FIXED VERSUS VARIABLE BULK CANOPY RESISTANCE FOR REFERENCE EVAPOTRANSPIRATION ESTIMATION USING THE PENMAN-MONTEITH EQUATION UNDER SEMIARID CONDITIONS

S. Lecina(1,2), A. Martínez-Cob(1), P.J. Pérez(3), F.J. Villalobos(4), J.J. Baselga(5)

(1) Laboratorio de Agronomía y Medio Ambiente (DGA-CSIC), Dpto. de Genética y Producción Vegetal (EEAD), Apdo. 202, 50080 Zaragoza, Spain.

(2) E-mail: lecina@eead.csic.es.

(3) Dpto. de Medi Ambient i Ciències del Sol, Universitat de Lleida, Av. Rovira Roure 191, 25198 Lleida, Spain.

(4) Instituto de Agricultura Sostenible (CSIC) and Dep. Agronomía, Universidad de Córdoba, Apdo. 4084, 14080 Córdoba, Spain.

(5) Departamento de Cultivos Herbáceos, Servicio de Investigación y Desarrollo Tecnológico, Junta de Extremadura, Finca La Orden, Apdo. 22, 06080 Badajoz, Spain.

SUMMARY

In this paper, daily ET_0 estimates at two semiarid locations, Zaragoza and Córdoba, were obtained with the Penman-Monteith equation using either fixed (70 s m^{-1}) or variable r_c values. Variable r_c values were computed with two models, Katerji and Perrier, and Todorovic. Daily ET_0 estimates were computed from 24-hour meteorological averages or from the sum of hourly estimates. Daily ET_0 measured values were obtained with a weighing lysimeter (Zaragoza) and an eddy covariance system (Córdoba). There was a good agreement at both locations between estimated and measured ET_0 values using a fixed r_c value and 24-hour meteorological averages. Estimates obtained from the sum of hourly estimates were somewhat worse. When 24-hour meteorological averages were used, the Katerji and Perrier model for variable r_c slightly improved ET_0 estimates at both locations. But that improvement does not support the effort to locally calibrate that model. When daily ET_0 estimates were obtained from the sum of hourly estimates, the Todorovic model improved the estimation at Zaragoza and, at a lesser degree, at Córdoba. Under the semiarid conditions of the two studied locations, the use of the Todorovic model is recommended to get hourly ET_0 estimates from which daily estimates can be obtained. If 24-hour meteorological averages are used, a fixed r_c value as proposed by Allen et al. (1998) should be enough for accurate ET_0 estimates.

1. INTRODUCTION

Evapotranspiration is a component of the hydrological cycle whose accurate computation is needed for an adequate management of water resources. In particular, a high level of accuracy in crop evapotranspiration estimation can result in saving economic and water resources for both planning and management of irrigated areas.

In 1977, the Food and Agriculture Organization of the United Nations (FAO) proposed a methodology for computing crop evapotranspiration, based in the use of reference evapotranspiration (ET_0) and crop coefficients (K_c) (Doorenbos and Pruitt, 1977), methodology that remains valid at the present day. In 1998, FAO published a new manual for computing crop water requirements (Allen *et al*., 1998), that redefined the concept of reference evapotranspiration and adopted the Penman-Monteith equation for its estimation, in substitution of the Penman equation recommended by Doorenbos and Pruitt (1977). This equation had been previously endorsed by the international scientific community as a consequence of the good results obtained in comparison with other equations in different regions of the world (Allen *et al*., 1989; Jensen *et al*., 1990; Smith et al., 1991, Allen et al., 1994a, b).

Later studies also showed lesser differences between estimated and measured ET_0 with the Penman-Monteith equation than with others (Choisnel et al., 1992; Hussein, 1999; Ventura et al., 1999; Berengena et al., 2001). Notwithstanding, many of these studies suggest an underestimation of the measured ET_0 in semi-arid and windy areas with high atmospheric evaporative demand, and overestimation with low demand. That underestimation varied between 2 % and 18 % (Rana et al., 1994; Steduto et al., 1996; Pereira et al., 1999; Todorovic, 1999; Ventura et al., 1999).

Bulk canopy resistance (r_c) is a primary factor in the evapotranspiration process (Monteith, 1965). This resistance is not only a physiological parameter, it also has an aerodinamic component. Hence, it depends on multiple factors such as meteorological variables, plant water potential, and position of leaves in the plant (Perrier, 1975; Alves et al., 1998; Pereira et al., 1999; Alves and Pereira, 2000).

Smith et al. (1991) and Allen et al. (1994a, b) proposed a constant value for bulk canopy resistance of 70 s m^{-1} to calculate grass reference evapotranspiration with the Penman-Monteith equation. This assumption was adopted by FAO (Allen et al., 1998) in order to obtain a standard equation that can be applied worldwide. Nevertheless, Rana et al. (1994), Steduto et al. (1996) and Ventura et al. (1999), among others, consider this fixed value of $\mathrm{r_c}$ as a possible cause of the previously mentioned underestimation of the Penman-Monteith equation.

An approach to estimate bulk canopy resistance is through relationships obtained between $\mathrm{r_c}$, computed by inverting the Penman-Monteith equation, and climatic variables, using the multiplicative model of Jarvis (1976). However, this approach has been questioned because of the same variables considered in the Jarvis model are already considered when computing r_c by inverting the Penman-Monteith equation. Also, this procedure only includes the physiological component of the r_c, but not consider the aerodynamic component (Alves and Pereira, 2000).

Katerji and Perrier (1983) proposed other approach through a linear model in which r_c depends on climate variables and aerodinamic resistance. This model has been tested with good results, and several authors have recommended it for practical purposes (Rana et al., 1994; Pereira et al., 1999; Alves and Pereira, 2000; Rana and Katerji, 2000). However, this model requires calibration to find its parameters and was developed for a limited range of Bowen ratio values. Recently, Todorovic (1999) developed a model, where r_c is also a function of climatic variables and aerodynamic resistance, but that does not requires calibration and can be applied regardless of Bowen ratio values. Application of this model to the computation of ET_0 with the Penman-Monteith equation showed a better adjustment to measured ET_0 than with a fixed r_c value (Todorovic, 1999).

In this paper, the Penman-Monteith equation with fixed (70 s m^{-1}, Allen et al., 1998) and variable r_c values was used to estimate daily values of ET_0 at the Ebro and Guadalquivir valleys, in Spain. About 42 % of the Spanish irrigated surface is located in these two valleys. Daily ET_0 estimates were obtained by directly applying the Penman-Monteith equation with 24-hour average meteorological variables or by applying that equation to hourly average meteorological variables and summing up the hourly estimates. Variable r_c values were obtained by applying the models of Katerji and Perrier (1983) and Todorovic (1999). Estimates were compared against measured ET_0 using a weighing lysimeter (Ebro River Valley) or an eddy covariance system (Guadalquivir River Valley). The main objective was to evaluate whether the use of variable rather than fixed r_c values would improve the ET_0 estimates obtained by applying the Penman-Monteith equation under the semiarid conditions of the Ebro and Guadalquivir River Valleys, where evaporative demand is high particularly during summer.

2. MATERIALS AND METHODS

2.1. Site description

This study was conducted in two locations representative of the central areas of the Ebro and Guadalquivir River Valleys, Zaragoza and Córdoba, respectively (Figure 1).

2.1.1. Ebro River valley

In this case, the study was conducted on an experimental farm located at Zaragoza, on the terraces of Gállego River, about 8 km north from its mouth to the Ebro River. Elevation is 225 m above sea level, latitude is 41° 43’ N, and longitude is 0° 49’ W (of Greenwich). Average annual precipitation is about 330 mm, mostly recorded in spring and fall although some stormy rainfalls are relatively frequent during summer. Average annual temperature is about 15 °C. The zone is within the windiest areas of Spain.

Measurements were taken over a 1.2 ha (120 m x 100 m) plot, which was uniformly covered with grass (*Festuca arundinacea* Moench.). Soils of the plot are described as Typic Xerofluvent. The plot was regularly irrigated and clipped all year round to maintain it as near as possible to the reference standard. The measurement period was March to October 1999 and March to September 2000.

A weighing lysimeter, 1.7 m depth and 6.3 m^2 effective surface area, was located in the center of the plot. A load cell connected to a Campbell Scientific datalogger (CR500) recorded lysimeter mass losses every 0.5 s from which hourly ET_0 rates were derived. Daily measured ET_0 values were obtained summing up the hourly ones. The combined resolution of both load cell and datalogger allowed the detection of mass losses of about 0.3 kg (0.05 mm water depth). Only days without incidences (irrigation, rainfall, lysimeter drainage and grass clipping), when measured grass height was between 0.10 and 0.15 m, were used for analyses.

An automatic weather station (CR10 Campbell Scientific) was located close to the lysimeter. The datalogger recorded hourly averages of air temperature and relative humidity, net radiation, soil heat flux, and wind speed direction. Table 1 lists the models and manufacturers of the sensors used as well as the measurement heights.

2.1.2. Guadalquivir River valley

In this case, the study was conducted on an experimental farm located on the terraces of the Guadalquivir River, near Córdoba. Elevation is 70 m above sea level, latitude is 37° 51’ N, and longitude is 4° 51’ W (of Greenwich). Average annual precipitation is about 600 mm, recorded during winter, spring and fall, with almost null rainfall recordings during summer. Average annual temperature is about 17 °C. Advective conditions during summer are more frequent than in Zaragoza. The area is significantly less windy than the middle Ebro River valley.

Measurements were taken over a 1.3 ha (115 m x 115 m) plot, which was uniformly covered with grass (*Festuca arundinacea* Moench.). Soils of the plot are also described as Typic Xerofluvent. This plot was also regularly irrigated and clipped all year round. The measurement period was July to October 1997 and July to August 1998. Only days where measured grass height was between 0.10 and 0.15 m were used for analyses.

A Campbell Scientific eddy covariance system was located in the center of the plot to measure ET_0. Sensors included a krypton hygrometer (model KH20), a single-axis sonic anemometer (model CA27), as well as two fine wire thermocouples (models 127 and TCBR-3), attached to the two previously mentioned sensors. Measurements of fluctuations of water vapor density, vertical wind speed and air temperature were recorded every 0.1 s and averaged every 10 minutes. These readings were used to obtain hourly measured latent heat flux values as described by Villalobos (1997). These values were transformed to hourly ET_0 rates by dividing by latent heat of vaporization derived from air temperature readings following Allen et al. (1998). Daily measured ET_0 rates were obtained by summing up the hourly ones. Likewise, an automatic weather station (CR10 Campbell Scientific) was located close to the eddy covariance system. Measured meteorological variables, as well as sensor models, manufacturers and measurement heights were the same as for the Ebro River valley case (Table 1).

2.2. ET_0 computations

2.2.1. Penman-Monteith equation

The well-known Penman-Monteith equation is based on the Penman (1948) equation, a combination method of the energy balance and mass transfer to compute the evaporation from an open water surface. Monteith (1965) introduced the effect of the architecture and the stomatal regulation of the canopy on the water vapor diffusion from a cropped surface. These effects were modeled through the bulk canopy (r_c) and the aerodynamic resistance (r_a). Bulk canopy resistance represents the resistance to water vapor flux from evaporating surfaces (plant stomata and soil), and aerodynamic resistance represents the resistance to air flux over vegetative surfaces. An important assumption of this model is that the whole canopy can be considered as a “big leaf” from which heat and vapor escape. This “big leaf” is located at $d+z_{0m}$ height, where d is the zero-plane displacement height and z_{0m} is the roughness length for momentum. Thus, the Penman-Monteith equation can be written as (Allen et al., 1998):

$$\lambda ET_0 = \frac{\Delta(R_n - G) + \rho_a c_p (e_s - e_a)/r_a}{\Delta + \gamma(1 + r_c / r_a)} \qquad (1)$$

where ET_0 is reference evapotranspiration, λ is latent heat of vaporization, R_n is net radiation, G is soil heat flux, Δ is the slope of the saturation vapor pressure versus temperature relationship, ρ_a is the mean air density at constant pressure, c_p is the specific heat of the air, e_s is saturation vapor pressure, e_a is actual vapor pressure and γ is the psychrometric constant. In this paper, measured rather than estimated R_n and G values were used to avoid the effect of any uncertainties in the estimation of these two variables on the comparison of the use of fixed versus variable r_c values. Units and computations of all elements (but R_n and G) of equation (1) (λ, Δ, ρ_a, c_p, e_s, e_a and r_a) followed Allen et al. (1998). Also, r_c was considered constant and equal to 70 s m^{-1} and grass height was set to 0.12 m (Allen et al., 1998). Equation (1) was applied to obtain daily ET_0 estimates using 24-hour average meteorological variables (ET_{24F}). Additionally, equation (1) was applied to obtain hourly ET_0 estimates using hourly average meteorological variables and then those estimates were summed up to get daily values (ET_{sumF}). These computations were done for all days selected as explained in sections 2.1.1 and 2.1.2.

2.2.2. Katerji and Perrier model

Katerji and Perrier (1983) proposed a model in which canopy resistance depends on climatological variables. The model is based on an approach by Perrier (1975) and has similar hypotheses than Monteith (1965). Thus, it is assumed that the vapor diffusion from the crop is influenced by the architecture of the canopy and the stomatal regulation of the leaves. However, the energy conservation boundary condition is applied to the top of the canopy. In other words, the "big leaf" is placed at the crop height, so that aerodynamic resistance is computed from the top of the canopy to the reference height (Alves and Pereira, 2000):

$$r_{aKP} = \frac{ln\left[\left(z_m - d\right)/\, z_{0m}\right] ln\left[\left(z_h - d\right)/\left(h_c - d\right)\right]}{k^2\ u_{zm}} \qquad (2)$$

where z_m is wind measurement height, z_h is air temperature measurement height, and h_c is the mean crop height. The term h_c - d substitutes to z_{oh} (roughness length for heat transfer) that was used to compute r_a following Allen et al. (1998). Again, h_c was set to 0.12 m.

Perrier et al. (1980) showed experimentally a relationship between aerodynamic resistance, bulk canopy resistance and a critical resistance (r*), which represents the canopy resistance for equilibrium evaporation and it depends on climate factors as follows (Pereira et al., 1999):

$$r^* = \frac{\Delta + \gamma}{\Delta}\ \frac{\rho_a\ c_p\ \left(e_s - e_a\right)}{\gamma\left(R_n - G\right)} \qquad (3)$$

Hence, Katerji and Perrier (1983) derived the following linear model for bulk canopy resistance, that they applied successfully to grass and alfalfa:

$$\frac{r_c}{r_{aKP}} = c_0 + c_1 \left(\frac{r^*}{r_{aKP}} \right) \tag{4}$$

where c_0 and c_1 are parameters that must be determined experimentally by regression and may vary among locations. Another constraint of this model is that it should only be applied within some limited range of Bowen ratio values. Thus, Alves and Pereira (2000) indicate that equation (4) is only valid for periods where the Bowen ratio varies between –0.3 and 0.3. This model has also been applied to wheat (Perrier et al. 1980), tomato (Katerji et al., 1988) and rice (Peterschmitt and Perrier, 1991). Alves et al. (1999) and Alves and Pereira (2000) presented a detailed discussion about the physical meaning of the regression parameters of equation (4).

In order to apply Katerji and Perrier (1983) model, the data set available in each location was divided in two groups: a) a calibration data set; b) a validation data set. Available days were ordered by dates and one of three days were selected for calibration, while the other two days were selected for validation. For the calibration data set, daily and hourly values of r_c were obtained by solving the Penman-Monteith equation (1) using daily and hourly measured ET_0 values, respectively, and the corresponding meteorological variables. Equations (2) and (3) were used to get aerodynamic and critical resistance values (daily and hourly), respectively. Then, a simple linear regression between r_c/r_{aKP} and r^*/r_{aKP} was fit to obtain daily and hourly values of parameters c_0 and c_1 for both locations, Zaragoza and Córdoba. In the case of hourly values, only those periods for which the Bowen ratio was between –0.5 and 0.5 were used for the linear regression analyses. Most of the diurnal hourly periods fell within this Bowen ratio value range. Later, the calibrated c_0 and c_1 parameters and equations (1) to (4) were applied to the validation data set to obtain daily estimates of ET_0 either by directly applying those equations to 24-hour averages of the recorded meteorological variables (ET_{24KP}) or by applying them to hourly averages and then summing up hourly ET_0 estimates (ET_{sumKP}). In the case of hourly averages, a fixed value of r_c (200 s m^{-1}) was considered for night time hours.

2.2.3. Todorovic model

A deep discussion on the theory and assumptions of the Todorovic model can be found in Todorovic (1999). Here, only the equations used to get r_c values are presented. Todorovic (1999) defines a climatological resistance (r_i) as follows:

$$r_i = \frac{\rho c_p (e_s - e_a)}{\gamma (R_n - G)} \tag{5}$$

Then, Todorovic (1999) uses r_i and r_a, defined following Allen et al. (1998), to set this 2nd degree equation:

$$a\left(\frac{r_c}{r_i}\right)^2 + b\left(\frac{r_c}{r_i}\right) + c = 0 \tag{6}$$

where

$$a = \frac{\Delta + \gamma (r_i / r_a)}{\Delta + \gamma} (r_i / r_a)(e_s - e_a) \tag{7}$$

$$b = -\gamma \left(\frac{r_i}{r_a}\right) \frac{\gamma}{\Delta} \frac{(e_s - e_a)}{\Delta + \gamma} \tag{8}$$

$$c = -(\Delta + \gamma) \frac{\gamma}{\Delta} \frac{(e_s - e_a)}{\Delta + \gamma} \tag{9}$$

Equation (6) has only one positive solution. Equations (6) to (9) were applied only to the validation data set to obtain daily and hourly estimates of r_c using the corresponding 24-hour and hourly averages of meteorological variables. Like in the case of Katerji and Perrier model, a fixed value of r_c (200 s m^{-1}) was considered for night time hours. Then, these variable r_c values were used, assuming a grass height of 0.12 m, to obtain daily ET_0 estimates either by directly applying equation (1) to 24-hour averages of the recorded meteorological variables (ET_{24T}) or by applying them to hourly averages and then summing up hourly ET_0 estimates (ET_{sumT}).

2.3. Statistical analyses

Comparisons between measured and estimated daily ET_0 values were carried out by simple linear regression ($y = b_0 + b_1 x$) where measured values were used as the dependent variable y and the estimated ones were used as the independent variable x. Additionally, the following statistics were computed as described by Willmott (1982): root mean square error (*RMSE*), systematic mean square error (*MSEs*) and index of agreement (*IA*).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2} \tag{10}$$

$$MSEs = \frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - x_i)^2 \tag{11}$$

$$IA = 1 - \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{\sum_{i=1}^{n}\left[\left|y_i - \bar{x}\right| + \left|x_i - \bar{x}\right|\right]^2} \tag{12}$$

where y_i is the i^{th} observed ET_0 value, x_i is the i^{th} estimated ET_0 value, $\hat{y}_i$ is the i^{th} predicted ET_0 value through the simple linear regression and $\bar{x}$ is the mean of the estimated values.

3. RESULTS AND DISCUSSION

Table 2 lists some statistics of the air temperature and wind speed recordings during the measurement period at both locations, Zaragoza and Córdoba. These values are presented only for description purposes, as a direct comparison between them is not possible due to the different measurement periods. The most important feature of Table 2 is that no days showed an average daily wind speed above 4.0 m s^{-1} at Córdoba, while this event occurred for 9 % of the days at Zaragoza. As stated in section 2.1.1, Zaragoza is located within one of the windiest areas of Spain.

3.1. Estimation with fixed r_c value

Figure 2 shows the results of the simple linear regression and error analysis of the comparison between measured and estimated (using fixed r_c value) daily ET_0 values for the whole measurement period at the two locations. All coefficients of determination were high, above 0.94, as well as all indices of agreement, above 0.97. These results suggest that the agreement between measured and estimated daily ET_0 was quite good whether 24-hour averages of metorological variables or sums of hourly estimates were used. Also, these results indicate that scatter of the data was relatively small (Figure 2). ET_{sumF} estimates were lower than ET_{24F} estimates at both locations. This has been also observed elsewhere (Allen et al., 1994). According to regression and error analysis statistics, differences between ET_{24F} and ET_{sumF} estimates were higher at Zaragoza. At this location, there was a tendency for Penman-Monteith to overestimate measured ET_0 at low evaporative demand values and to underestimate it at high evaporative demand values (Figure 2), particularly for the ET_{sumF} case. For the ET_{24F} case, this underestimation at high evaporative demand values was negligible. At Córdoba, the opposite was observed although agreement between measured and estimated ET_0 values was higher according to results shown in Figure 2. This behavior of the Penman-Monteith equation, overestimation for low ET_0 values and underestimation for high ET_0 values, has been reported at other Mediterranean locations (Steduto et al., 1996). One reason for the different behavior seen at Córdoba might be the uncertainties of any measurement system. It has been reported that eddy covariance systems may underestimate this variable in some instances depending on the horizontal sensor separation and measurement height among other factors (Foken and Wichura, 1996). In this work, the method proposed by Villalobos (1997) to correct this problem was applied and the energy balance closure for each day was evaluated. Only those days for which the energy balance closure was less than 10 % of the latent heat flux (LE) were used for further analyses.

Another reason for the differences between the two locations was the different wind conditions. Zaragoza typically has higher wind speeds than Córdoba (Table 2). The agreement between lysimeter and Penman-Monteith ET_0 values has been shown to decrease as wind speed increases (Lecina and Martínez-Cob, 2000). Under high evaporative demand conditions (mostly sunny days during summer), the ET_0 rates are expected to further increase under windy conditions. In these situations, the Penman-Monteith equation with fixed r_c value seemed unable to adequately represent the water vapor flux from crops to the atmosphere and leads to underestimation of ET_0 (Rana et al., 1994; Steduto et al., 1996; Pereira et al., 1999; Todorovic, 1999; Ventura et al., 1999).

Under these high evaporative demand and windy conditions, the underestimation of hourly estimates is added when those estimates are summed up to get daily values and so these are underestimated. When 24-hour averages of meteorological variables are used several errors may cancel each other leading to better daily ET_0 estimates. For instance, Allen et al. (1994) pointed out that daily vapor pressure deficit may be overestimated when estimated from maximum and minimum air temperature and relative humidity values instead of averaging hourly vapor pressure deficits. But this error may be cancelled by the underestimation that could be expected from using average daily wind speed instead of average daytime wind speed in the ET_0 computations.

3.2. Calibration of the Katerji and Perrier model

Table 3 shows the parameters c_0 and c_1, equation (4), determined by regression fit for the calibration period at both locations, Zaragoza and Córdoba. Coefficients of determination were moderate to moderately high. Better R^2 values were obtained when using hourly r_c estimates. For this later case, R^2 was slightly lower than that reported by Alves and Pereira (2000) but the measurement period was larger in the present work so weather changes from day to day and within each day were higher. Estimates of daily r_c obtained by inverting the Penman-Monteith equation showed great variations from day to day likely due to day to day errors and biases in the lysimeter and weather measurements (Todorovic, 1999). Thus, for the calibration period, 27.0 and 13.8 % of the daily r_c estimates were less than 70 s m^{-1} at Zaragoza and Córdoba, respectively, while 43.2 and 55.2 % of those estimates were higher than 100 s m^{-1}. Hourly r_c estimates were limited to periods for which Bowen ratio was less than $\left|0.5\right|$ and so less variation was observed as indicated by the higher R^2 listed on Table 3.

Alves and Pereira (2000) indicated that c_0 and c_1 are functions of the Bowen ratio. However, a previous knowledge of the energy partitioning would be required to use those functions to estimate r_c for the direct use of the Penman-Monteith equation. If regression fits are used instead to estimate c_0 and c_1, as in this paper, the need for a previous calibration of the Katerji and Perrier model still remains as an important limitation for its widespread use.

3.3. Estimation with variable r_c values

Figure 3 shows the results of the simple linear regression and error analysis of the comparison between measured and estimated daily ET_0 values for the validation data set at Zaragoza, for each of the r_c models studied (fixed value, Katerji and Perrier, and Todorovic), using either 24 hour averages of meteorological variables or summing up hourly estimates. Figure 4 shows the same type of results for the case of Córdoba. Results indicate that there were not great differences whether a fixed or a variable r_c value was used. All coefficients of determination and indices of agreement were higher than 0.91 and 0.97, respectively. The *RMSE* values were less than 0.55 mm day^{-1} and most of them varied between 0.34 and 0.46 mm day^{-1}. Perhaps, the most important differences were noticed in some instances for the *MSEs* statistics. Nevertheless, some improvement was obtained at each location by using variable r_c.

Using a fixed r_c value, the results seen for the validation period were quite similar to those seen for the whole measurement period at both locations (Figures 3 and 4). Again, best estimates were obtained when using 24-hour average meteorological variables. When using variable r_c values (Katerji and Perrier model), there was an improvement on the ET_0 estimation at both locations when 24-hour average meteorological values were used. However, daily ET_0 estimates obtained by summing up hourly estimates were worse at both locations when using the Katerji and Perrier model than when using a fixed r_c value (Figures 3 and 4). According to results from Table 3, perhaps an improvement on the estimation of hourly values could have been expected, but this was not the case. As stated previously, r_c values showed important variations within each day and from day to day. Also, the weather conditions and Bowen ratios on the validation period were certainly different than those for the calibration period. Bowen ratios at some hourly periods may have been out of the calibration range used (-0.5, 0.5). It has been stated that the effect of r_c errors on ET_0 estimation is relatively small (Todorovic, 1999). All of these circumstances, and the possible effect of 24-hour averaging cancelling hourly errors discussed on section 3.1, therefore caused that the benefits of applying the Katerji and Perrier model were only noticed for the ET_{24KP} case.

Alves and Pereira (2000) indicated that the parameters of equation (4) can be expressed as functions of the Bowen and the $\Delta/(\Delta+\gamma)$ ratios. Then, the direct application of the Penman-Monteith equation with variable r_c using the Katerji and Perrier model would require a previous knowledge of the energy partitioning. Of course, this is difficult and, for practical purposes, it would more feasible to obtain those parameters by regression fit. But, under this situation, the application of that model must rely on a previous local calibration to find adequate parameters for equation (4). The improvement on ET_0 estimation seen in this work has been modest and then the need for that calibration has not likely enough support to the use of variable r_c values estimated from the Katerji and Perrier model, from a practical point of view.

Regarding to the Todorovic model, there was an improvement for the ET_{sumT} case estimates at Zaragoza. Now, these estimates were quite similar to those obtained in the cases ET_{24F} and ET_{24KP}. But, at Córdoba, such improvement was lower and the results for the ET_{sumT} were similar to those for the ET_{24F}. For the ET_{24T} case, the application of the Todorovic model also worsened ET_0 estimates particularly at Zaragoza. Improvements seen at Zaragoza for the ET_{sumT} case were similar to those reported by Todorovic (1999). However, this author also reported some improvement when 24 hour average meteorological values were used.

Todorovic model is based on the extra sensible heat energy provided by advection. Under windy conditions, the advection effects increase at least at a regional scale. This would explain why the improvement of ET_0 estimation (ET_{sumT} case) was higher at Zaragoza.

It is unclear the reasons for the different results seen with the two tested variable r_c models depending on the time scale considered. Figure 5 shows the average hourly (8:00 to 18:00 Greenwich Meridian Time) r_c values estimated for the validation period for both models at the two locations. These r_c values were relatively similar at Zaragoza regardless of the model although, in general, values for the Todorovic model were lower. At Córdoba, differences between the two variable r_c sets were higher and again the lower values were those of Todorovic model. Of course, the coefficients of variation of those average values were quite high indicating the important variations on r_c estimates from day to day. It can be argued that hourly estimation of ET_0 and later summing up of these estimates to get daily values should be preferable in order to better take account of weather effects on the evapotranspiration process and to avoid errors occurring by 24 hour averaging of meteorological variables. If so, the use of Todorovic model, which seems to better describe the effect of weather on the time variability of r_c (without the need for a previous local calibration), would lead to a decrease of the biases of the Penman-Monteith equation when applied for hourly time scales.

4. CONCLUSIONS

The results presented in this paper suggest that daily ET_0 estimates can be obtained accurately enough with the Penman-Monteith, using 24 hour meteorological averages, and assuming a fixed r_c value of 70 s m^{-1} as suggested by Allen et al. (1998), under the semiarid conditions of both the Ebro and Guadalquivir River Valleys. However, if hourly ET_0 estimates are required either for their direct use or for summing up to get daily estimates, the use of Todorovic model should be considered to get variable r_c values at least under semiarid and windy conditions such those of the Ebro River valley. Under semiarid conditions such those of the Guadalquivir River valley the use of Todorovic model would not be as necessary but it will probably not decrease the accuracy of the estimates.

The use of the Katerji and Perrier model to compute variable r_c values should not be adopted for practical purposes due to the minimal improvement of daily ET_0 estimates when 24 hour meteorological averages were used and the lack of improvement when sums of hourly estimates were obtained. Such improvement does not support the effort to locally calibrate this model.

In summary, under the semiarid conditions of this study, it is recommended the use of a fixed r_c value, as proposed by Allen et al. (1998), if daily ET_0 estimates are going to be computed from 24-hour meteorological averages. But the use of the Todorovic model for variable r_c is recommended if daily ET_0 estimates are going to be computed by summing up hourly estimates.

ACKNOWLEDGEMENTS

This work was funded by the projects *HID96-1295* and *REN2001-1630/CLI* (Spanish Ministry of Science and Technology). The first author was also funded with a fellowship from the High Council of Research and Development of the Autonomous Government of Aragón (Spain). Thanks are also due to Jesús Gaudó, Miguel Izquierdo and Enrique Mayoral for their field work and to the private company TILCA for the periodical maintenance of the lysimeter equipment at Zaragoza.

Table 1. Recorded meteorological variables, measurement sensor height and sensor model used at the weather stations of Zaragoza and Córdoba.

Meteorological variable	Measurement height (m)	Sensor model (manufacturer)
Air temperature and relative humidity	1.50	HMP35D (Vaisala)
Net radiation	1.50	Q-7 (Radiation and Energy Balance Systems, REBS)
Wind speed	2.00	Switching anemometer A100R (Vector Instruments)
Wind direction	2.00	Wind vane W200P (Vector Instruments)
Soil heat flux	0.08 (soil heat flux plates)	Two HFT1 soil heat flux plates (REBS)
	0.02-0.06 (soil temperature[1])	TCAV averaging soil temperature probe (Campbell Scientific)

[1] Used to correct soil heat flux data following ASCE (1996).

Table 2. Meteorological conditions (maximum and minimum air temperature and wind speed) during the measurement period at Zaragoza and Córdoba.

Meteorological variable	Zaragoza			Córdoba		
	Average	Maximum	Minimum	Average	Maximum	Minimum
Maximum temperature (ºC)	26.6	38.2	12.1	33.3	38.6	24.4
Minimum temperature (ºC)	11.3	20.1	-2.6	18.2	22.7	9.2
Average wind speed ($m\ s^{-1}$)	2.1	7.6	0.4	1.7	3.6	0.7
Days with daily wind speed above 4.0 $m\ s^{-1}$ (%)	9.0			0.0		

Table 3. Parameters of the Katerji and Perrier model, equation (4), obtained by regression fit at Zaragoza and Córdoba for the calibration period: a) using 24 hour r_c estimates; b) using hourly r_c estimates. N, sample size; R^2, coefficient of determination; c_0, intercept of the regression; c_1, regression slope.

Location	r_c estimates	N	R^2 ($^0/_1$)	c_0 (dimensionless)	c_1 (dimensionless)
Zaragoza	24hour	37	0.414	0.759(1)	0.175(1)
	hourly	356	0.725	0.395(1)	0.385(1)
Córdoba	24hour	29	0.557	0.042(2)	0.330(1)
	hourly	301	0.780	0.377(1)	0.340(1)

(1) Significantly different than 0 (α = 0.95).

(2) Not significantly different than 0 (α = 0.95).

Figure 1. Location of the study areas.

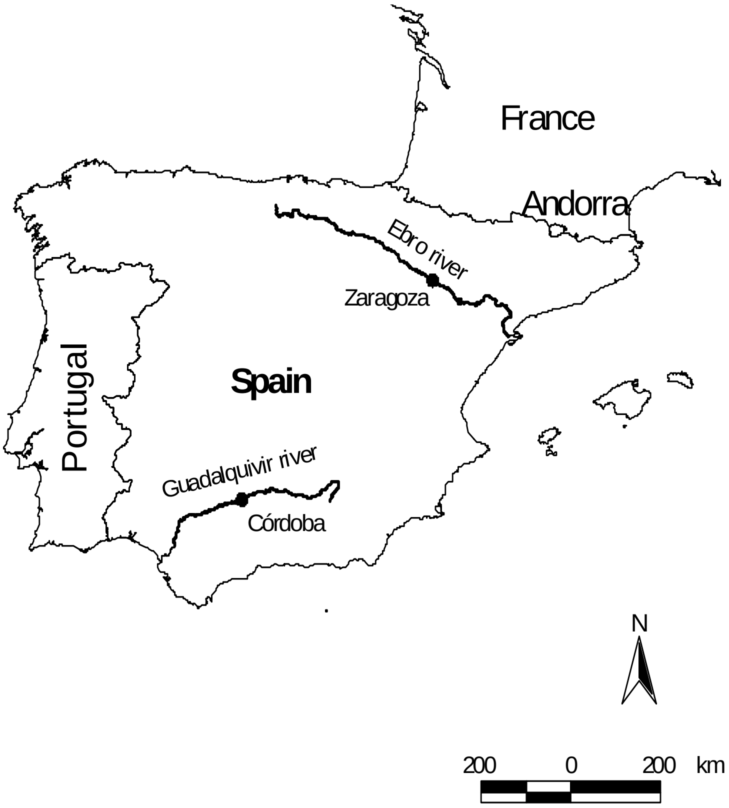

France
Andorra
Ebro river
Zaragoza
Spain
Portugal
Guadalquivir river
Córdoba
N
200
0
200
km

Figure 2. Simple linear regression ($y = b_0 + b_1 x$) and error analysis statistics of the comparison between measured (dependent variable y) and estimated (independent variable x) daily ET_0 values at two locations, Zaragoza and Córdoba, for the whole measurement period. Estimates were obtained using the Penman-Monteith equation with fixed r_c value (70 s m^{-1}) either using 24-hour averages of meteorological variables (ET_{24F}) or summing up hourly estimates (ET_{sumF}). R^2, coefficient of determination ($^0/_1$); b_0, intercept of the regression (mm day^{-1}); b_1, regression slope (dimensionless); *RMSE*, root mean square error (mm day^{-1}); *MSEs*, systematic mean square error (%); *IA*, index of agreement ($^0/_1$); *N*, sample size. (a) b_0 significantly different than 0; (b) b_0 not significantly different than 0; (c) b_1 significantly different than 1; (d) b_1 not significantly different than 1 ($\alpha = 0.95$).

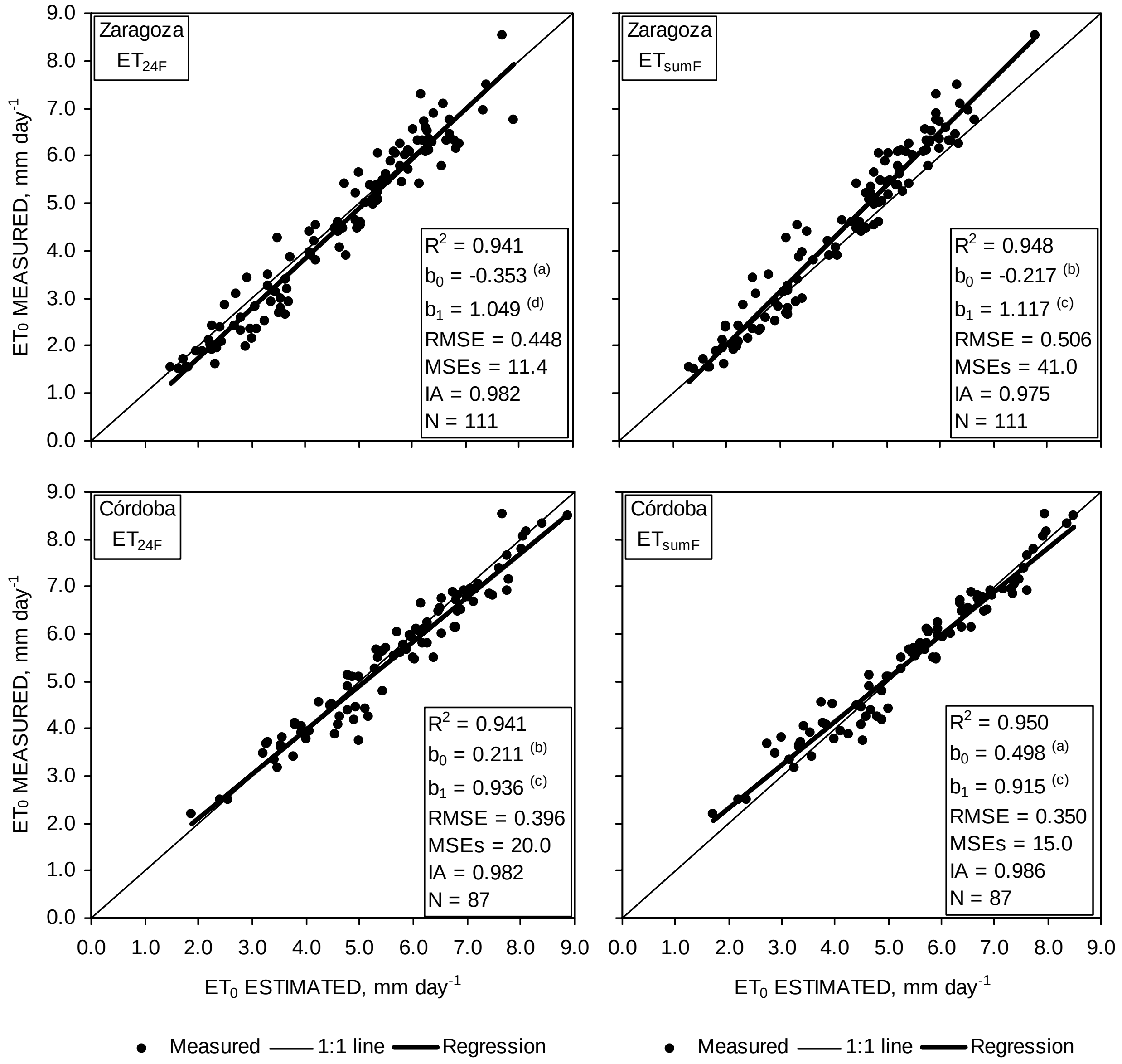

Zaragoza
ET_{24F}
R^2 = 0.941
b_0 = -0.353 (a)
b_1 = 1.049 (d)
RMSE = 0.448
MSEs = 11.4
IA = 0.982
N = 111
Zaragoza
ET_{sumF}
R^2 = 0.948
b_0 = -0.217 (b)
b_1 = 1.117 (c)
RMSE = 0.506
MSEs = 41.0
IA = 0.975
N = 111
Córdoba
ET_{24F}
R^2 = 0.941
b_0 = 0.211 (b)
b_1 = 0.936 (c)
RMSE = 0.396
MSEs = 20.0
IA = 0.982
N = 87
Córdoba
ET_{sumF}
R^2 = 0.950
b_0 = 0.498 (a)
b_1 = 0.915 (c)
RMSE = 0.350
MSEs = 15.0
IA = 0.986
N = 87
ET_0 MEASURED, mm day^{-1}
ET_0 ESTIMATED, mm day^{-1}
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
● Measured
1:1 line
Regression

Figure 3. Simple linear regression ($y = b_0 + b_1 x$) and error analysis statistics of the comparison between measured (dependent variable y) and estimated (independent variable x) daily ET_0 values at Zaragoza for the validation data set. Estimates were obtained using the Penman-Monteith equation with: a) fixed r_c value, either using 24-hour average meteorological variables (ET_{24F}) or summing up hourly estimates (ET_{sumF}); b) variable r_c values (Katerji and Perrier model), either using 24-hour average meteorological variables (ET_{24KP}) or summing up hourly estimates (ET_{sumKP}); and c) variable r_c values (Todorovic model), either using 24-hour average meteorological variables (ET_{24T}) or summing up hourly estimates (ET_{sumT}). R^2, coefficient of determination; b_0, intercept of the regression; b_1, regression slope; *RMSE*, root mean square error; *MSEs*, systematic mean square error; *IA*, index of agreement; *N*, sample size; (a) b_0 significantly different than 0; (b) b_0 not significantly different than 0; (c) b_1 significantly different than 1; (d) b_1 not significantly different than 1 ($\alpha = 0.95$).

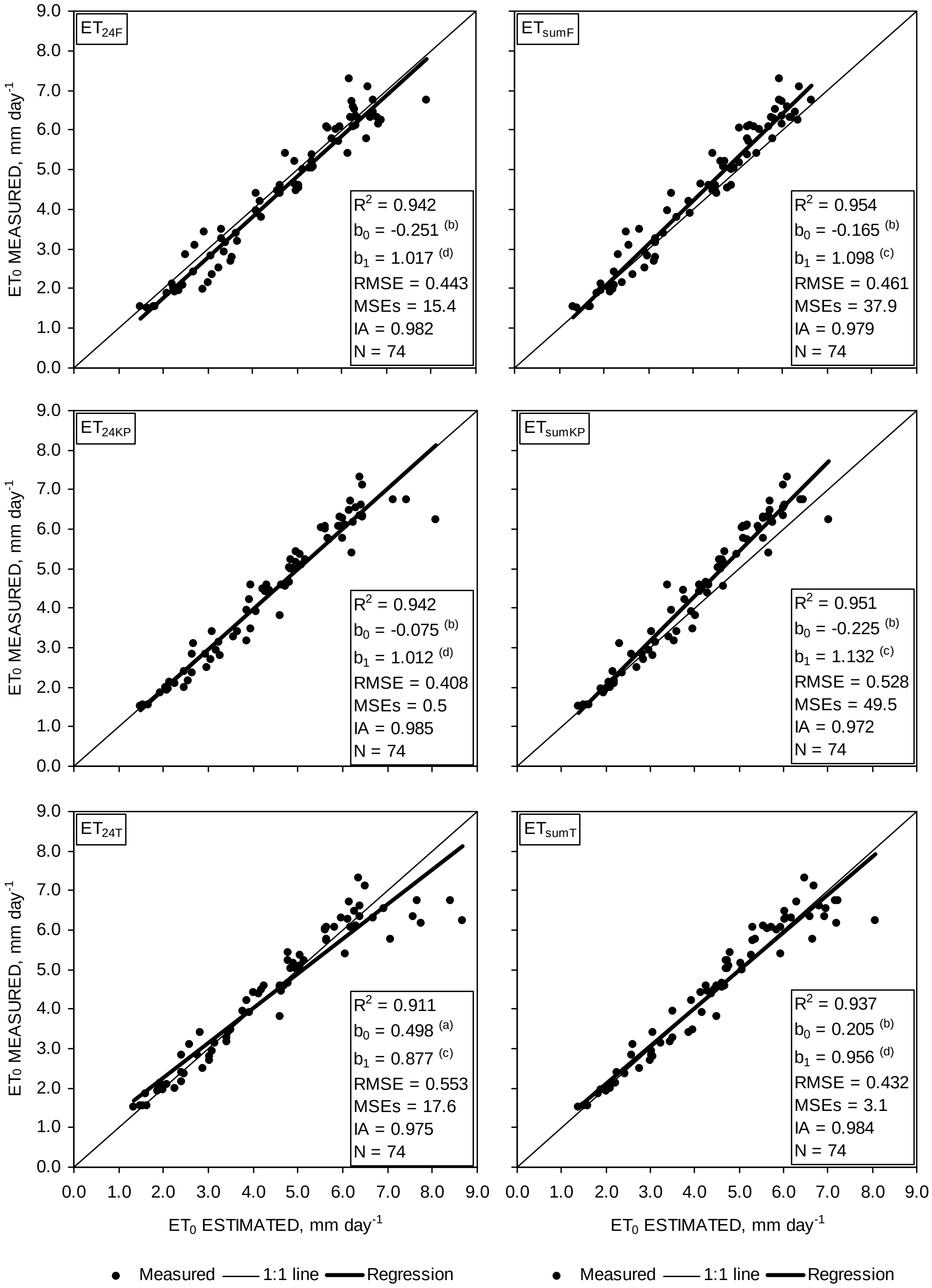

ET$_{24F}$
R^2 = 0.942
b$_0$ = -0.251 (b)
b$_1$ = 1.017 (d)
RMSE = 0.443
MSEs = 15.4
IA = 0.982
N = 74
ET$_{sumF}$
R^2 = 0.954
b$_0$ = -0.165 (b)
b$_1$ = 1.098 (c)
RMSE = 0.461
MSEs = 37.9
IA = 0.979
N = 74
ET$_{24KP}$
R^2 = 0.942
b$_0$ = -0.075 (b)
b$_1$ = 1.012 (d)
RMSE = 0.408
MSEs = 0.5
IA = 0.985
N = 74
ET$_{sumKP}$
R^2 = 0.951
b$_0$ = -0.225 (b)
b$_1$ = 1.132 (c)
RMSE = 0.528
MSEs = 49.5
IA = 0.972
N = 74
ET$_{24T}$
R^2 = 0.911
b$_0$ = 0.498 (a)
b$_1$ = 0.877 (c)
RMSE = 0.553
MSEs = 17.6
IA = 0.975
N = 74
ET$_{sumT}$
R^2 = 0.937
b$_0$ = 0.205 (b)
b$_1$ = 0.956 (d)
RMSE = 0.432
MSEs = 3.1
IA = 0.984
N = 74
ET0 MEASURED, mm day^{-1}
ET$_0$ ESTIMATED, mm day^{-1}
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
● Measured
1:1 line
Regression

Figure 4. Simple linear regression ($y = b_0 + b_1 x$) and error analysis statistics of the comparison between measured (dependent variable y) and estimated (independent variable x) daily ET_0 values at Córdoba for the validation data set. Estimates were obtained using the Penman-Monteith equation with: a) fixed r_c value, either using 24-hour average meteorological variables (ET_{24F}) or summing up hourly estimates (ET_{sumF}); b) variable r_c values (Katerji and Perrier model), either using 24-hour average meteorological variables (ET_{24KP}) or summing up hourly estimates (ET_{sumKP}); and c) variable r_c values (Todorovic model), either using 24-hour average meteorological variables (ET_{24T}) or summing up hourly estimates (ET_{sumT}). R^2, coefficient of determination; b_0, intercept of the regression; b_1, regression slope; *RMSE*, root mean square error; *MSEs*, systematic mean square error; *IA*, index of agreement; *N*, sample size; $^{(a)}$ b_0 significantly different than 0; $^{(b)}$ b_0 not significantly different than 0; $^{(c)}$ b_1 significantly different than 1; $^{(d)}$ b_1 not significantly different than 1 ($\alpha = 0.95$).

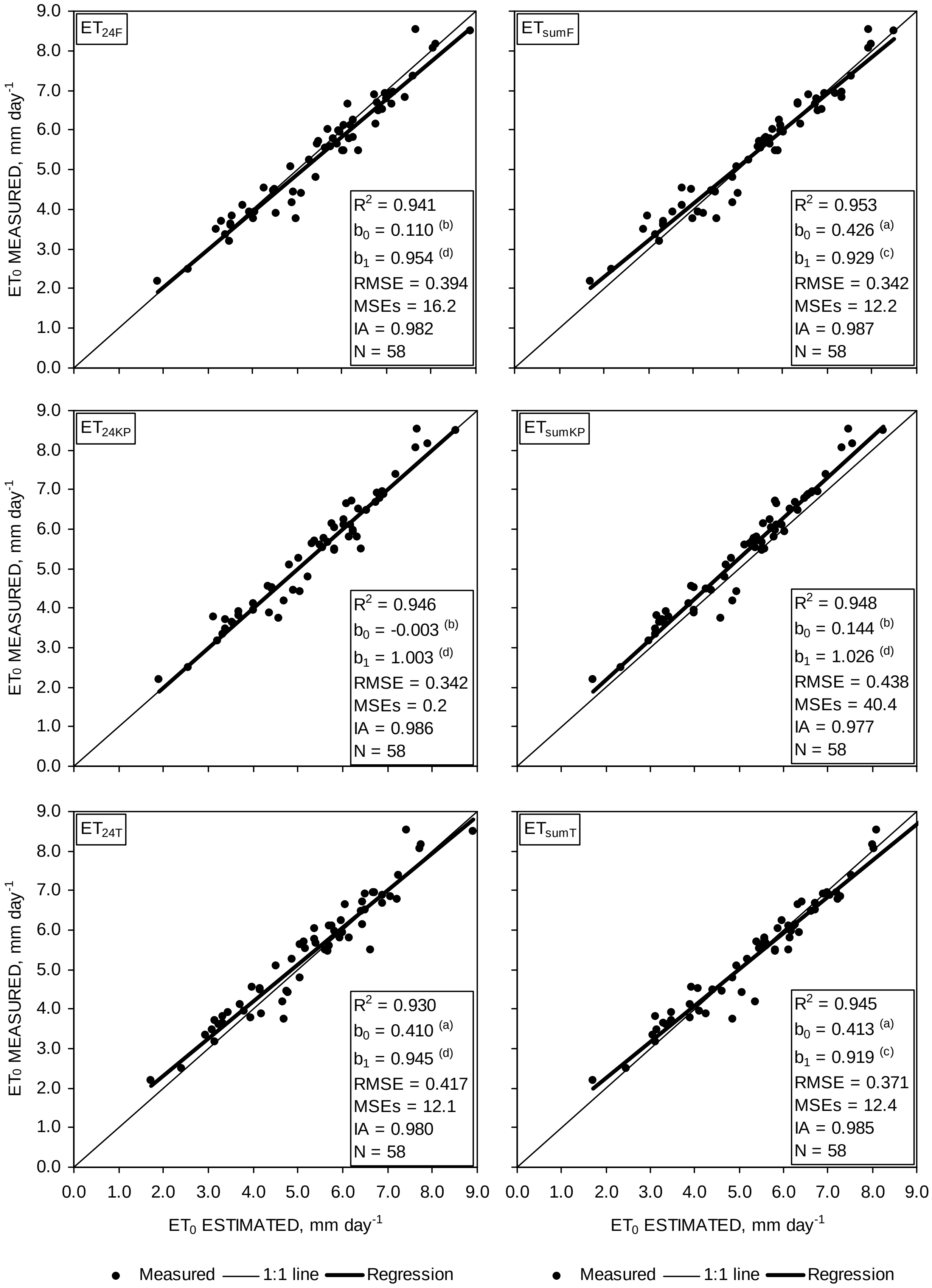
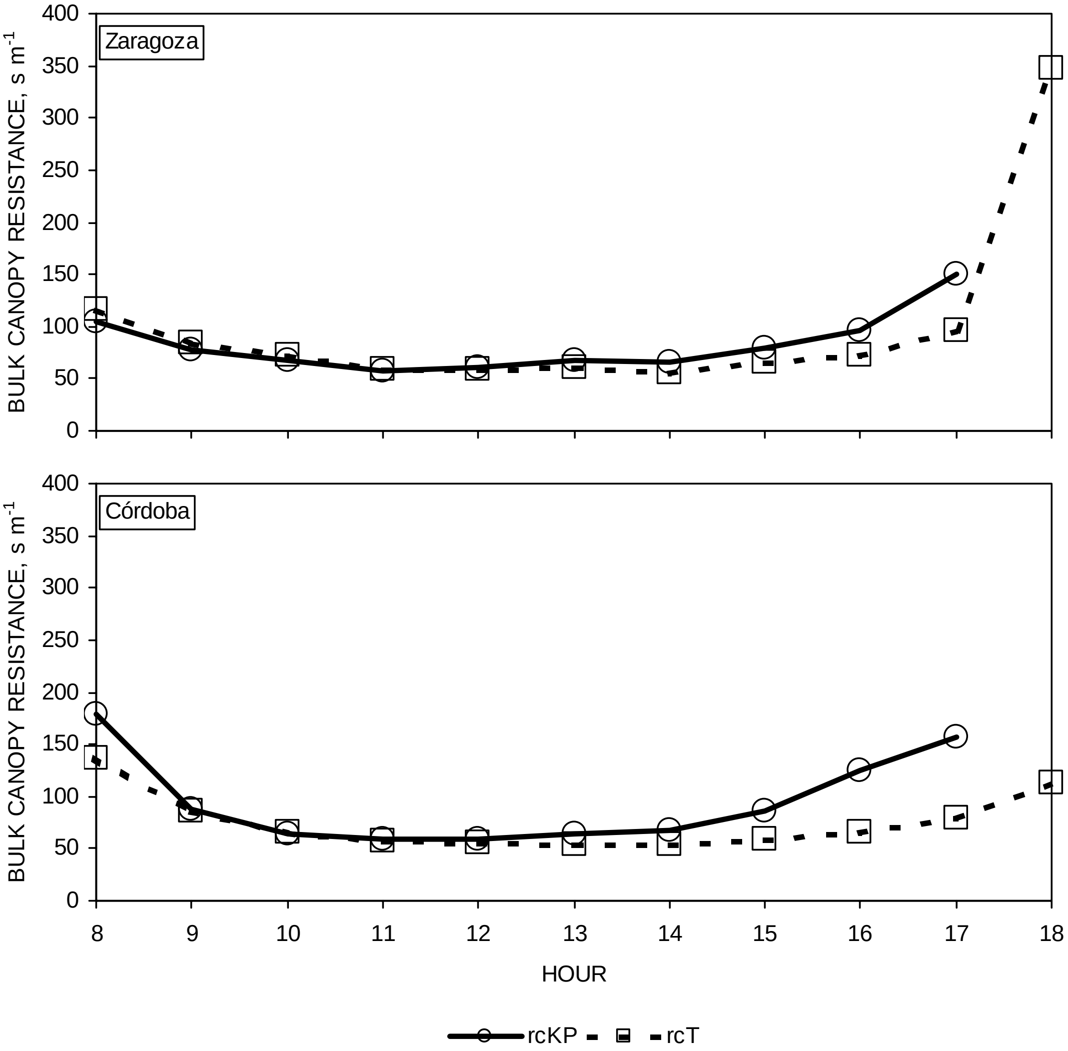

ET_{24F}
R^2 = 0.941
b_0 = 0.110 (b)
b_1 = 0.954 (d)
RMSE = 0.394
MSEs = 16.2
IA = 0.982
N = 58
ET_{sumF}
R^2 = 0.953
b_0 = 0.426 (a)
b_1 = 0.929 (c)
RMSE = 0.342
MSEs = 12.2
IA = 0.987
N = 58
ET_{24KP}
R^2 = 0.946
b_0 = -0.003 (b)
b_1 = 1.003 (d)
RMSE = 0.342
MSEs = 0.2
IA = 0.986
N = 58
ET_{sumKP}
R^2 = 0.948
b_0 = 0.144 (b)
b_1 = 1.026 (d)
RMSE = 0.438
MSEs = 40.4
IA = 0.977
N = 58
ET_{24T}
R^2 = 0.930
b_0 = 0.410 (a)
b_1 = 0.945 (d)
RMSE = 0.417
MSEs = 12.1
IA = 0.980
N = 58
ET_{sumT}
R^2 = 0.945
b_0 = 0.413 (a)
b_1 = 0.919 (c)
RMSE = 0.371
MSEs = 12.4
IA = 0.985
N = 58
ET_0 MEASURED, mm day^{-1}
ET_0 ESTIMATED, mm day^{-1}
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0
● Measured
1:1 line
Regression

Figure 5. Average hourly bulk canopy resistance estimated at Zaragoza and Córdoba using the Katerji and Perrier (r_{cKP}) and the Todorovic (r_{cT}) models for the validation period.



Zaragoza
Córdoba
BULK CANOPY RESISTANCE, s m-1
400
350
300
250
200
150
100
50
0
8
9
10
11
12
13
14
15
16
17
18
HOUR
rcKP
rcT

REFERENCES

Allen, R.G., Jensen, M.E., Wright, J.L., Burman, R.D., 1989. Operational estimates of evapotranspiration. Agron. J. 81, 650-662.

Allen, R.G., Smith, M., Perrier, A., Pereira, L.S., 1994a. An update for the definition of reference evapotranspiration. ICID Bull. 43 (2), 1-34.

Allen, R.G., Smith, M., Perrier, A., Pereira, L.S., 1994b. An update for the calculation of reference evapotranspiration. ICID Bull. 43 (2), 35-92.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56, FAO, Rome.

Alves, I, Perrier, A., Pereira, L.S., 1998. Aerodynamic and surface resistances of complete cover crops: how good is the “big leaf”?. Trans. ASAE. 41 (2), 345-351.

Alves, L.S., Perrier, A., Allen, R.G., 1999. Evapotranspiration: concepts and future trends. J. Irrig. and Drain. Engr. 125 (2), 45-51.

Alves, I., Pereira, L.S., 2000. Modelling surface resistance from climatic variables?. Agric. Water Manage. 42, 371-385

ASCE, 1996. Hydrology Handbook. ASCE Manuals and Reports on Engineering Practice, No. 28. American Society of Civil Engineers, New York.

Berengena J., Gavilán, P., Márquez, F., 2001. Precisión de las estimaciones de la ET_0 en un ambiente advectivo. XIX Congreso Nacional de Riegos, 12 June-14 June 2001, at Zaragoza, Spain, 67-68. Confederación Hidrográfica del Ebro, Zaragoza, Spain.

Choisnel, E., de Villele, O., Lacroze, F., 1992. Une approche uniformisée du calcul de l'évapotranspiration potentielle pour l'ensemble des pays de la Communauté Européene. EUR 14223, Commsission of the European Communities. Luxembourg.

Doorenbos, J., Pruitt, W.O., 1977. Crop water requirements. FAO Irrigation and Drainage Paper No. 24, FAO, Rome.

Foken, T., Wichura, B., 1996. Tools for quality assessment of surface-based flux measurements. Agric. For. Meteorol. 78: 83-105.

Hussein, A.S.A., 1999. Grass ET estimates using Penman-type equations in Central Sudan. J. Irrig. and Drain. Engr. 125 (6), 324-329.

Jarvis, P.G., 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. Phil. Trans. R. Soc. Lon. B. 273, 595-610

Jensen, M.E., Burman, R.D., Allen, R.G. 1990. Evapotranspiration and Irrigation Water Requirements. ASCE Manuals and Reports on Engineering Practice, No. 70. American Society of Civil Engineers, New York.

Katerji, N., Perrier, A., 1983. Modélisation de l'évapotranspiration réelle d'une parcelle de luzerne: role d'un coefficient culturale. Reveu d'agronomie, 3 (6), 513-521.

Katerji, N., Itier, B. Ferreira, M.L., 1988. Etudes de quelques critères indicateurs de l'état hydrique d'une culture de tomate en région semi-aride. Agronomie, 5, 425-433.

Lecina, S., Martínez-Cob, A., 2000. Evaluación lisimétrica de la evapotranspiración de referencia semihoraria calculada con el método FAO Penman-Monteith. XVIII Congreso Nacional de Riegos, 20 June-22 June 2000, at Huelva, Spain, 37-38. Junta de Andalucía, Sevilla, Spain.

Monteith, J.L., 1965. Evaporation and environment. In: Fogg, G. (ed.) The state and movement of water in living organisms. Symp. of the Soc. for Exper. Biol. XIX, Cambridge University Press, 205-234.

Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. Proc. R. Soc. London, 193, 120-146.

Pereira, L.S., Perrier, A., Allen, R.G., Alves, I., 1999. Evapotranspiration: concepts and future trends. J. Irrig. and Drain. Engrg., ASCE, 125 (5), 235-245.

Perrier, A., 1975. Etude de l’évapotranspiration dans les conditions naturelles. III Evapotranspiration réelle et potentielle des couverts végétaux. Ann. Agron., 26, 229-243.

Perrier, A., Katerji, M., Gosse, G., Itier, B., 1980. Etude “in situ” de l’évapotranspiration réelle d’une culture de blé. Agric. Meteor., 21, 295-311.

Peterschmitt, J.M., Perrier, A., 1991. Evapotranspiration and canopy temperature of rice and groundnut in southeast Coastal India. Crop coefficient approach and relationship between evapotranspiration and canopy temperature. Agric. Forest. Meteor., 56, 273-298.

Rana, G., Katerji, N., Mastrorilli, M., El Moujabber, M., 1994. Evapotranspiration and canopy resistance of grass in a Mediterranean region. Theor. Appl. Climatol. 50, 61-71.

Rana, G., Katerji, N., 2000. Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review. Europ. J. Agronomy, 13, 125-153.

Smith, M., Allen, R.G., Monteith, J.L., Perrier, A., Pereira, L.S., Segeren, A., 1991. Report on the expert consultation on revision of FAO methodologies for crop water requirements. FAO Land and Water Development Division, FAO, Rome.

Steduto, P., Caliandro, A., Rubino, P., Ben Mechlia, N., Masmoudi, M., Martínez-Cob, A., Faci, J.M., Rana, G., Mastrorilli, M., El Mourid, M., Karrou, M., Kanber, R., Kirda, C., El-Quosy, D., El-Askari, K., Ait Ali, M., Zareb, D., Snyder, R.L., 1996. Penman-Monteith reference evapotranspiration estimates in the mediterranean region. In: Camp C. R., Sadler, E. J., Yoder, R. E. (Eds). Proc. Int. Conf. On Evapotranspiration and Irrig. Scheduling, November 3-6 1996, at San Antonio, TX, USA, 357-364.

Todorovic, M., 1999. Single-layer evapotranspiration model with variable canopy resistance. J. Irrig. and Drain. Engrg., 125(5), 235-245.

Ventura, F., Spano, D., Duce, P., Snyder, R. L., 1999. An evaluation of common evapotranspiration equations. Irrig. Sci. 18 (4), 163-170.

Villalobos, F.J., 1997. Correction of eddy covariance water vapor flux using additional measurements of temperature. Agric. For. Meteorol. 88, 77-83.

Willmott, C.J., 1982. Some comments on the evaluation of model performance. Bul. Am. Meteorol. Soc. 63 (11), 1309-1313.