**A SIMPLE MODEL FOR ESTIMATING THE BOWEN RATIO FROM CLIMATIC
FACTORS FOR DETERMINING LATENT AND SENSIBLE HEAT FLUX**

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A SIMPLE MODEL FOR ESTIMATING THE BOWEN RATIO FROM CLIMATIC FACTORS FOR DETERMINING LATENT AND SENSIBLE HEAT FLUX

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ABSTRACT

The energy partitioning or Bowen ratio β at the surface, can be expressed as a function of a climatic factor C (which depends on the climatic characteristics through the climatological resistance r_i) and of a surface factor S (which depends on the surface characteristics through the surface resistance r_e). This paper explains an approach for estimating S and therefore β as a function of standard meteorological variables. The empirical approach is then validated by estimating the latent (λE) and sensible (H) heat flux. The experimental data were measured over grass at two semiarid locations in the Ebro river valley, NE Spain, with typical Mediterranean climates: at Mas Bove, using a Bowen ratio-energy balance method from 1991 to 1993, and at Zaragoza, using a weighing lysimeter from 1999 to 2000.

Results show that the surface factor S depends on the square root of the absolute value of r_i/r_a (where r_a is the aerodynamic resistance), with two locally calibrated empirical parameters. This result is valid for the largest possible range of situations (β values) throughout the day. Using three different hypotheses for computing r_a , results for β (following hypothesis 1) indicate a good level of performance by the model, although with a high degree of variability. The estimated latent heat flux $\lambda E_{est,1}$ tends to slightly underestimate the measured values. Under the semiarid conditions of the region, λE_{PM} estimates obtained with the Penman-Monteith equation produce relative errors that are greater than those obtained with the proposed model once it has been calibrated. On average, sensible heat flux tends to be overestimated with the proposed method.

Keywords: Bowen ratio, energy partitioning, surface resistance, evapotranspiration, Penman-Monteith equation

1. INTRODUCTION

Evapotranspiration is a component of the hydrological cycle whose accurate calculation at the local and regional scales is needed to achieve an appropriate management of water requirements. A high degree of precision in estimating crop evapotranspiration may permit important water savings in the planning and management of irrigated areas. In 1977, the Food and Agriculture Organisation (FAO) proposed a methodology for computing crop evapotranspiration based on the use of reference evapotranspiration (ET_o) and crop coefficients (K_c). Allen et al. (1998) redefined the concept of ET_o and adopted the Penamn-Monteith (PM) equation with constant canopy resistance (r_c) to estimate ET_o .

The PM model combines the energy balance with the expressions that describe heat fluxes to derive a method for estimating the vapour flux from a vegetated surface. It has been applied in different regions of the world and has provided better results over the reference crop than using other approaches (Kustas et al., 1996; Monteith and Unsworth, 1990; Jensen et al., 1990; Allen et al., 1998; Hussein, 1999; Pereira et al., 1999; Ventura et al., 1999). Later studies involving the PM equation have also suggested the underestimation of the high measured values of ET_o in semiarid and windy areas, with a high evaporative demand, and overestimation in cases with low ET_o values (Steduto et al., 2003; Lecina et al., 2003; Todorovic, 1999; Rana et al., 1994).

When using the PM equation in a one-step approach, two kinds of parametric data must be known: aerodynamic resistance r_a ($s\ m^{-1}$) and bulk canopy or surface resistance r_c ($s\ m^{-1}$) to water vapour transport. On the basis of turbulent transfer and assuming a logarithmic wind profile, r_a can be calculated from the top of the canopy (h_c) to the reference height through commonly used formulations (Hall, 2002; Alves and Pereira, 2000; Pereira et al., 1999; Alves et al., 1998; Verhoef, 1995; Perrier, 1975). The net resistance to diffusion through the crop and soil surfaces, is represented in the PM model by the bulk surface resistance r_c . It is therefore not only a physiological parameter but also has an aerodynamic component (Lhomme, 1991). It is not easy to estimate r_c for different climatic and crop water conditions, as it is influenced by solar radiation, temperature, vapour pressure deficit and soil water content (Alves et al., 1998; Huntingford, 1995; Kim and Verma, 1991; Jarvis, 1976).

Several authors have developed simple methodologies for modelling r_c as a linear function of a climatic resistance r_i . The value of r_i mainly depends on climatic characteristics influenced by net radiation R_n , soil heat flux G and air vapour pressure deficit. The model has been applied to wheat (Perrier et al., 1980), grass and alfalfa (Steduto et al., 2003; Lecina et al., 2003; Rana et al., 1994; Katerji and Perrier, 1983), tomato (Katerji et al., 1988) and lettuce (Alves and Pereira, 2000). These empirical relationships of the form $r_c / r_a = a + b (r_i / r_a)$, make it possible to estimate r_c using only standard meteorological variables, although the parameters a and b must be empirically calibrated. Alves and Pereira (2000) have shown that these parameters actually depend on the temporary value of the Bowen ratio β , the only factor that is not readily available. Therefore, for practical purposes the Bowen ratio needs to be estimated. However, for well-watered crops and over short periods of time β is not expected to exhibit large variations, unless solar radiation varies drastically.

The partitioning between latent λE and sensible H heat flux, that is, the Bowen ratio $\beta = H/\lambda E$, is critical in determining the hydrological cycle, boundary layer development, weather and climate. The surface resistance for a vegetated surface plays an important role in determining how the available energy $R_n - G$ is partitioned between H and λE , as β can be interpreted as an indicator of water stress. The process of accommodation of plants to water demand is coupled with that of thermal accommodation in the lower atmosphere (Monteith, 1995). The behaviour of stomata in response to the environment is seen as a physiological response. The response to radiation is linked to the process of photosynthesis and this is the basis for optimizing models of stomatal resistance. It seems that the dependence between the energy partitioning β and r_c shows that attention should focus on estimating and quantifying the energy partitioning (Alves and Pereira, 2000; Wilson et al., 2000).

At the surface, energy partitioning is a complex function of interactions between plant physiology and the development of the atmospheric boundary layer. The Bowen ratio can be expressed as (Wilson et al., 2002; Lockwood, 1979):

$$\beta = \frac{1 + \frac{r_c}{r_a} - \frac{r_i}{r_a}}{\frac{\Delta}{\gamma} + \frac{r_i}{r_a}} \quad (1)$$

where the climatological resistance r_i is (Monteith, 1965)

$$r_i = \frac{\rho_a c_p (e^* - e)}{\gamma (R_n - G)} = \frac{\rho_a c_p D}{\gamma (R_n - G)} \quad (2)$$

ρ_a is the mean air density at constant pressure (kg m^{-3}), c_p is the specific heat of moist air at constant pressure ($1004 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$); e^* and e are respectively the saturation and actual vapour pressure of the air (Pa), and $D = e^* - e$ (Pa) the atmospheric vapour pressure deficit; γ is the psychrometric constant ($\text{Pa }^\circ\text{C}^{-1}$) and Δ is the slope of the saturation vapour pressure curve with respect to temperature ($\text{Pa }^\circ\text{C}^{-1}$); R_n and G are respectively the net radiation and soil heat flux and $R_n - G$ the available energy (W m^{-2}).

The objective of this work is to estimate the Bowen ratio from a surface factor and a climatic factor using standard meteorological data, and to apply this method to estimate latent and sensible heat flux. Equations (1) and (2) illustrate that the partitioning of turbulent energy fluxes is a function of atmospheric demand through r_i , turbulent transport through r_a , surface resistance r_c and air temperature through Δ . The model presented below seeks to satisfy two different objectives. Firstly, it seeks to offer an approach for estimating a surface factor S , depending on surface resistance r_c , as a function of standard meteorological variables. Secondly, the method seeks to evaluate the magnitude of the Bowen ratio and the ability of the model to estimate latent and sensible heat fluxes at the surface. Climate models including r_c and β variability may improve the calculated surface energy fluxes in studies of future climate change.

2. MODEL

The partition of energy at the surface between sensible and latent heat flux is usually obtained by the Bowen ratio-energy balance method (Perez et al., 1999; Kustas et al., 1996) by means of the Bowen ratio

$$\beta = \frac{H}{\lambda E} \quad (3)$$

The Bowen ratio combined with the surface energy balance equation, which for uniform surfaces can be simplified to

$$R_n = G + H + \lambda E \quad (4)$$

yields the following expressions for λE and H

$$\lambda E = \frac{1}{1 + \beta} (R_n - G) \quad (5)$$

$$H = \frac{\beta}{1 + \beta} (R_n - G) \quad (6)$$

Over an averaging period (traditionally 30 min), empirical relationships between fluxes and vertical gradients can be formulated as

$$\lambda E = -\frac{\rho_a c_p}{\gamma} k_v \frac{\partial e}{\partial z}, \quad H = -\rho_a c_p k_h \frac{\partial T}{\partial z} \quad (7)$$

Assuming $k_h = k_v$ (Verma et al., 1978) and taking measurements between two levels within the adjusted surface layer, β is obtained as

$$\beta = \gamma \frac{\partial T / \partial z}{\partial e / \partial z} = \gamma \frac{\Delta T}{\Delta e} \quad (8)$$

where ΔT and Δe are the temperature and vapour pressure differences between the two measurement levels. This technique allows us to obtain λE and H from Eqs. (5) and (6) when the available energy ($R_n - G$) is accurately measured. The convention used for the energy flux signs is R_n positive downward and G positive when it is conducted downward from the surface (Fig. 1). Latent and sensible heat fluxes are positive upward for negative vapour pressure and temperature gradients (Eq. 7). Any advection term in Fig. 1 has been omitted according to the simplified energy balance (Eq. 4).

The K-theory assumes that the turbulent transfer coefficients for heat and water vapour are identical, which is not always true, particularly under conditions of local advection. In this case, an incomplete adjustment of the fluxes within the internal boundary layer may cause deviations from unity of the turbulent coefficient ratio k_h/k_v . Results reported by different authors are often contradictory but, despite this, assuming $k_h = k_v$ and using the Bowen ratio method to calculate surface energy fluxes will usually only result in minor errors (McNaughton and Laubach, 1998). Moreover, Eq. (8) is often limited to short canopies due to fetch requirements (Stannard, 1997) and large errors in λE can occur when the Bowen ratio $\beta \approx -1$ such as near sunrise and sunset (Perez et al., 1999).

Another of the methods based on flux-gradient theory and commonly used to estimate λE is the Penman-Monteith (PM) combination model, which represents a basic general description of the evaporative process from a vegetative surface. However, in this method the water vapour flux is from the canopy or vegetated surface to a level above the canopy, rather than between two heights above the surface (Drexler et al., 2004). The PM model is expressed as (Allen et al., 1998):

$$\lambda E = \frac{\Delta(R_n - G) + \rho_a c_p (e^* - e) / r_a}{\Delta + \gamma(1 + \frac{r_c}{r_a})} \quad (9)$$

where λE is the latent heat flux density (W m^{-2}), R_n and G are respectively the net radiation and soil heat flux (W m^{-2}), r_a is the aerodynamic resistance (s m^{-1}) and r_c is the canopy or bulk surface resistance (s m^{-1}). r_a is the resistance to the turbulent transfer of vapour between the source and the reference level. For homogeneous canopies, the source of water vapour and heat is located at height $d+z_{oh}$, which is considered the effective crop surface (Allen et al., 1998), where d (m) is the zero-plane displacement and z_{oh} (m) is the roughness length for heat. r_c is the bulk surface resistance of the entire vegetation canopy considered as a 'big leaf' (taken as the parallel sum of the stomatal resistances) or simply the canopy resistance.

Over a very large, homogeneous, moist surface and under steady conditions, e tends to the saturation value e^* and $r_c \ll r_a$. Consequently, the first term on the right hand side in Eq. (9) dominates, and in that case Eq. (9) (with $r_c \approx 0$) describes the 'equilibrium' evaporation conditions (Pereira et al., 1999; Monteith and Unsworth, 1990)

$$\lambda E_e = \frac{\Delta}{\Delta + \gamma} (R_n - G) \quad (10)$$

Eq. (10) may be considered as the lower limit of evaporation from moist surfaces. The aerodynamic term, or second term on the right in Eq. (9), is therefore a measure of the departure from equilibrium in the atmosphere. The atmospheric boundary layer is hardly ever uniform and tends to maintain a humidity deficit, even over oceans. Thus, equilibrium is rarely observed over a wet surface and the success of the PM model for estimating evapotranspiration may depend on the accuracy of modelling average surface resistance r_c .

The prior Eq. (9) can be written in the form

$$\lambda E = \frac{\Delta(R_n - G) \left[1 + \frac{\rho_a c_p (e^* - e)/r_a}{\Delta(R_n - G)} \right]}{(\Delta + \gamma) + \gamma \frac{r_c}{r_a}}$$

and, taking the equilibrium evaporation expression (Eq. (10)) as a common factor and rearranging terms, the above expression can then be rewritten as

$$\lambda E = \frac{\Delta}{\Delta + \gamma} (R_n - G) \frac{1 + \frac{\rho_a c_p (e^* - e)}{\Delta(R_n - G) r_a}}{1 + \frac{\gamma}{\Delta + \gamma} \frac{r_c}{r_a}} \quad (11)$$

On the right-hand side of the expression, the numerator can be expressed in the same form as the denominator, by defining a climatological resistance r_i (Monteith, 1965) given by Eq. (2), so that, through substitution in Eq. (11) we obtain

$$\lambda E = \frac{\Delta}{\Delta + \gamma} (R_n - G) \frac{1 + \frac{\gamma}{\Delta} \frac{r_i}{r_a}}{1 + \frac{\gamma}{\Delta + \gamma} \frac{r_c}{r_a}} \quad (12)$$

The value for climatological resistance depends on the specific climatic characteristics, although R_n and G are also influenced by the characteristics of the vegetative surface. This r_i can be considered as the upper limit of surface resistance, since λE tends to λE_e in Eq. (12) for a specific value for the surface resistance $r_c \equiv r_e = [(\Delta + \gamma)/\Delta] r_i$. For non-saturated surfaces under normal or dry conditions is $\lambda E \geq \lambda E_e$ and then $r_c \leq r_e$ (Pereira et al., 1999; Culf, 1994; De Bruin and Holtslag, 1982). It therefore seems advisable to analyse r_c as a function of r_i for land surfaces covered with homogeneous vegetation where there is not shortage of water.

Equation (12) depends on time, but in practice meteorological variables are continuously measured and averaged on a half-hourly or hourly basis, so the PM model can still be applied. The fraction on the right-hand side of Eq. (12) is a dimensionless quantity that mainly depends on climatic (through r_i) and surface (through r_c and r_a) characteristics. Therefore Eq. (12) can be written as

$$\lambda E = \frac{\Delta}{\Delta + \gamma} (R_n - G) \frac{1 + C}{1 + S} \quad (13)$$

where C and S

$$C = \frac{\gamma}{\Delta} \frac{r_i}{r_a}, \quad S = \frac{\gamma}{\Delta + \gamma} \frac{r_c}{r_a} \quad (14)$$

are dimensionless and are respectively referred to as the *climatic factor* and *surface factor*.

When the big leaf model expressed by Eq. (13) is combined with Eq. (5), the Bowen ratio can be obtained as

$$\beta = \frac{\Delta + \gamma}{\Delta} \frac{1 + S}{1 + C} - 1 \quad (15)$$

This expression is equivalent to that obtained by Wilson et al. (2002). Eq. (15) together with Eqs. (14) show that the partitioning of surface turbulent energy fluxes is a function of: atmospheric demand through climatic factor C (which is sensitive to available energy $R_n - G$ and vapour pressure deficit D);

surface resistance to water vapour transport (r_c) through surface factor S ; turbulent transport through r_a and air temperature through Δ .

The climatic C and the surface S factors control β . However, results reported in the literature (Lockwood, 1979; Wilson et al., 2000, 2002) indicate some general differences, mostly between maritime and continental climates. Large-scale differences in climate influence atmospheric demand, so more continental sites will tend to be drier and to have a higher D relative to R_n-G (large C and may be low β). Maritime sites will tend to be cooler and more humid resulting in a lower D relative to R_n-G (small C and perhaps high β). But the response of r_c and therefore of S to changes in atmospheric demand (stomatal resistance often increases with an increase in D), may compensate for factors S and C in control β (Kelliher et al., 1995).

In an agricultural region with well-defined climatic characteristics (such as the semiarid continental zone of this study), the climatic factor C could be expected to be constant for the entire region and to be representative of the whole climatic zone. Thus, in order to extrapolate Eq. (15) to the whole climatic region, the next step would be to analyse surface factor S and suggest some operational approaches for estimating S and therefore β as a function of standard meteorological variables.

3. MATERIALS AND METHODS

3.1. Experimental data and site description

This study was conducted at two locations that are representative of the Ebro river basin: at Zaragoza (41° 43' N, 0° 49' W, 225 m asl), in the central area of the valley, and at Mas Bove (41° 9' N, 1° 10' E, 76 m asl) in the Mediterranean area (Fig. 2). In the case of the central Ebro site, the study was conducted at an experimental farm located on the terraces of the river Gállego, in Zaragoza province, about 8 km north of its confluence with the river Ebro. The site is located in one of the windiest areas in Spain which has semi-continental climatic characteristics. The zone is a semiarid region (average annual precipitation about 330 mm) but with important water resources. Precipitation is mostly recorded in spring and autumn, though storm precipitation is also relatively frequent during summer. Average annual temperature is about 15 °C. Measurements were taken over a 1.2 ha plot with uniform grass cover (*Festuca arundinacea* Moench.). The plot was regularly irrigated and cut throughout the year to maintain it as near as possible to the reference standard.

A weighing lysimeter, 1.7 m in depth and covering an effective surface area of 6.3 m², was located at the centre of the plot. A load cell connected to a datalogger (CR500, Campbell Sci. Inc.) recorded lysimeter mass losses at 0.5 s intervals. These data were used to derive hourly evapotranspiration rates. The combined resolutions of the load cell and the datalogger made it possible to detect mass losses of about 0.3 kg (0.04 mm water depth). Measurements were taken from March to October 1999 and from March to September 2000. Only days without incidences (irrigation, rainfall, lysimeter drainage and grass cutting), and when measured grass height was between 0.10 and 0.15 m were used for analysis. An automatic weather station (CR10, Campbell Sci. Inc.) that was close to the lysimeter recorded hourly average air temperature, relative humidity and net radiation at a height of 1.5 m. Wind speed and direction were measured at a height of 2.0 m. Soil heat flux was measured using two plates buried at a depth of 8 cm and with an averaging soil temperature probe placed at a depth of between 2 and 6 cm (Allen et al., 1996).

In the case of the Mediterranean site, data were collected in the period from August 1991 to March 1993 using the Bowen Ratio-energy balance method at an experimental farm located at Mas Bove, in the Ebro River basin; the site was 12 km from the Mediterranean coast. The average annual precipitation at the site is below 520 mm. The main climatic characteristic is that maximum precipitation occurs in autumn. Other local characteristics are temperate winters, warm summers and humidity values ranging from 65% to 75% throughout the year (Castellvi et al., 1996).

The BREB was located on plots of festuca rye-grass sprinkler-irrigated. The grass height was maintained between 0.10 and 0.15 m during the measurement periods. The equipment (Bowen-ratio system, Campbell Scientific Inc.) 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 un aspirated chromel-constantan thermocouples, and the vapour pressure gradient with a single cooled-mirror dew-point hygrometer. Net radiation and soil heat flux were measured with a net radiometer and heat flux plates respectively (Allen et al., 1996). The data were averaged over 30 minutes.

3.2. Method for estimating the surface factor S and the Bowen ratio β .

Based on the results obtained by Perrier et al. (1980) several authors (Katerji and Perrier, 1983; Rana et al., 1997, 1994; Alves and Pereira, 2000) proposed a model in which an empirical relationship of the form $r_c / r_a = a + b (r_i / r_a)$ exists between surface r_c and climatological r_i resistance.

Since r_c depends on the source, coefficients a and b depend on the type of crop, on its phenological state or on soil water status (Rana et al., 1997). Some of these experimental results referred to reference crops such as grass and alfalfa grown in a Mediterranean climate (Steduto et al., 2003; Rana et al., 1994; Katerji and Perrier, 1983), wheat (Perrier et al., 1980), tomato (Katerji et al., 1988) and rice (Peterschmitt and Perrier, 1991). In these approaches, parameters a and b must be empirically calibrated (Alves and Pereira, 2000).

Taking the Katerji and Perrier (1983) approach as a reference, it is possible to explore any linear model that relates surface factor S to r_i . The aim of this work was to find the best approach for making estimations based on global empirical parameters, that are valid for any range of β values. If they do exist, these parameters would be representative of the crop for any climatic conditions. In order to analyse this simple model, we propose exploring a functional relationship of the form

$$S_{est} = \frac{\gamma}{\Delta + \gamma} \frac{r_c}{r_a} = \frac{\gamma}{\Delta + \gamma} \left[a + b f\left(\frac{r_i}{r_a}\right) \right] \quad (16)$$

for the reference crop, where a and b are global parameters that are to be determined empirically. With S estimated empirically from Eq. (16), we can estimate β (Eq. 15) as a function of standard meteorological variables.

In the most commonly used formulations, aerodynamic resistance r_a is estimated by considering that apparent sources of heat and vapour within the canopy are at a lower level than the apparent sink of momentum (Monteith and Unsworth, 1990). In the 'big leaf' model the big leaf is implicitly located at the height $d + z_{oh}$, where z_{oh} (m) is the roughness length for sensible heat transfer. When the leaves at the top of the canopy, between $d + z_{oh}$ and crop height h_c , are the most important source of vapour flux, the use of the $d + z_{oh}$ level as the evaporative surface can lead to an overestimation of r_a and to negative values for bulk surface resistance r_c when it is computed by inverting the PM equation. Notwithstanding, Wilson et al. (2002) found that hypothetical errors in r_a of as much as 100% resulted in mean errors of only about 10% in the computed value of r_c . In order to ascertain whether the proposed approach for surface factor S (Eq. 16) is sensitive to aerodynamic resistance, we therefore used several hypotheses to compute r_a for the reference crop.

Hypothesis 1: r_a is computed between the top of the canopy h_c and the reference height in the atmosphere (Alves et al., 1998; Perrier, 1975) as

$$r_{a1} = \frac{\ln\left(\frac{z_m - d}{z_{om}}\right) \ln\left(\frac{z_h - d}{h_c - d}\right)}{k^2 u_{zm}} \quad (17)$$

(denoted hereafter as r_{a1}) where z_m and z_h are respectively the wind and air temperature measurement heights, h_c is the crop height, k is the dimensionless von Karman constant, and u_{zm} is the wind speed measured at height z_m . The term $h_c - d$ substitutes the roughness length for heat transfer used to compute r_a according to Allen et al. (1998).

Hypothesis 2: In this case, the method proposed to compute r_a for the reference crop is that proposed by Allen et al. (1998) for grass, in which r_a is obtained as

$$r_{a2} = \frac{208}{u_{zm}} \quad (18)$$

where u_{zm} is the wind speed measured at height z_m .

Hypothesis 3: In order to establish whether dependence on wind speed can be avoided, for grass r_a is considered with constant average values during the diurnal and nocturnal periods: it was therefore considered as

$$r_{a3} = \begin{cases} 90 \text{ s m}^{-1} & (R_n > 0) \\ 70 \text{ s m}^{-1} & (R_n \leq 0) \end{cases} \quad (19)$$

The experimental or measured hourly values of surface resistance r_c (s m^{-1}) were obtained by inverting the PM equation (top-down approach) as

$$r_c = r_a \left[\frac{\Delta}{\gamma} \frac{R_n - G}{\lambda E} - \frac{\Delta + \gamma}{\gamma} \right] + \frac{\rho c_p}{\gamma} \frac{D}{\lambda E} \quad (20)$$

where λE is the latent heat flux (W m^{-2}) measured by a lysimeter (Zaragoza) or by a Bowen ratio system (Mas Bove). Hourly values measured for R_n , G , D , u and λE were used to compute hourly r_c values with Eq. (20), aerodynamic resistances with Eqs. (17) to (19) and climatological resistances with Eq. (2). In the PM equation (Eq. 9), hereafter denoted as λE_{PM} , units and computations followed Allen et al. (1998), r_c was considered constant and equal to 70 s m^{-1} and grass height was set to 0.12 m .

For the present analysis, the data set available for each location was divided into two groups: a *calibration* data set and a *validation* data set. Available days were organised by date and one of three days was selected for calibration, while the other two were selected for validation. Using only the calibration data sets from both locations, we subsequently explored several simple relationships between r_c/r_a and r_i/r_a for Eq. (16).

3.3. Statistical methods

In the evaluation of the different relationships represented by Eq. (16), the ability to predict S was compared using the coefficient of determination R^2 as the measure of the goodness of fit, that is, of the performance of the model; R^2 is a measure of the total variance accounted for by the model. Parameters a and b in Eq. (16) are then obtained for the best fit using the calibration data set.

A complication may arise when the model that maximizes R^2 for r_c , fails to maximize this value when predicting energy partitioning or evapotranspiration. Once the best parameterization of S had been chosen and the optimum coefficient values in Eq. (16) had been found, comparisons between measured β and estimated β_{est} values were carried out. To test the performance of the resulting approach, a simple linear regression between the predicted and observed values was made, based on the value of R^2 . However, in order to make a better quantitative comparison between the models for λE , predicted results could also be evaluated with reference to several statistics (Alexandris and Kerkides, 2003; Lee and Singh, 1998; Verhoef et al., 1997; Mayer and Butler, 1993; Willmot, 1981, 1982).

The first statistic is the bias or mean deviation error, $MBE = [\sum (O_i - P_i)]/n$. The second is the root mean square error, $RMSE = \sqrt{\sum (O_i - P_i)^2 / n}$, which is considered a better indicator of model performance than the correlation statistics. They can be expressed as percentages of the mean observed value (relative $RMSE(\%) = 100RMSE / |\overline{O}|$). In the above expressions, P_i and O_i represent the predicted (estimated) and observed (measured) values, n is the total number of data and $\overline{O}$ is the mean of observed data. RMSE provides a measure of the total difference between the predicted and observed values. The closer RMSE is to zero, the better the prediction.

The statistic that we will use as the model selection criterion is modelling efficiency (Lee and Singh, 1998) defined as $EF = 1 - [\sum (O_i - P_i)^2] / [\sum (O_i - \overline{O})^2]$, which is similar to the index of agreement (Willmot, 1982). Modelling efficiency is a dimensionless statistic that measures the fraction of the variance of the observed values which is explained by the model. It therefore provides a good measure of the model's performance. The best model is the one in which the value of EF is closest to 1 and which has the lowest RMSE.

4. RESULTS AND DISCUSSION

The available data set for each location was divided into calibration and validation data. Using only the calibration data sets, we explored several simple relationships between r_c/r_a and r_i/r_a for estimating the surface factor S (Eq. 16). In order to select the appropriate data, we first considered necessary to assess the consistency and reliability of both the calibration and validation data sets.

a. Data processing

For the two data sets (Zaragoza and Mas Bove) considered for this study, the measured values of latent λE and sensible H heat flux must be physically consistent with the flux-gradient relationship (Fig. 1). In the experimental measurements we required an adequate fetch, in order to have confidence that the heat fluxes were in equilibrium with the surface. Nevertheless, sometimes the measurements can give incorrect signs for those fluxes, at least for the estimates provided by the BREB method (Perez et al., 1999). We therefore scrutinized both datasets from a practical point of view before considering them for analysis. The objective was to apply some set of criteria to select appropriate data or to reject physically inconsistent data. When available energy $R_n - G$ is positive (downward with the convention used in Fig. 1), energy fluxes λE and H are positive upward with a direction opposite to that of the vapour pressure and temperature gradients (Eq. 7).

In the analysis of data, three different situations were observed (hereafter denoted as *Cases 1, 2 and 3*). *Case 1* corresponds to data with $\lambda E > 0$ and $H > 0$, representing 40% of total data. *Case 1* is the usual for unstable conditions during the daytime (mainly from 07h to 19h) with values of available energy $R_n - G > 0$. The case denoted as *Case 2* corresponds to hourly data values with $\lambda E > 0$ and $H < 0$ and represents 45% of total data. Of this 45%, one third appears during the day and even during the central hours of the day. They are associated with a downward sensible heat flux with positive temperature gradients, corresponding to periods just after irrigation or precipitation.

The remaining two thirds of *Case 2* appear at sunset (18h-19h) in inversion conditions ($\partial T / \partial z > 0$) and persist throughout the night and until sunrise. They are associated with low values of latent heat flux and of available energy $R_n - G$ (mainly between -70 and 70 W m⁻²). An 8% of total data corresponds to what we denoted *Case 3*: data with $\lambda E < 0$ and $H < 0$. These cases, which indicate condensation, also appear at night under stable conditions. They are associated with positive and low

vapour pressure gradients and also with small negative values of R_n-G , usually within the range of experimental errors. Data with $\lambda E=0$ or data with $\lambda E<0$ and $H>0$ represent the remaining 7%. These data were directly excluded from the analysis as it was assumed that the air near the surface was not supersaturated (Andreas and Cash, 1996; Andreas, 1989; Philip, 1987).

In order to select the appropriate data from the data sets, another constraint was also taken into account. Eq. (10) shows that equilibrium evaporation λE_e is a lower limit of evaporation from moist surfaces. Combining Eq. (10) with Eq. (5), it can be seen that for equilibrium evaporation the Bowen ratio tends towards an *equilibrium* value $\beta_e = \gamma/\Delta$. Therefore, for unsaturated surfaces under normal daytime conditions (incoming available energy $R_n-G>0$, evaporation $\lambda E>0$ and $H>0$, so that $\beta>0$), the condition $\lambda E \geq \lambda E_e$ applied to Eq. (5) requires that $\beta \leq \beta_e$. The equilibrium Bowen ratio β_e is an upper boundary for Bowen ratio values when there is evaporation $\lambda E \geq 0$ (Andreas, 1989; Philip, 1987). During condensation at the surface under conditions of nocturnal inversion and outgoing available energy ($\lambda E<0$ and $H<0$), λE_e is an upper limit of latent heat flux and β_e is a lower boundary for the Bowen ratio, i.e., $\beta_e \leq \beta$. These constraints on β were added to Cases 1 and 3 and all of the criteria were applied to our data sets. We then excluded the small percentage of data that did not fit into any of the three cases.

b. Model calibration

When we examined the behaviour of r_c for Cases 1 and 2, we observed a similar degree of diurnal variability to that shown in Fig. 3. Values of r_c tend to remain relatively constant throughout the diurnal period from 9h to 16h. But there was an observed fall in early morning values and then a gradual increase in late afternoon. This pattern was also reported by other authors (Alves and Pereira, 2000) and reflects the daily course of the environmental variables affecting r_c . The most important factor were net radiation and variables like vapour pressure deficit (D) and temperature. The rise of r_c which was observed in late afternoon is consistent with the closure of stomata due to a decrease in radiation (Fig. 3). Independently of the time of day, negative values were obtained for r_c , but these were mainly registered early in the morning and at night, when the available energy tends to be small and negative and when the vapour pressure deficit is also small.

The response of r_c to net radiation seems to indicate the need to consider data corresponding to the diurnal period ($R_n-G>0$) separately from those corresponding to the nocturnal period ($R_n-G \leq 0$). The main drawback is that when R_n-G and D are low, such as at sunrise and sunset and during the

nocturnal period, the canopy r_c and climatological r_i resistances register either very high positive or very low negative values. This also leads to very high positive or very low negative β values. In general, these results correspond to data with R_n-G within the range of experimental errors (20-30 W m^{-2}). Figure 4 shows the dependence of β on r_i/r_a ; in it, it is possible to observe that $\beta = -1$ is a critical value to consider. It therefore seems that our attention should not focus on separate data in diurnal and nocturnal values. The key to our analysis should center on the fact that the variability of β versus r_i/r_a presents a symmetrical pattern with respect to the critical value $\beta = -1$.

This behaviour of β led us to select two sets of data: one in which the data interval was $\beta > -1$ (subset ' $\beta > -1$ ') and the other in which it was $\beta < -1$ (subset ' $\beta < -1$ ') (Fig. 4). From a physical point of view, the critical value $\beta = -1$ leads to non-defined values in λE and H (Eqs. 5 and 6). It also produces the change of sign from positive to negative values in the heat fluxes. In general, data with $\beta < -1$ correspond to the two thirds of nocturnal Case 2. On the contrary, data with $\beta > -1$ correspond to all types of Cases 1, 2 and 3, appearing in both the diurnal and nocturnal periods, as well as with positive and negative values of available energy.

Our objective is to try to find the best empirical relationship between r_c/r_a and r_i/r_a that provides us with an approach for estimating the surface factor S (Eq. 16) and then the Bowen ratio β (Eq. 15). Results reported by other authors (Steduto et al., 2003; Alves and Pereira, 2000; Rana et al., 1997) seemed to show a linear relationship between r_c/r_a and r_i/r_a on an hourly basis. But these results were generally obtained for a limited range of β values throughout the diurnal period. Alves and Pereira (2000) found such results for β values in the interval $[-0.3, 0.3]$, corresponding to situations when crop evapotranspiration was at its maximum and when available energy R_n-G had values corresponding to the middle of the day. Previously found results obtained for our semiarid region using the same methodology (Perez et al., 2006), showed that the functional form of the dependence of r_c/r_a on r_i/r_a departs from linearity. The response of r_c/r_a tends towards saturation when r_i/r_a increases (Fig. 5). Since we have included the largest possible range of situations throughout the day, these results effectively extend those reported by other authors.

Within the global calibration data set for the two measurement zones, each data subset was analysed separately. For subset ' $\beta > -1$ ', low values of R_n-G at sunrise, sunset or during the night, produced imprecise values of r_c and r_i (very high positive or very low negative values) and therefore led to an imprecise calibration. For subset ' $\beta < -1$ ' all data appeared during the night with small negative R_n-G values in the interval $[-60, -1]$ (W m^{-2}), and with low values of $r_i < 0$. A typical error associated with the measurement of net radiation is $\pm 5\%$, and the resolution of the weighing lysimeter is 0.04 mm

($\approx 30 \text{ W m}^{-2}$) in the measurement of evapotranspiration. To avoid large errors in the computed surface and climatological resistances, all the calibration data with $|R_n - G| \leq 10 \text{ W m}^{-2}$ were excluded from the analysis independently of β values.

For the global calibration data set, Figure 5 shows the measured and estimated values of r_c/r_a versus r_i/r_a after calibration obtained according to hypothesis 1. For subset ' $\beta > -1$ ' (Fig. 5, right) data correspond mainly to the diurnal period with $R_n - G \geq 10 \text{ W m}^{-2}$, $r_i > 0$ and β values in the interval $[-0.88, 0.86]$. For subset ' $\beta < -1$ ' (Fig. 5, left) data correspond to the nocturnal period with $R_n - G \leq -10 \text{ W m}^{-2}$, $r_i < 0$ and β values in the interval $[-5.3, -1.17]$. Table 1 shows the values of the empirical coefficients locally calibrated for the whole calibration data set. Our results confirmed the previously reported (Perez et al., 2006), showing that the best-fit relationship corresponds to a dependence of r_c/r_a on the square root of r_i/r_a . Subset ' $\beta < -1$ ' showed a symmetrical behaviour respect to that of subset ' $\beta > -1$ ', but for negative values of r_i/r_a . This was demonstrated after separately applying the calibration obtained for subset ' $\beta > -1$ ' to subset ' $\beta < -1$ '. Results showed that the calibration is perfectly valid if the sign of r_i is previously changed. Calibration was therefore made in function of the absolute values of r_i/r_a (Table 1), so that the result could be applied to any range of β values both during the diurnal and nocturnal periods.

c. Model validation: estimation of Bowen ratio and heat fluxes

Differences in the values of empirical coefficients obtained under the different hypotheses (Table 1) were due to aerodynamic resistance. The hourly values of r_{a1} obtained under hypothesis 1 (Eq. 17) were lower than those obtained using the method proposed by FAO (Allen et al., 1998) for the reference crop r_{a2} (Eq. 18). On average, r_{a1} was half the value of r_{a2} as seen in Fig. 3 for any typical day. This confirmed results obtained by other authors over both short and tall vegetation (Hall, 2002; Alves et al., 1998). According to Verhoef (1995), differences in the estimation of r_a for dense or sparse canopies or even for grass, are the result of problems associated with the parameterization of an excess resistance.

The calibrated values of parameters a and b in Eq. (16) allowed us to obtain an estimated surface factor S_{est} . This was applied to the validation data set, together with the climatic factor C (Eq. 14), to estimate hourly Bowen ratio values β_{est} from Eq. (15), hourly latent heat flux values λE_{est} from

Eq. (5) or Eq. (13), and sensible heat flux values H_{est} from Eq. (6). Estimated values β_{est} were validated throughout the study period for the global validation data set. Estimated values λE_{est} were validated by comparison with measured values λE obtained using a weighing lysimeter (Zaragoza) and a Bowen ratio system (Mas Bove). They were also compared to estimates λE_{PM} obtained by applying the Penman-Monteith equation (Eq. 9).

Once empirical calibration was applied, the statistics used to validate the method for estimating S and β are reported in Tables 1 and 2. These results indicated that surface factor S was estimated similarly under hypotheses 1 and 2 (modeling efficiency EF=0.6), but with a relatively high RMSE of 70% (Table 2). When the estimated $(r_c/r_a)_{est}$ or S_{est} were compared with the experimental values (Fig. 6), a higher scatter of data was observed for the high S values. As a consequence, the proposed model led to an average underestimation of the surface factor (positive MBE) for the whole validation data set. However, this result improved substantially when only the diurnal period (subset ' $\beta > -1$ ') was considered (positive S values between 0 and 2.2).

The climatic factor C and the surface factor S control the Bowen ratio β (Eq. 15). The response of C and S (or r_c) to changes in atmospheric demand can therefore lead to a compensation of both factors in the β values. However, when β is estimated from Eq. (15), it should be noticed that the climatic factor C in the denominator leads to non-defined β values for $C \approx -1$. These negative C values around -1 only appear during the nocturnal period with negative available energy $R_n - G < 0$ ($r_i < 0$). Therefore, prior to the validation of the model, all validation data with C values belonging to the interval [-1.1, -0.9] were excluded from the analysis.

Application of the model showed good performance for β under hypotheses 1 and 2, with high modeling efficiencies (Table 2). However, there was a high degree of variability, as indicated by the RMSE = 104% for $\beta_{est,1}$. As can be seen in Fig. 7, this was probably due to the higher errors obtained for the nocturnal period (subset ' $\beta < -1$ '). There was a slight overestimation of β under hypothesis 1 (MBE=-8.3%) and a similar underestimation under hypothesis 3 (MBE=8.6%), but the global comparison between estimated and measured values showed slopes of linear regression close to 1 (Table 2).

The variable values for S and β estimated with the proposed model were used in Eqs. (5) or (13) and (6), to respectively estimate the latent (λE_{est}) and sensible (H_{est}) heat flux values. Table 3 shows the results obtained for the global validation data set and for each hypothesis. Measured heat fluxes λE and H were obtained using a weighing lysimeter (Zaragoza) and a Bowen ratio system (Mas

Bove). For comparison purposes, latent heat fluxes λE_{PM} obtained with the Penman-Monteith equation (Eq. 9), with a fixed value of $r_c = 70 \text{ sm}^{-1}$, were also computed. The value of modelling efficiency for λE_{PM} (EF=0.95) showed good agreement for this method (Table 3). However, relative MBE and RMSE were higher for λE_{PM} than for the proposed model λE_{est} under any of the three hypotheses. Simple linear regressions between estimated and measured λE values showed that λE_{PM} displayed a lower slope ($c_1=0.86$) with respect to those obtained for λE_{est} . This indicates the greater tendency for λE_{PM} to underestimate high latent heat fluxes under semiarid conditions (Fig. 8b). This behaviour has already been reported in previous works carried out in the same region (Lecina et al., 2003; Perez et al., 2006) and at other Mediterranean locations (Steduto et al., 2003; Rana et al., 1994).

For the proposed method, results of the comparison between estimated and measured fluxes (Table 3) showed that the relative RMSE for $\lambda E_{est,1}$ was smaller than for hypotheses 2 and 3 and for λE_{PM} . The slope of the linear regression between $\lambda E_{est,1}$ and λE ($c_1=0.97$) was very close to 1, as can be seen in Fig. 8. For $\lambda E_{est,2}$ and $\lambda E_{est,3}$, the slopes were closer to 1 than for λE_{PM} . Furthermore, the small relative deviation error indicates that $\lambda E_{est,1}$ tended to slightly underestimate the measured values, but in any case less than λE_{PM} does (Fig. 8). Together with the above results, the values for the modeling efficiencies showed the good performance of the proposed method under hypothesis 1 for estimating β , λE and H . Results obtained with $\lambda E_{est,2}$ were similar to those obtained with $\lambda E_{est,1}$ but with a higher degree of variability.

With respect to the estimation of β and sensible heat flux H , hypotheses 2 and 3 led to similar results (Table 3) with high RMSE values. On average H was overestimated, as indicated by the negative MBE, but the slopes of the linear regressions were close to 1 for $H_{est,1}$ and $H_{est,2}$ (Fig. 9a). Hypothesis 3 may also be considered appropriate for estimating λE and H . In particular for the sensible heat flux, the values of modeling efficiency obtained were just a little lower than those obtained under hypotheses 1 or 2. Comparison between $H_{est,3}$ and measured values of H showed good agreement, particularly for the nocturnal period (subset of validation data with $\beta < -1$) as can be seen in Fig. 9b. It should also be noted that in hypothesis 3 aerodynamic resistance r_a was taken as constant (Eq. 19), and that wind speed is therefore not needed to estimate the surface factor $S_{est,3}$ or the Bowen ratio $\beta_{est,3}$. Taking into account this advantage and the results obtained, hypothesis 3 could also be considered useful for estimating λE and H under semiarid and windy conditions such as those found in the Ebro river valley.

5. CONCLUSIONS

We explored an approach for estimating the surface factor S (Eq. 16) or the surface resistance r_c as a function of standard meteorological variables. This empirical approach was then applied for estimating the Bowen ratio β (Eq. 15) and the latent λE and sensible H heat fluxes over grass (Eqs. 13 and 6, respectively). The issue is that when r_c is calculated in a 'top-down' approach by inverting the Penman-Monteith equation, the relationship obtained shows that r_c depends on environmental variables (Eq. 20). An approach for modeling r_c or S as a function of climatic conditions, could therefore be regarded as potentially useful for improving the estimation of energy partitioning β and surface energy fluxes.

Experimental results reported by other authors showed that, for a limited range of β values throughout the diurnal period, there is a linear relationship between r_c/r_a and r_i/r_a . For our semiarid region with a Mediterranean climate, results obtained using the same methodology show that the functional form of the dependence between r_c/r_a and r_i/r_a departs from linearity. The response of r_c/r_a tends towards a certain saturation value when r_i/r_a increases. Using the calibration data set, the best empirical approach for estimating S and β on an hourly basis is a function of the square root of the absolute value of r_i/r_a . This result is valid for any range of β values: it includes the largest possible range of situations encountered in the course of the day, thereby extending the results reported by other authors.

The estimated surface factor S_{est} was applied to the validation data set, using three different hypotheses for computing r_a . Hourly values of Bowen ratio and latent and sensible heat fluxes were thus estimated and validated by comparison with measured values. Results for β indicate good performance by the model under hypothesis 1, although with a high degree of variability. Estimated latent heat flux performed relatively better under hypothesis 1 than under the other two hypotheses. The small relative deviation error and root mean square error indicate that $\lambda E_{est,1}$ tends to slightly underestimate measured values. Estimates λE_{PM} obtained with the PM equation lead to relative errors that are larger than those obtained for the proposed model once it has been calibrated. There is a tendency for λE_{PM} to underestimate the high latent heat fluxes under semiarid conditions.

Values for modeling efficiency indicate that the proposed method is appropriate for estimating β , λE and H under hypothesis 1. Although the improvement found in this work seems to be somewhat limited, the estimation of evapotranspiration tends to perform better than the PM method with constant

r_c . On average, sensible heat flux is overestimated with the proposed method. However, the estimated values show good agreement with measured ones for the nocturnal period, even under hypothesis 3. Since aerodynamic resistance is taken as constant in hypothesis 3, wind speed is not needed to estimate the Bowen ratio $\beta_{est,3}$.

The empirical approach for estimating the surface factor as a function of standard meteorological variables can be considered potentially useful for estimating β , λE and H under the semiarid conditions of the Ebro river valley. This approach has the drawback that it requires local calibration, but the small improvement observed in the estimation of λE may contribute to produce water savings.

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TABLES

Table 1. Locally calibrated empirical coefficients for the best-fit relationship found for the whole calibration data set, of the form $(r_c/r_a)_{est,j} = a_j + b_j \sqrt{r_i/r_a}$. The last three columns show the values of the statistics used for comparison between estimated and experimental values of r_c/r_a , when empirical calibration was applied to the validation data set.

Hypothesis*	Calibration data set				Validation data set				
	n	a _j	b _j	R ²	n	$\bar{O}$	MBE	RMSE	EF
1. $(r_c/r_a)_{est,1}$	705	-1.0	1.90	0.65	1402	2.93	0.076	1.98	0.57
2. $(r_c/r_a)_{est,2}$	702	-0.49	1.38	0.66	1391	1.60	0.022	1.08	0.57
3. $(r_c/r_a)_{est,3}$	689	-0.95	1.67	0.59	1386	1.59	0.088	1.58	0.52

* n: number of hourly data; a_j: intercept; b_j: slope; R²: coefficient of determination; $\bar{O}$: measured mean value; MBE: mean deviation error; RMSE: root mean square error; EF: modelling efficiency.

Table 2. Simple linear regression ($P = c_0 + c_1 O$) and statistics for comparison between estimated (P) and measured (O) hourly values of: a) surface factor S and b) the Bowen ratio β . Results are for the global validation data set (Zaragoza and Mas Bove) and for the three hypotheses considered.

Method*		Validation data set							
		n	c ₀	c ₁	R ²	$\bar{O}$	MBE	RMSE	EF
Hypothesis 1	$S_{est,1}$	1402	0.3	0.61	0.60	0.88	0.046	0.62	0.60
	$\beta_{est,1}$		-0.01	0.86	0.93	-0.23	-0.019	0.24	0.92
Hypothesis 2	$S_{est,2}$	1391	0.17	0.60	0.60	0.48	0.02	0.34	0.60
	$\beta_{est,2}$		0.05	1.24	0.88	-0.21	0.004	0.44	0.72
Hypothesis 3	$S_{est,3}$	1386	0.20	0.51	0.53	0.47	0.03	0.46	0.52
	$\beta_{est,3}$		0.02	1.17	0.81	-0.21	0.018	0.52	0.62

* n: number of hourly data; c₀: intercept; c₁: slope; R²: coefficient of determination; $\bar{O}$: measured mean value; MBE: mean deviation error; RMSE: root mean square error; EF: modelling efficiency.

Table 3. Simple linear regression ($P = c_0 + c_1 O$) and statistics for comparison between estimated (P) and measured (O) hourly values of: *a*) latent heat flux λE (W m^{-2}), and *b*) sensible heat flux H (W m^{-2}). Results are for the global validation data set (Zaragoza and Mas Bove) and for the three hypotheses considered. Estimates obtained using the PM equation (λE_{PM}) have also been included for comparison purposes. Measured λE and H values were obtained using a weighing lysimeter (Zaragoza) and a Bowen ratio system (Mas Bove).

Method*	Validation data set							
	n	c_0 (W m^{-2})	c_1	R^2	$\bar{O}$ (W m^{-2})	MBE (W m^{-2})	RMSE (W m^{-2})	EF
$\lambda E_{est,1}$	1402	6.1	0.97	0.96	199.3	0.28	27.6	0.97
$\lambda E_{est,2}$	1391	0.29	0.92	0.97	200.6	15.6	30.8	0.96
$\lambda E_{est,3}$	1386	3.5	0.91	0.95	201.2	15.0	35.4	0.94
λE_{PM}	1402	14.7	0.86	0.96	186.3	13.0	33.5	0.95
$H_{est,1}$	1402	2.9	0.76	0.74	10.9	-0.28	27.6	0.74
$H_{est,2}$	1391	18.1	0.78	0.76	11.4	-15.6	30.8	0.67
$H_{est,3}$	1386	19.3	0.63	0.64	11.7	-15.0	35.4	0.56

*: n: number of hourly data; c_0 : intercept; c_1 : slope; R^2 : coefficient of determination; $\bar{O}$: measured mean value; MBE: mean deviation error; RMSE: root mean square error; EF: modelling efficiency.

FIGURE CAPTIONS

Figure 1.- Energy fluxes at the surface showing the sign convention. Δe and ΔT are the vapour pressure and temperature difference between the two measurement levels. $\partial e/\partial z$ and $\partial T/\partial z$ are the corresponding vapour pressure and temperature gradients.

Figure 2.- Study region in northeast Spain showing the location of the measurement sites.

Figure 3.- Daily evolution for a specific day (July 4, 2000, Zaragoza) of: bulk surface resistance r_e ($s\ m^{-1}$) and aerodynamic resistance r_a ($s\ m^{-1}$), calculated according to Eq. (17) (r_{a1}) and Eq. (18) (r_{a2}).

Figure 4.- Relationship between the Bowen ratio values β and r_e/r_a on an hourly basis for the global calibration data set (Zaragoza and Mas Bove). Data correspond to both diurnal and nocturnal periods for all Cases 1, 2 and 3.

Figure 5.- Variation of measured values of r_e/r_a vs r_i/r_a (hypothesis 1) on an hourly basis for the global calibration data set. On the right, data for the subset ' $\beta > -1$ ' corresponding mainly to the diurnal period. On the left, data for the subset ' $\beta < -1$ ', corresponding to the nocturnal period. The estimated values $(r_e/r_a)_{est,1}$ correspond to the calibration obtained under hypothesis 1 (Table 1).

Figure 6.- Comparison between estimated and experimental values of: a) r_e/r_a , b) surface factor S , on an hourly basis for the global validation data set (hypothesis 1).

Figure 7.- Results for application of the model to estimate the Bowen ratio β values under hypothesis 1 (a) and under hypothesis 3 (b). Results are on an hourly basis for the global validation data set.

Figure 8.- a) Comparison between estimated $\lambda E_{est,1}$ and measured λE values of latent heat flux, under hypothesis 1 for the global validation data set. $\lambda E_{est,1}$ was obtained from Eq. (13) using the estimated surface factor $S_{est,1}$ or the estimated Bowen ratio $\beta_{est,1}$. b) Comparison between hourly estimates of λE_{PM} obtained with the PM equation and measured latent heat flux. Measured values λE were obtained using a weighing lysimeter (Zaragoza) and a Bowen ratio system (Mas Bove).

Figure 9.- a) Comparison between estimated $H_{est,2}$ and measured H values of sensible heat flux, under hypothesis 2 for the global validation data set. $H_{est,2}$ was obtained from Eq. (6) using the estimated Bowen ratio $\beta_{est,2}$. b) Comparison between estimated $H_{est,3}$ and measured values under hypothesis 3, for the subset of validation data with Bowen ratio values $\beta < -1$, i.e., for the nocturnal period only.

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

a)

b)

FIGURE 7

a)

b)

FIGURE 8

a)

b)

FIGURE 9

a)

b)