λE) heat flux is usually obtained by the Bowen ratio-energy balance method (Tanner et al., 1987; Kustas et al., 1996) by means of the Bowen ratio

$$\beta = \frac{H}{\lambda E} \tag{1}$$

The Bowen-ratio is used with the energy balance, which for uniform surfaces can be simplified to

$$R_n = G + H + \lambda E \tag{2}$$

yielding the following expressions for λE and H:

$$\lambda E = \frac{R_n - G}{1 + \beta} \tag{3}$$

$$H = \frac{\beta}{1 + \beta}(R_n - G) \tag{4}$$

where R_n is the net radiation and G the surface soil heat flux.

Over an averaging period, t, (20–60 min) empirical relationships between fluxes and vertical gradients can be formulated as:

$$H = -\rho_a c_{p_a} k_h \frac{\partial T}{\partial z}, \quad \lambda E = -\frac{\rho_a c_{p_a}}{\gamma} k_v \frac{\partial e}{\partial z} \tag{5}$$

and assuming $k_h = k_v$ (Verma et al., 1978) and measuring the temperature and vapor pressure gradients between two levels within the adjusted surface layer, β is obtained as

$$\beta = \gamma \frac{\partial T/\partial z}{\partial e/\partial z} = \gamma \frac{\Delta T}{\Delta e} \tag{6}$$

where ΔT and Δe are the temperature and vapor pressure difference between the two measurement levels, $\gamma = c_p p/\epsilon L_v$ is the psychrometric constant, c_p (1.01 kJ kg^{-1} °C^{-1}) the specific heat of air at constant pressure, p the atmospheric pressure (kPa), ϵ the ratio between the molecular weights of water vapor and air (0.622), and L_v the latent heat of vaporization (kJ/kg). The convention used for the signs of the energy fluxes is R_n positive downward and G positive when it is conducted downward from the surface (Fig. 1). Sensible and latent heat fluxes are positive upward, with a direction opposite to that of the gradients (Eq. (5)). For a temperature gradient $(\partial T/\partial z) < 0$, the sensible heat flux H is positive; and for a vapor pressure gradient $(\partial e/\partial z) < 0$, the latent heat flux λE is positive (Fig. 1).

The mean daily G value is often one or more orders of magnitude lower than R_n (Allen et al., 1994). However, over short periods, it can be quite large and show

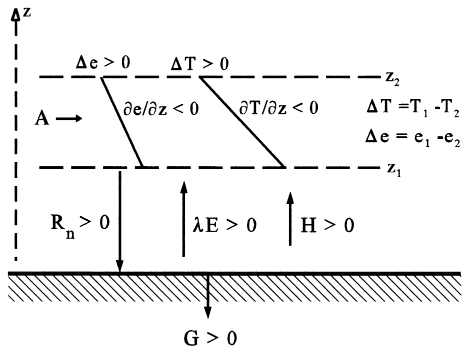

Fig. 1. Representation of the energy fluxes at the interface between the air and the surface showing the sign convention. *A* represents any advection energy flux into the block of air above the surface, R_n is the net radiation, λE the latent heat flux, *H* the sensible heat flux, *G* the surface soil heat flux, Δe and ΔT are the vapor pressure and temperature difference between the two measurement levels, and $\partial e/\partial z$ and $\partial T/\partial z$ are the corresponding vapor pressure and temperature gradients.

large variations since it involves the thermal properties of the soil that vary largely with moisture content. When precipitation or irrigation have been present, the soil heat flux pattern can be distorted considerably due to the soil water movement. The energy advection term *A* in Fig. 1 represents the total energy advected to or away from the layer to which the energy budget is applied. Irrigation or precipitation is a source of vertical advection at the upper surface of the layer, and horizontal advection of sensible and latent heat may be either positive or negative; that is, it may represent energy delivered to or extracted from the layer. This term, which can be large in certain conditions, has been neglected in the simplified energy balance equation used (Eq. (2)).

2.2. Problems inherent to the BREB method

The accuracy of the method can be assessed by comparing the calculated fluxes with an independent measurement of evaporation such as that supplied by a lysimeter or eddy covariance instrument, and finding when the method works. From Eqs. (3) and (4), the accuracy of λE and *H* depends on the accuracy of β, so the errors in the fluxes can be calculated by knowing the experimental errors of the different sensors used in the Bowen ratio technique. This allows a second way to discuss the errors in λE according to error analysis (Fuchs and Tanner, 1970; Blad and Rosenberg, 1974; Sinclair et al., 1975; Andreas and Cash, 1996), although some assumptions and requirements must be specified.

The assumptions in the use of this method are that the turbulent transfer coefficients for heat and water vapor are identical, which is true in neutral conditions; but may not be valid in stable conditions. Furthermore, there must be an extensive fetch over a homogeneous surface, so that the upwind distance compared to the upper measurement height is of the order 1 : 100 (Heilman and Brittin, 1989; Monteith and Unsworth, 1990; Horst and Weil, 1992; Stannard, 1997). This ensures that the two measurement levels for temperature and humidity are within the adjusted surface layer. Also, the closure of Eq. (2) for the natural surface is required from Eqs. (3) and (4), so the technique is not recommended for heterogeneous surfaces and sloping terrain (Brutsaert, 1982).

Finally, the solution supplied by the BREB for *H* and λE must be consistent with the flux-gradient relationships. If any experimental value of $R_n - G$ and β cannot give a solution with the correct signs and values of the fluxes, then the BREB method fails in that case and the data must be discarded. Here, Δe and ΔT are measured as the difference between the measurements at the lower minus the upper level; so the signs of the fluxes *H* or λE are the same as those of the difference ΔT or Δe (Fig. 1).

3. Analysis

3.1. Criteria for rejecting inappropriate data from the BREB method

From a practical point of view, to determine correct fluxes it is necessary to apply some set of criteria to select the appropriate Bowen ratio data. The simplest criterion of rejection may be to discard the surface flux values obtained when the differences of temperature and vapor pressure are of the same order of magnitude as the resolution limits of the sensors, as considered by some authors (Unland et al., 1996). However, this does not always imply that the flux values are incorrect.

The present study is based on a physical analysis of the method to find some criteria to reject the physically inconsistent data, including those cases that lie outside of the instrumental resolution limits. The estimates of λE and H provided by the BREB method must be consistent with the flux-gradient relationships, but sometimes the measurements give incorrect signs for those fluxes. The Eqs. (3) and (6) can be arranged to give

$$R_n = \left(1 + \gamma \frac{\Delta T}{\Delta e}\right) \lambda E + G \tag{7}$$

and

$$\frac{\Delta e}{\lambda E} = \gamma \frac{\Delta T}{H} = \frac{\Delta e + \gamma \Delta T}{R_n - G} > 0 \tag{8}$$

This expression must always be >0, according to the sign conventions (Fig. 1). The data provided by the BREB method will be correct when they fulfill the above inequality for every sign of $R_n - G$.

Therefore, when $R_n - G > 0$, $\Delta T > -\Delta e/\gamma$. That is, $\beta > -1$ if $\Delta e > 0$, but $\beta < -1$ if $\Delta e < 0$. When $R_n - G < 0$, $\Delta T < -\Delta e/\gamma$. That is, $\beta < -1$ if $\Delta e > 0$, but $\beta > -1$ if $\Delta e < 0$. Therefore, from Eqs. (3) and (4), Eq. (8) shows that only some combinations of values of H and λE are possible (Table 1):

(a) When $R_n - G > 0$: if $\beta > -1$, from Eq. (3) it is deduced that λE must be always positive, whereas H may be positive or negative (Eq. (4)) depending on the sign of β. If $\beta < -1$, the only possible cases are $\lambda E < 0$ and $H > 0$.

(b) When $R_n - G < 0$: If $\beta < -1$, the only possible cases are $\lambda E > 0$ and $H < 0$. If $\beta > -1$ then λE must be always negative, whereas H can be positive or negative depending on the sign of β.

If these conditions are not satisfied (Table 1), the BREB will provide an incorrect direction to the flux so the data must be discarded. This usually only occurs in early morning and late afternoon, when heat fluxes change their sign; during irrigation or precipitation with low values of Δe (close to the resolution limit $\delta\Delta e$); and with low values of $R_n - G$. As can be seen in Table 1, the above conditions mean that negative values of the latent heat flux $\lambda E < 0$, indicating condensation, are not forbidden in the BREB method under non-advective conditions. However, these cases usually appear under stable conditions and during the night, with vapor pressure differences $\Delta e < 0$ within the range of experimental errors.

On the other hand, when the conditions shown in Table 1 are not satisfied, a possible advection of energy A may exist (Bertela, 1989). If such a term is included in Eq. (2), then it must be added to $R_n - G$ in Eqs. (3) and (4), so there could exist values of A that would make consistent those cases with the conditions shown in Table 1. If there is no advection and the requirements mentioned in Section 2.2 are met, the failure of the BREB could be due to the uncertainties in the measurement, which indicates the need to use sensors with improved resolution limits. Alternatively, the conditions could be varying rapidly, so that the measured gradients averaged over time t are not representative of the energy balance also averaged over time t (Table 2).

3.2. Boundaries on Bowen-ratio around −1

Another problem inherent in the BREB method arises when β approaches −1, since the denominator in Eqs. (3) and (4) approaches 0, causing the calculation of λE and H to become impossible because they lose their physical meaning. The values $\beta \approx -1$ appear at sunrise and sunset and during precipitation when the direction of the temperature gradient changes to be opposite to that of the vapor pressure gradient. In these cases, with extremely inaccurate flux values, the problem is to find out which non-permissible range around −1 to consider. Some ranges have been proposed; for example, β values of less than −0.75 or values in the range $-1.3 < \beta < -0.7$ (Ortega-Farias et al., 1996; Unland et al., 1996); but that range should depend on the accuracy of measurement, that is, on the sensors used.

The interval around $\beta = -1$ that can produce unreliable values of latent and sensible heat fluxes can be found by means of the error analysis of the Bowen ratio. If it is considered that random measurement errors caused by fluctuations in the actual temperature and vapor pressure gradients are usually smaller than the values for instrumental resolution when a large number of measurements are taken for each averaging period (20 or 30 min), then the excluded interval of β values will appear when $[-\gamma(\Delta T \pm \delta\Delta T)]$ is within the interval $[\Delta e \pm \delta\Delta e]$, where $\delta\Delta T$ and $\delta\Delta e$ are the resolution limits for the temperature and vapor pressure gradients. Applying error analysis to β, its error

Table 1
Conditions to be satisfied by the BREB method under non-advective conditions for data to be reliable and consistent with Eq. (8). R_n is the net radiation, G the surface soil heat flux, Δe the vapor pressure difference between the lower and the upper measurement levels, and λE and H the latent and sensible heat flux, respectively

Available energy	Vapor pressure difference	Bowen ratio	Heat fluxes
$R_n - G > 0$	$\Delta e > 0$	$\beta > -1$	$\lambda E > 0$ and $H \leq 0$ for $-1 < \beta \leq 0$ or $H > 0$ for $\beta > 0$
	$\Delta e < 0$	$\beta < -1$	$\lambda E < 0$ and $H > 0$
$R_n - G < 0$	$\Delta e > 0$	$\beta < -1$	$\lambda E > 0$ and $H < 0$
	$\Delta e < 0$	$\beta > -1$	$\lambda E < 0$ and $H \geq 0$ for $-1 < \beta \leq 0$ or $H < 0$ for $\beta > 0$

Table 2
Summary of cases when the BREB method fails. $R_n - G$ is the available energy, Δe the vapor pressure difference between the lower and the upper measurement levels, β the Bowen ratio, T and e the air temperature and vapor pressure, and ε the error interval defining the excluded interval of Bowen ratio values around -1 (Eqs. (10) and (11)).

Error	Condition
A	$R_n - G > 0$, $\Delta e > 0$ and $\beta < -1 + \lvert\varepsilon\rvert$
B	$R_n - G > 0$, $\Delta e < 0$ and $\beta > -1 - \lvert\varepsilon\rvert$
C	$R_n - G < 0$, $\Delta e > 0$ and $\beta > -1 - \lvert\varepsilon\rvert$
D	$R_n - G < 0$, $\Delta e < 0$ and $\beta < -1 + \lvert\varepsilon\rvert$
E	Rapidly changing T and e

$\varepsilon = \delta\beta$ is given by

$$\varepsilon = \left|\frac{\partial\beta}{\partial\Delta T}\right|\delta\Delta T + \left|\frac{\partial\beta}{\partial\Delta e}\right|\delta\Delta e$$

$$= \left|\frac{\gamma}{\Delta e}\right|\delta\Delta T + \left|-\gamma\frac{\Delta T}{(\Delta e)^2}\right|\delta\Delta e$$

where, after dividing by β, we obtain

$$\varepsilon = \beta\left(\frac{\delta\Delta T}{\Delta T} + \frac{\delta\Delta e}{\Delta e}\right) \tag{9}$$

Since we are determining the error interval of β around -1, when $\beta \to -1$ then by the above expression $\varepsilon \to -(\delta\Delta T/\Delta T + \delta\Delta e/\Delta e)$, that is, its absolute value $\varepsilon \approx \delta\Delta T/\Delta T + \delta\Delta e/\Delta e$. And substituting $\Delta T \approx -\Delta e/\gamma$ from Eq. (6), then the excluded interval of β values, $-1-|\varepsilon| < \beta < -1+|\varepsilon|$, can be determined exactly using the dimensionless quantity

$$\varepsilon = \frac{\delta\Delta e - \gamma\delta\Delta T}{\Delta e} \tag{10}$$

This expression shows that, rather than being fixed, the range of the excluded interval of β around -1 depends on the vapor pressure gradient measured in each sampling period and on the resolution limits of the sensors. With the range defined by Eq. (10), it is easy to recognize when the BREB method is invalid around $\beta = -1$.

3.3. Numerical example

Using the Campbell Scientific Bowen-ratio system, the dew-point temperature is measured at both levels with a single cooled-mirror dew-point hygrometer and then the vapor pressure is calculated. The resolution of the dew-point temperature measurement and the stability of the hygrometer yield a vapor pressure resolution of less than $\pm$0.01 kPa over most of the environmental range. Therefore, a resolution of 0.02 kPa was assumed for Δe ($\delta\Delta e = 0.02$ kPa). Air temperature is measured at the two levels with thermocouples that give errors in the temperature gradient measurement of >0.01°C (Tanner et al., 1987); so $\delta\Delta T = 0.02$°C was assumed. Then, taking into account the small variation of the psychrometric constant with temperature, on average 0.066 kPa °C^{-1} between 0 and 30°C, and the above values for $\delta\Delta e$ and $\delta\Delta T$, Eq. (10) becomes

$$\varepsilon = \frac{0.019}{\Delta e} \tag{11}$$

where Δe is in kPa, which is the interval shown in Fig. 2. It is, therefore, not justified to use a constant excluded interval to reject the β values near -1 as several authors do (Ortega-Farias et al., 1996; Unland et al., 1996; Tanner et al., 1987). If all the data with β values within an interval as for example $-1.3 < \beta < -0.7$ are rejected, then the data corresponding to vapor pressure gradients greater than 0.07 kPa/m will be taken as inaccurate, whereas they can be reliable data if the conditions of Table 1 are satisfied.

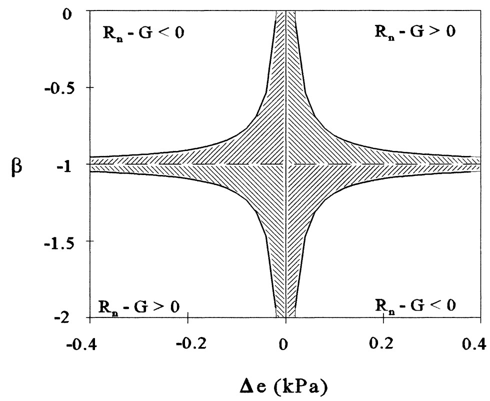

Fig. 2. Excluded interval of Bowen ratio (β) values around -1 (shaded area), where the energy fluxes obtained by the Bowen ratio-energy balance (BREB) method are invalid. Each quadrant defines the valid β values corresponding to the indicated available energy $R_n - G$, and the solid line bounds the interval $[-1 \pm |\varepsilon|]$, where ε is the error interval defined by Eq. (11) and Δe the vapor pressure difference between the two measurement levels.

4. Application and results

As can be seen in Fig. 2, when there is evaporation ($\Delta e > 0$ or $\partial e/\partial z < 0$) in dry or semiarid climates with very limited soil moisture available (where Δe will be small, since the crop and the surface are dry), the excluded interval will be large. For irrigated surfaces where Δe is larger, the interval around $\beta = -1$ is smaller. The shaded areas in Fig. 2 define the invalid β values, and the white areas contain the reliable β values in the BREB method, depending on the sign of the available energy as indicated in each quadrant. The solid line bounds the interval $[-1 \pm |\varepsilon|]$.

The data measured with values $\Delta e < 0$ (vapor pressure gradients $\partial e/\partial z > 0$), must be indicative of condensation ($\lambda E < 0$) to be consistent with the flux-gradient relationships. All the combinations shown in Table 1 are physically possible, but what is important is their frequencies of occurrence in the BREB method. According to the above analysis, data not fulfilling the conditions shown in Table 1 and those within the error interval of β around -1 are the data that should be rejected in the BREB method under non-advective conditions. Then, taking into account the sign of Δe in Eq. (11), all the cases when the BREB fails are indicated as errors *A–D* in Table 2. Moreover, the cases with $\lambda E < 0$ were analysed separately since when these data are measured by the BREB, usually they are within the range of experimental errors or measured under weak local advection.

4.1. Experimental measurements

The data used to apply the above analysis were collected using the Bowen Ratio–energy balance method at four sites in Catalonia (NE Spain) from August to November 1991 at Mas Bove (41°9′N, 1°10′E, elevation 76 m, in the Mediterranean area), from March to September 1992 at Raimat (41°37′N, 0°40′E, elevation 290 m), from March to June 1993 at Montejulia (41°49′N, 0°3′W, elevation 300 m), and from June to August 1994 at Zaragoza (41° 38′N, 0° 53′E, elevation 236 m). These measurement sites are located in the Ebro River basin. The sites of Raimat, Montejulia, and Zaragoza are in a region with semi-continental climatic characteristics with annual precipitation below 420 mm, whereas the site of Mas Bove (12 km from the coast) has a Mediterranean climate (Castellvi et al., 1996).

The BREB was located at all the sites on plots of festuca rye-grass, which was well irrigated by sprinklers and had a height of 10–15 cm during the measurement periods. The equipment (Bowen-ratio system, Campbell Scientific, Logan, UT) whose detailed description can be found in the literature (Tanner et al., 1987; Fritschen and Simpson, 1989), measures the gradient of air temperature by means of unaspirated chromel-constantan thermocouples (7.62 10^{-3} cm in diameter), and the vapor pressure gradient with a single cooled-mirror dew-point hygrometer. Net radiation and soil heat flux were measured with a net radiometer (Model Q*6) and heat flux plates, respectively. The data were averaged over 20 or 30 min depending on the site.

4.2. Analysis of data

When these data are analysed, it can be observed that the total number of cases with some type of error are of the order of 30–40% (Table 3). With the present analysis, problems in the sensors can be identified because these cases are usually associated with some type of error. When an initial quality control of

Table 3
Percentage of cases in which the data measured by the BREB method at the different sites fall into the four types of errors and, within them, number of cases corresponding to the excluded interval $-1-|\varepsilon| < \beta < -1+|\varepsilon|$ (where ε is the error interval defined by Eq. (11)).

Site[a]	All errors (%)	Error (%)[b]				Cases with[c]			Excluded interval[c]
		A	*B*	*C*	*D*	$\lambda E<0$	$\lambda E<0$ and $H>0$	$R_n-G<0$ and $H>0$	
Mas Bove (7948)	38.5	10	17	11	0.5	2089	647	224	1333 (17%)
Raimat (4897)	44.0	18	11.5	14	0.5	935	615	100	1221 (25%)
Montejulia (2581)	30.0	6	3	17	4	909	214	101	723 (28%)
Zaragoza (1399)	41.0	17	11	12.5	0.5	406	257	80	272 (19%)

[a]In parenthesis the total number of observations at that site.
[b]Types of error defined in Table 2.
[c]Number of cases. In parentheses, percentage of cases with respect to the total number.

the data is not made, as for example at Montejulia (Table 3) where the measurements of soil heat flux were in error for some weeks, then the total number of data to be rejected increased up to 59%. During the daytime and for unstable conditions, cases associated with Error *A* appear with a downward sensible heat flux ($H<0$) for negative temperature gradients ($\Delta T>0$). They correspond to periods just after irrigation or precipitation. But most of the cases in which the BREB method fails appear in the evening, during the night, and in the early morning when net radiation and soil heat flux have changed from positive to negative, with positive and negative values of the available energy or with values of β in the excluded interval (Fig. 3).

For inversion conditions ($\partial T/\partial z>0$ or $\Delta T<0$) during the night, the cases with $\lambda E<0$ or with $\lambda E<0$ and $H>0$ (Table 3) appear. Thirty percent of these data are associated with the Errors *A* or *C* or with cases in the excluded interval of β, with values of vapor pressure gradients of the order of $\delta\Delta e$. As can be seen in Fig. 3, most of these inconsistent data start appearing at sunset (18–19 h) and go on throughout the night until sunrise (6–7 h) for negative values of net radiation between 0 and $-80\,\mathrm{W/m^2}$, although with positive or negative values of $R_\mathrm{n}-G$ mainly between -70 and $70\,\mathrm{W/m^2}$. In general, 90% of the inconsistent data indicating condensation ($\lambda E<0$) correspond to low values of latent heat flux ranging from 0 to $-50\,\mathrm{W/m^2}$, that is, they are data within the range of experimental errors or measured under weak local advection. Fifty-five percent of these data correspond to positive vapor pressure gradients ($\Delta e<0$) and 45% to negative gradients ($\Delta e>0$), but in both cases they have very low values (on average 0.03 kPa/m). The β

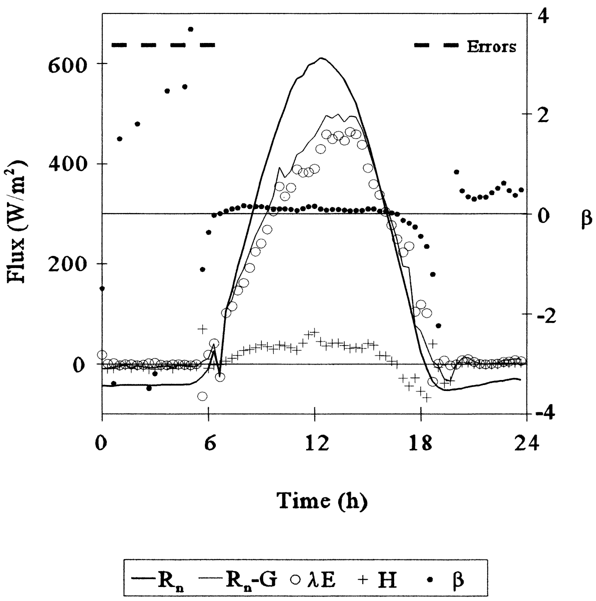

Fig. 3. Example of inconsistent data in the BREB method, corresponding to 13 August 1991 at Mas Bove. The times of day when the BREB method fails are indicated by the upper dashed lines. R_n is the net radiation, $R_\mathrm{n}-G$ the available energy, λE the latent heat flux, H the sensible heat flux and β the Bowen ratio.

values near -1 appear when Δe is near the resolution limit (0.02 kPa) (Fig. 4); all these cases have β values within the excluded interval 95% of the time.

4.3. Sensitivity considerations

The above analysis and results imply that if the temperature and vapor pressure gradients and the resolution limits of the sensors are known, the data to be rejected in the BREB can be clearly identified by the

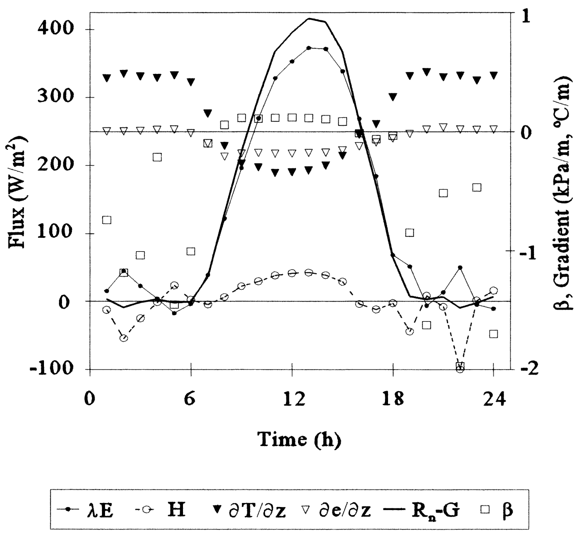

Fig. 4. Mean hourly values of the surface fluxes (available energy, $R_n - G$, latent heat flux, λE, and sensible heat flux, H) and the Bowen ratios (β) and corresponding values of the temperature ($\partial T/\partial z$) and vapor pressure ($\partial e/\partial z$) gradients for all the data measured at Mas Bove in August 1991.

conditions of Table 2, with the limits of the excluded interval of β values defined by Eq. (10). However, when reliable data are measured and not discarded, there still remains the question of how accurate the estimates of the computed values of the sensible and latent heat fluxes are.

When an error analysis is carried out following other authors criteria (Fuchs and Tanner, 1970; Angus and Watts, 1984; Andreas and Cash, 1996), the relative uncertainties of the sensible and latent heat fluxes are obtained. These uncertainties show how sensitive the estimates of λE and H are to uncertainties in the variables used to estimate them, R_n, G and β. According to Eq. (9), the maximum relative uncertainty in β can be expressed as

$$\left|\frac{\delta\beta}{\beta}\right| = \frac{\delta\Delta T}{|\Delta T|} + \frac{\delta\Delta e}{|\Delta e|} \tag{12}$$

whereas, after applying the error analysis to Eqs. (3) and (4), the relative uncertainties in λE and H are given, respectively, by

$$\left|\frac{\delta\lambda E}{\lambda E}\right| = \frac{\delta R_n + \delta G}{|R_n - G|} + \frac{\delta\beta}{|1+\beta|} \tag{13}$$

and

$$\left|\frac{\delta H}{H}\right| = \frac{\delta R_n + \delta G}{|R_n - G|} + \frac{\delta\beta}{|\beta(1+\beta)|} \tag{14}$$

A typical accuracy of $\pm 5\%$ in R_n is a reasonable choice taking into account the sensor accuracy and the errors related to the levelling of the sensor under normal conditions, which can be a considerable source of measuring errors (Linkosalo et al., 1996). The soil heat flux G is determined by adding the heat flux (F) measured with plates buried in the soil at 80 mm to the change of energy stored in the soil layer (S) above the plate (Clothier et al., 1986). This storage term, calculated by measuring the change in the soil temperature (ΔT_s) over the averaging period, is the most important term in G. It can represent up to 70–80% G, whereas F is usually 20–30% G. Then, taking into account the instrumental error of the soil heat flux plate and the overall accuracy of the thermistor used to measure T_s (in the worst case $\delta\Delta T_s = 0.2°C$), an average uncertainty in G of 30% was obtained. This error can be reduced with more accurate thermistors and by placing the heat flux plates as close to the soil surface as allowed by the soil type.For the cases not rejected but in which the values of the temperature or vapor pressure gradients are of the order of the resolution limits of the sensors, i.e., $|\Delta e| \approx \delta\Delta e$ or $|\Delta T| \approx \delta\Delta T$, Eq. (12) shows that the relative uncertainty in β can be large (for example 100% for $|\Delta e| = |\Delta T| = 0.04$). This is the criterion used by some authors to assess whether the fluxes are reliable (Unland et al., 1996). However, a large relative uncertainty in β does not necessarily imply a large one in λE (Fig. 5). As can be seen in Eqs. (13) and (14), when $R_n - G$ is close to 0, even a small uncertainty in R_n or G would give a large relative uncertainty in λE and H. Furthermore, if β is near -1, a small relative uncertainty in β would also give a large relative uncertainty in both energy fluxes.

All the possible situations appear in the measurements for the reliable cases during the 24 h, although the largest uncertainties appear during the night (Fig. 5). Some cases have large relative uncertainties in β (higher than 1000%) when β is near 0, but at the same time low relative uncertainties in λE (<10%) because $R_n - G$ is large, and large relative uncertainties in H since it depends inversely on the β value (Eq. (14)). At other times there are cases with low relative uncertainties in β and large ones in λE and H when the value of $R_n - G$ is close to 0. Therefore, also for re-

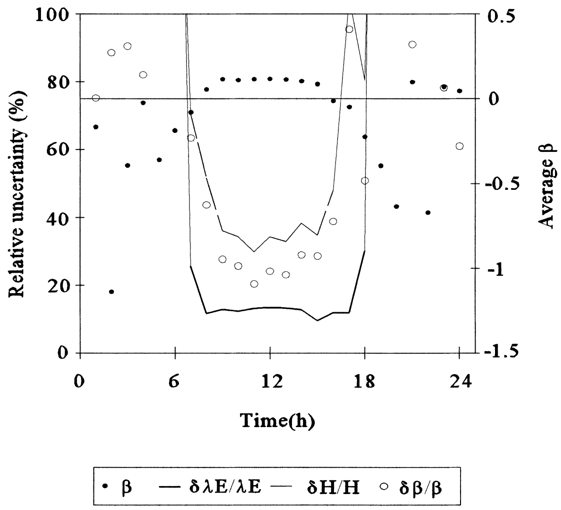

Fig. 5. Average hourly relative uncertainties (%) of the Bowen ratio ($\delta\beta/\beta$), of the latent heat flux ($\delta\lambda E/\lambda E$) and of the sensible heat flux ($\delta H/H$) for the reliable data measured by the BREB method (Mas Bove, August 1991).

liable data it may be useful to limit the uncertainty in λE to a maximum value for considering the fluxes as correct. This limit may vary from 10% under ideal conditions (Sinclair et al., 1975; Kustas et al., 1996) to 20% for heterogeneous surfaces (Nie et al., 1992) or 60% depending on the β value (Angus and Watts, 1984). In our case, for reliable data and during the daytime period from 7–18 h, the uncertainty in λE ranges from 9 to 30% whereas for H it is between 30 and 80%. These uncertainties occur for the average β values shown in Fig. 5, with most of the actual values of β ranging from -0.5 to 0.5. The interval of β values complementary to that one, can be a simple condition to be used in order to consider the fluxes measured by the BREB method as inaccurate.

5. Conclusions

There are cases when the BREB method fails to provide reliable measurements of evaporation, so certain criteria for rejecting inaccurate data are required. With the present analysis it is easy to recognize the failure of the method determining the surface fluxes. The criteria that have been found depend on the physical inconsistency of the data and on the resolution limits of the sensors.

If the temperature and vapor pressure gradients and the resolution limits of the sensors are known, the data to be rejected using the BREB method are clearly identified by the conditions given in Table 2, and the limits of the excluded interval of β values around -1 are defined by Eq. (10). The results show that on average 40% of the total data, which correspond to the night-time period and to precipitation or irrigation events, must often be rejected. For consistent data and depending on the site, the average uncertainty in the latent heat flux has relatively large values ranging from 9 to 40%, with higher values for the uncertainty in the Bowen ratio and the sensible heat flux. This analysis is general enough to be easily applied to any other situation of measurement with the BREB method.

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