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Daily reference evapotranspiration estimates by the Penman-Monteith equation in Southern Italy. Constant vs. variable canopy resistance

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With 3 Figures

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Summary

The performance of the Penman-Monteith (PM) equation to estimate daily reference evapotranspiration (ET_O) was investigated by attributing three distinct features to the canopy resistance ($\boldsymbol{r}_c$): (i) $\boldsymbol{r}_c$ constant at $70\,\mathrm{s\,m^{-1}}$ (Allen et al., 1998; FAO *Irrigation and Drainage* Paper n. 56), (ii) $\boldsymbol{r}_c$ variable as linear function of a critical resistance $\boldsymbol{r}^*$, depending on weather variables and empirical parameters relating $\boldsymbol{r}_c$ to $\boldsymbol{r}^*$ (Katerji and Perrier, 1983; *Agronomie*, 3[6]: 513–521) and (iii) $\boldsymbol{r}_c$ variable as a mechanistic function of weather variables only (Todorovic, 1999; *J. Irrig. Drainage Eng.*, ASCE, 125[5]: 235–245). Daily weather and grass lysimeter data, measured for a period of seven years at Policoro (Southern Italy), were used. The results confirmed the relative robustness of the PM method with constant $\boldsymbol{r}_c$ while better estimates were obtained only when variable $\boldsymbol{r}_c$ was used. The mechanistic approach of Todorovic (1999) provided the best estimates, while the approach of Katerji and Perrier (1983), with empirically derived parameters, has shown to be not conservative enough to be extended to different locations without calibration.

1. Introduction

During the last decade, the Penman-Monteith (PM) equation (Monteith, 1965) has been widely accepted as the standard method for reference evapotranspiration (ET_O) estimates. A series of investigations conducted by the FAO (Smith et al., 1991; Allen et al., 1994a; Allen et al., 1998) have proposed the FAO-PM approach to address properly daily ET_O, where the reference evapotranspiration concept is understood as ET estimate from a standardized hypothetical crop having fixed height, albedo and canopy resistance.

Tests comparing estimated and measured data under many climatic conditions proved, on one side, the robustness and consistency of the FAO-PM method (Jensen et al., 1990; Choisnel et al., 1992; Allen et al., 1994b) and, on the other, a clear-cut underestimation of lysimeter data, especially at high rates of evapotranspiration in Southern Italy (Caliandro et al., 1990; Rana et al., 1994) as well as in arid and semi-arid regions of the Mediterranean (Steduto et al., 1996). One of the most relevant hypotheses explaining the observed underestimation of ET_O at high rates is related to the difficulties to express properly the canopy, or surface, resistance ($\boldsymbol{r}_c$) since it is not a purely physiological term, but it depends also on the prevailing climatic conditions get established over the canopy (Verma et al., 1986; Finnigan and Raupach, 1987; Stewart, 1989; Baldocchi et al., 1991; Todorovic, 1999). This is particularly pertinent when the crop is under well-watered conditions, i.e. when the physiological component of $\boldsymbol{r}_c$ is at its minimum. Therefore, it is expected that models introducing a variable $\boldsymbol{r}_c$ in relation to the climatic changes should perform better than models retaining a constant $\boldsymbol{r}_c$.

This study aims to compare three different ways of considering the canopy resistance in the PM equation: (i) taking $\boldsymbol{r}_c$ fixed at 70 s m^{-1}, as proposed by the FAO (Allen et al., 1998); (ii) modeling $\boldsymbol{r}_c$ as a variable function of weather, through the approach proposed by Katerji and Perrier (1983) and with the empirical parameters suggested by Rana et al. (1994); and (iii) taking $\boldsymbol{r}_c$ as a variable function of weather through the mechanistic approach proposed by Todorovic (1997, 1999). The comparison is performed against lysimeter ET_O data collected in Southern Italy over a period of seven years.

2. Materials and methods

2.1 Constant canopy resistance: FAO-PM method

The latent heat flux of evaporation ($\lambda\boldsymbol{E}$) from a fully cropped, homogeneous and extended surface, can be modeled as a "big-leaf" (Monteith, 1965, 1973) and expressed by the well-known Penman-Monteith combination equation (PM) as

$$\lambda\boldsymbol{E} = \frac{s(\boldsymbol{R}_n - \boldsymbol{G}) + \frac{\rho_a c_p}{\boldsymbol{r}_a} D}{s + \gamma\left(1 + \frac{\boldsymbol{r}_c}{\boldsymbol{r}_a}\right)} \tag{1}$$

where: s is the slope of the function relating saturation water vapor pressure to temperature (kPa K^{-1}), $\boldsymbol{R}_n$ is the net radiation flux (Wm^{-2}), $\boldsymbol{G}$ is the soil heat flux (W m^{-2}), ρ_a is the air density (g m^{-3}), c_p is the specific heat capacity of air at constant pressure (J g^{-1} K^{-1}), γ is the psychrometric constant (kPa K^{-1}), $\boldsymbol{r}_a$ and $\boldsymbol{r}_c$ are the aerodynamic and canopy resistances (s m^{-1}) respectively, and D is the saturation water vapor pressure deficit of the atmosphere (kPa). The resulting unit of $\lambda\boldsymbol{E}$ is the same as the other energy flux terms (Wm^{-2}). When Eq. (1) takes the form proposed by the FAO (Allen et al. 1998), $\boldsymbol{r}_a$ becomes a specific inverse proportion of wind speed and $\boldsymbol{r}_c$ takes the fixed value of 70 s m^{-1}. The daily ET_O estimates in mm d^{-1} of Eq. (1) are labeled as FAO-PM (abbreviation for FAO modified Penman-Monteith equation).

2.2 Variable canopy resistance: semi-empirical approach

In Eq. (1), $\boldsymbol{R}_n - \boldsymbol{G}$ represents the available energy at the surface and it is partitioned between latent heat ($\lambda\boldsymbol{E}$) and sensible heat ($\boldsymbol{H}$) fluxes according to the energy balance equation

$$\boldsymbol{R}_n - \boldsymbol{G} = \lambda\boldsymbol{E} + \boldsymbol{H} \tag{2}$$

From Eq. (1), when $\boldsymbol{r}_a$ tends to infinity, $\lambda\boldsymbol{E}$ tends to the so-called *equilibrium* evaporation ($\lambda\boldsymbol{E}_{eq}$), expressed as

$$\lambda\boldsymbol{E}_{eq} = \frac{s}{s+\gamma}(\boldsymbol{R}_n - \boldsymbol{G}) \tag{3}$$

Analyzing the behavior of $\lambda\boldsymbol{E}$ vs. aerodynamic resistance $\boldsymbol{r}_a$, Daudet and Perrier (1968) indicated that when *equilibrium* evaporation (Eq. 3) is established over the canopy, a *critical* resistance can be derived equating $\lambda\boldsymbol{E}_{eq}$ to the flux-gradient expression of $\lambda\boldsymbol{E}$, i.e.,

$$\lambda\boldsymbol{E} = \frac{\rho_a c_p D}{\gamma\boldsymbol{r}} \tag{4}$$

$$\therefore\ \lambda\boldsymbol{E}_{eq} = \frac{s}{s+\gamma}(\boldsymbol{R}_n - \boldsymbol{G}) = \frac{\rho_a c_p D}{\gamma\boldsymbol{r}} \Rightarrow \boldsymbol{r} = \frac{s+\gamma}{s}\cdot\frac{\rho_a c_p D}{\gamma(\boldsymbol{R}_n - \boldsymbol{G})}.$$

Since, under *equilibrium*, evaporation $\boldsymbol{r}$ becomes function of the climatic variables only, it takes the name of *critical* resistance ($\boldsymbol{r} \equiv \boldsymbol{r}^*$), i.e.,

$$\boldsymbol{r}^* = \frac{s+\gamma}{s}\cdot\frac{\rho_a c_p D}{\gamma(\boldsymbol{R}_n - \boldsymbol{G})}. \tag{5}$$

The relevance of this *critical* resistance lies in its link with the actual canopy resistance ($\boldsymbol{r}_c$), indicated to be linear according to Katerji and Perrier (1983). In this way, $\boldsymbol{r}_c$ does not remain fixed, as in the FAO-PM equation, but it varies depending on the prevailing climatic conditions get established over the canopy. The link between $\boldsymbol{r}_c$ and $\boldsymbol{r}^*$ reflects on the relationship between actual and *equilibrium* evapotranspiration, according to the following form

$$\lambda\boldsymbol{E} = C\cdot\lambda\boldsymbol{E}_{eq} = C\cdot\frac{s}{s+\gamma}\cdot(\boldsymbol{R}_n - \boldsymbol{G}) \tag{6}$$

where

$$C = \frac{1 + \frac{\gamma}{s+\gamma}\cdot\frac{\boldsymbol{r}^*}{\boldsymbol{r}_a}}{1 + \frac{\gamma}{s+\gamma}\cdot\frac{\boldsymbol{r}_c}{\boldsymbol{r}_a}} \tag{7}$$

Equation (6) can be seen as a form of the Priestley-Taylor equation (Priestley and Taylor, 1972) where the variable C replaces the constant α of the original equation. In Eq. (7) the C accounts for both the canopy and the climate and, according to Katerji and Perrier (1983), if $\boldsymbol{r}_\mathrm{c}$ is unknown, C and $\frac{\boldsymbol{r}^*}{\boldsymbol{r}_\mathrm{a}}$ can be linearly related as

$$C = a\left(\frac{\boldsymbol{r}^*}{\boldsymbol{r}_\mathrm{a}}\right) + b \tag{8}$$

where a and b are empirical parameters experimentally derived. Then, the reference evapotranspiration can be estimated through Eqs. (8) and (6) making use of the *critical* resistance $\boldsymbol{r}^*$ (Eq. 5), i.e.,

$$\lambda \boldsymbol{E} = \left(a\frac{\boldsymbol{r}^*}{\boldsymbol{r}_\mathrm{a}} + b\right) \cdot \frac{s}{s+\gamma} \cdot (\boldsymbol{R}_\mathrm{n} - \boldsymbol{G}). \tag{9}$$

Following the suggestion of Katerji and Perrier (1983), Rana et al. (1994) demonstrated that, using the parameters $a = 0.11$ and $b = 0.90$, derived empirically for a location in Southern Italy (Rutigliano), the daily $\mathrm{ET_O}$ estimates were significantly improved, as compared to the estimates obtained using the FAO-PM equation. These parameters were similar to those derived by Gosse (1976) in the humid equatorial climate of the Ivory Coast, which led Rana et al. (1994) to suppose them to be invariant from place to place. The same parameters are used in this study for the experimental farm of Policoro, located about 120 km Southeast from the experimental farm of Rutigliano (again in Southern Italy). When expressed in terms of daily $\mathrm{ET_O}$ estimates (in mm d^{-1}), Eq. (9) is labeled as KP-PM (abbreviation for Katerji-Perrier modified Penman-Monteith equation).

2.3 Variable canopy resistance: mechanistic approach

Using always the PM Eq. (1), Todorovic (1999) compared the reference latent heat flux of evaporation ($\lambda \boldsymbol{E}$), where $\boldsymbol{r}_\mathrm{c} > 0$, with the potential latent heat flux of evaporation ($\lambda \boldsymbol{E}_p$) obtained when $\boldsymbol{r}_\mathrm{c} = 0$, i.e.,

$$\lambda \boldsymbol{E}_\mathrm{p} = \frac{s(\boldsymbol{R}_\mathrm{n} - \boldsymbol{G}) + \rho_\mathrm{a} c_\mathrm{p} D/\boldsymbol{r}_\mathrm{a}}{s+\gamma}. \tag{10}$$

Equation (10) corresponds to the original derivation of the Penman equation for free water evaporation (Penman, 1948). Assuming that the input of available energy ($\boldsymbol{R}_\mathrm{n} - \boldsymbol{G}$) remains the same for both states of the vegetation-atmosphere system, when $\boldsymbol{r}_\mathrm{c} > 0$ (i.e. $\lambda \boldsymbol{E} < \lambda \boldsymbol{E}_\mathrm{p}$) any decrease of latent heat flux due to $\boldsymbol{r}_\mathrm{c}$ increase is balanced out by an increase in sensible heat ($\boldsymbol{H}$). Then, a higher canopy temperature is established to drive $\boldsymbol{H}$ and the energy balance Eq. (2) may be rewritten as:

$$\boldsymbol{R}_\mathrm{n} - \boldsymbol{G} = \lambda \boldsymbol{E} + \boldsymbol{H}^* + \boldsymbol{H}' \tag{11}$$

where the sensible heat ($\boldsymbol{H}$) is split into $\boldsymbol{H}^*$, corresponding to the conditions where $\boldsymbol{r}_\mathrm{c} = 0$, and $\boldsymbol{H}'$, corresponding to the energy difference between potential and reference latent heat fluxes, i.e.,

$$\boldsymbol{H}' = \lambda \boldsymbol{E}_\mathrm{p} - \lambda \boldsymbol{E}. \tag{12}$$

This additional sensible heat flux ($\boldsymbol{H}'$) is always directed upward and is driven by the temperature difference t between the evaporating surface with $\boldsymbol{r}_\mathrm{c} > 0$ (T') and the corresponding surface with $\boldsymbol{r}_\mathrm{c} = 0$ (T_s). Then, $\boldsymbol{H}'$, originated at some level z' in the canopy (Fig. 1), may be expressed as

$$\boldsymbol{H}' = \frac{\rho_\mathrm{a} c_\mathrm{p} (T' - T_s)}{\boldsymbol{r}'} = \frac{\rho_\mathrm{a} c_\mathrm{p} t}{\boldsymbol{r}'} \tag{13}$$

where $\boldsymbol{r}'$ presents the ⟨⟨pseudo⟩⟩ resistance term for heat transfer between z' and $d + z_o$ with canopy temperature of T' and T_s respectively, where $T' > T_s$ when $\boldsymbol{r}_\mathrm{c} > 0$. Since $\boldsymbol{r}_\mathrm{c}$ and $\boldsymbol{r}'$ share the same pathway from z' to $d + z_o$ (Fig. 1) and the diffusivities of water vapor and heat are close to each other, it is assumed that $\boldsymbol{r}_\mathrm{c} = \boldsymbol{r}'$.

At this point, it is useful to introduce the *isothermal* (or *climatological*) resistance $\boldsymbol{r}_i$, after Monteith (1965), to make some of the intermediary variables needed for the derivation of t dimensionless. Similarly to the *critical* resistance ($\boldsymbol{r}^*$), $\boldsymbol{r}_i$ is obtained by equating the flux-gradient expression of $\lambda \boldsymbol{E}$ (Eq. 4) to the *equilibrium* evaporation, except that Monteith considered $\lambda \boldsymbol{E}_\mathrm{eq} = \boldsymbol{R}_\mathrm{n} - \boldsymbol{G}$, from the energy-balance Eq. (2) with $\boldsymbol{H} = 0$, and not as in Eq. (3), so that

$$\boldsymbol{r}_i = \frac{\rho c_\mathrm{p} D}{\gamma(\boldsymbol{R}_\mathrm{n} - \boldsymbol{G})}. \tag{14}$$

Then, setting

$$X = \frac{\boldsymbol{r}_\mathrm{c}}{\boldsymbol{r}_i} \tag{15}$$

$$Y = \frac{\boldsymbol{r}_i}{\boldsymbol{r}_\mathrm{a}}, \tag{16}$$

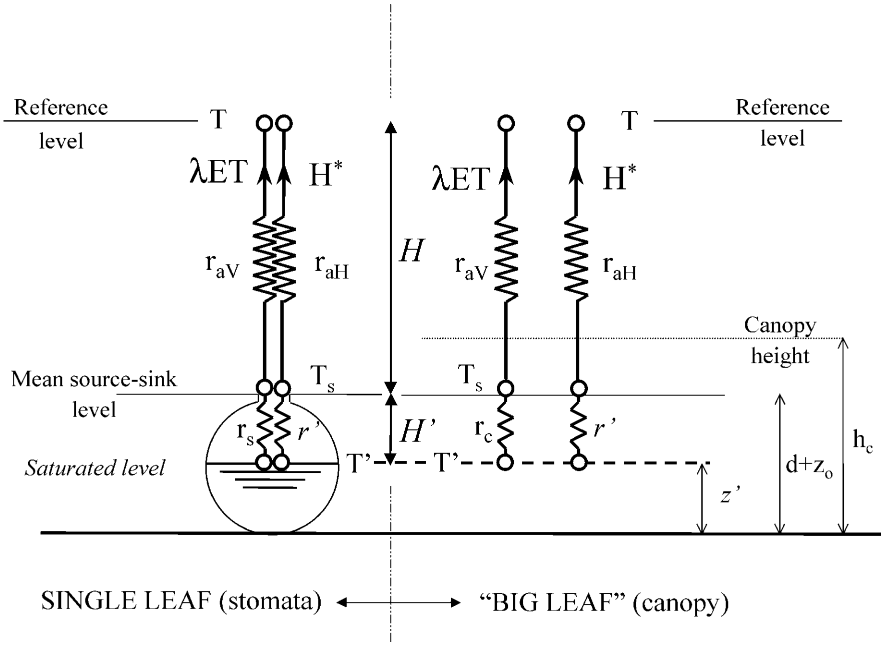

Fig. 1. Distribution of the fluxes for the single leaf (stomata) and the "big-leaf" (canopy) when $r_c > 0$ and $\lambda E < \lambda E_p$ (adapted after Todorovic, 1999)

substituting (1), (10) and (13) in (12) and rearranging the terms, Todorovic (1997, 1999) arrived to the following form of quadratic equation:

$$a^* X^2 + b^* X + c^* = 0 \tag{17}$$

with

$$a^* = \frac{s + \gamma Y}{s + \gamma} YD \tag{18}$$

$$b^* = -\gamma Y t \tag{19}$$

$$c^* = -(s + \gamma)t. \tag{20}$$

The quadratic Eq. (17) has only one positive solution, provided the temperature difference t between z' and $d + z_o$ is known.

Similarly to Penman (1948), Todorovic (1997, 1999) assumed linear relationship between saturation vapor pressure and temperature for small temperature differences and he invoked the neutral stability conditions where $T_s = T_{air}$. Then, the temperature difference t is derived as

$$t = \frac{\gamma}{s} \frac{D}{(s + \gamma)}, \tag{21}$$

i.e., a function of air temperature and vapor pressure deficit. Finally, solving the Eqs. (21), (14), (16), (18), (19) and (20) one can develop and solve the quadratic Eq. (17), calculate $\boldsymbol{r}_c$ from Eq. (15), and then substitute $\boldsymbol{r}_c$ in the PM Eq. (1) to estimate ET_O. Preliminary testing of this approach has shown very convincing results on both hourly and daily basis (Todorovic, 1997, 1999).

The daily ET_O estimates (in $mm\,d^{-1}$) obtained with this approach are labeled as TD-PM method (abbreviation for Todorovic modified Penman-Monteith equation).

2.4 The experimental site and data

Daily data of weather variables and lysimeter ET_O were obtained from the experimental farm of the University of Bari, located in Policoro (province of Matera, Southern Italy) at latitude 40° 17′ N, longitude 16° 40′ E, and altitude 15 m above sea level. The study area is situated at about 3 km from the Ionian Sea and is characterized by semi-arid Mediterranean climate. The experimental site was equipped with a standard agro-meteorological station and a high-precision weighing lysimeter (2×2 m wide, 1.3 m deep, 0.025 mm resolution), centered in a 60×60 m surface cropped with tall fescue (*Festuca arundinacea* L.) and maintained under optimal water and nutritional conditions.

The data set, recorded over a period of 7 years (1981–1987) and controlled for quality, includes 898 daily values crossing virtually all the seasons, with about 60% of the data located between April and September. The plots surrounding the experimental site were subjected to variable crop rotations introducing the impact of the fetch variability from year to year. This means that the seven-year data were affected by some flux-divergence problems since both the lysimeter and the weather station were not always within the same adjusted and equilibrated boundary-layer. Nevertheless, the relevance of the relative comparison between the various ET_O estimates is retained.

Solar radiation, vapor pressure deficit, aerodynamic resistance and all the other parameters used in the ET_O estimates are calculated according to the standard procedure proposed by the FAO (Allen et al., 1998). The procedure suggested by Allen (1996) and Jensen et al. (1997) was adopted to evaluate the accuracy of the solar radiation estimates (R_S), which resulted in the introduction of a correction factor of 1.11 for R_S.

3. Results and discussion

The results of ET_O estimates, presented in Fig. 2 and Table 1, demonstrated that both the TD-PM (Fig. 2c) and the FAO-PM (Fig. 2a) are superior to the KP-PM method (Fig. 2b). The statistics, reported in Table 1, indicated that the RMSE of estimates for TD-PM was about 6% lower than for FAO-PM and it was about 23% lower than for KP-PM. Furthermore, the TD-PM method has the slope much closer to one (0.932) than the FAO-PM (0.881) and the KP-PM (0.825) methods. Similarly, the coefficient of determination (r^2) of TD-PM was slightly higher than for the two other methods. While the intercept of FAO-PM showed the highest value of the three methods ($+0.548$), indicating a significant over-estimation of the low values of ET_O (winter season), the intercept of the KP-PM showed the value closest to zero ($+0.154$). Finally, the test of Student at 5% level of significance revealed that the intercept was not significantly different from zero only for the KP-PM method and that the slope was not significantly different from one only for the TD-PM method, while both intercept and slope were significantly different from zero and one, respectively, for the FAO-PM method.

The presented results indicated that the parameters of the KP-PM equation, fixed by Rana et al. (1994) at a location 120 km away from Policoro and supposed to be invariant from place to place, cannot be generalized and successfully used for the location under study. For this reason, a best

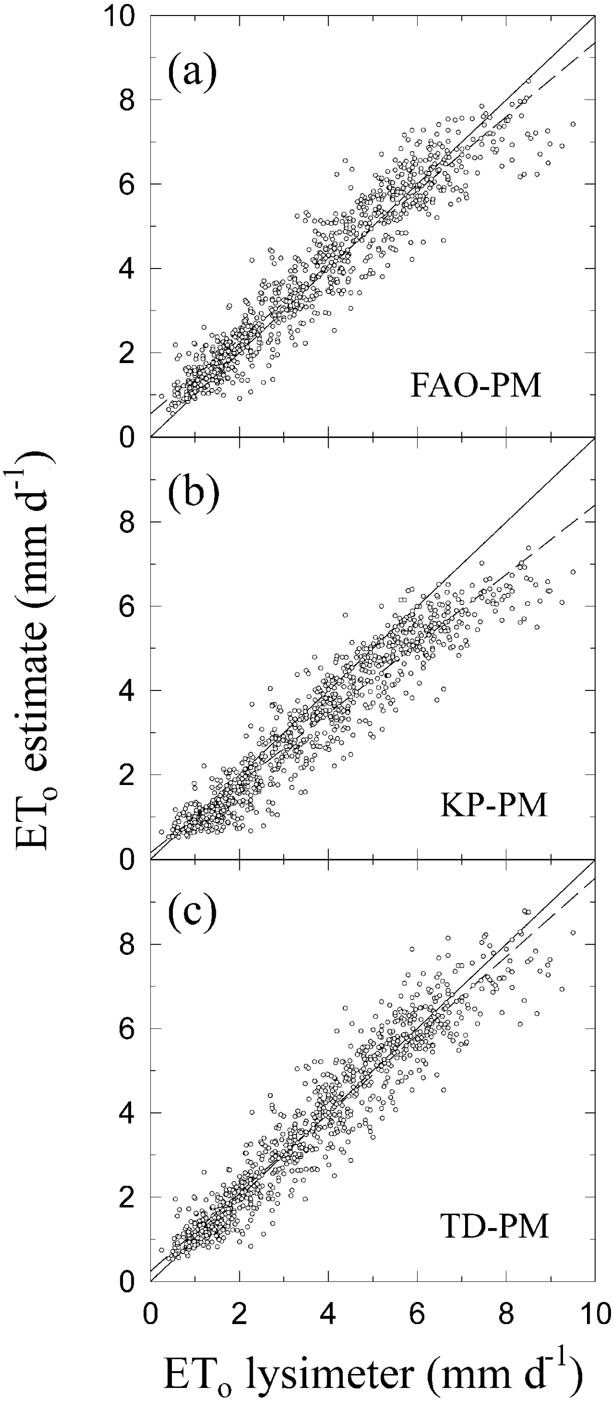

Fig. 2. Regressions between ET_O estimates and ET_O measured by lysimeter when using (**a**) the FAO-PM equation, with $r_c = 70\,s\,m^{-1}$, (**b**) the KP-PM method, with $a = 0.11$ and $b = 0.90$, and (**c**) the TD-PM method

fitting procedure by the least square method, was used to derive new parameters for Eq. (9) over the whole data set. Similarly, a constant r_c for the FAO-PM method was fitted, again by the least square method, to make the comparison on a

Table 1. Root mean square error (RMSE) of ETo estimate and intercept, slope and coefficient of determination (r^2) of the regressions presented in Fig. 2. The $\boldsymbol{r}_c$ of the FAO-PM equation was fixed at $70\,s\,m^{-1}$ and the parameters used in the KP-PM equation were $a = 0.11$ and $b = 0.90$

Equation	Intercept	Slope	r^2	RMSE
FAO-PM	0.548	0.881	0.904	0.653
KP-PM	0.154	0.825	0.906	0.829
TD-PM	0.242	0.932	0.913	0.613

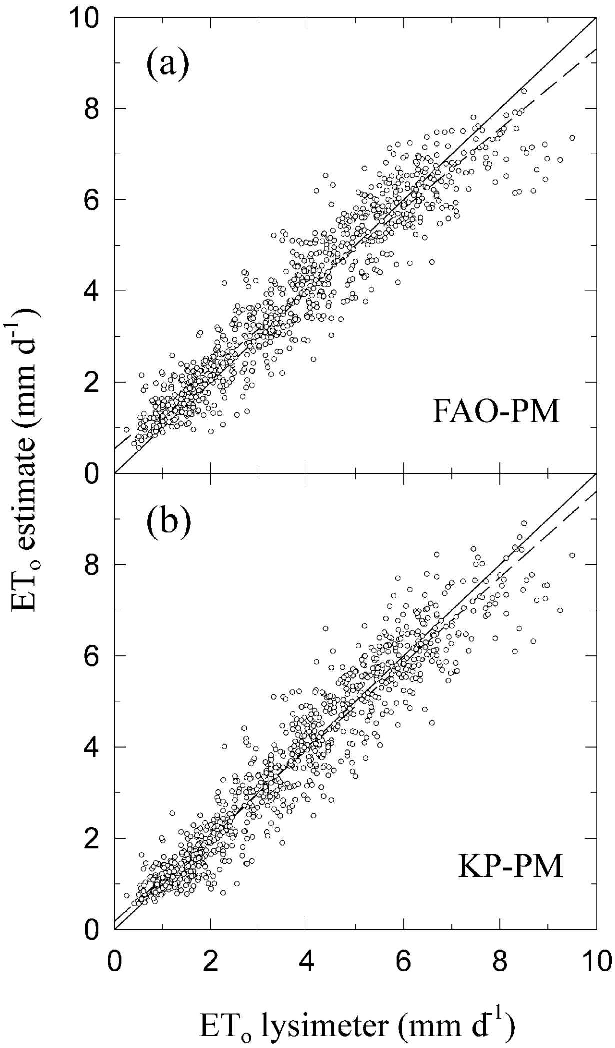

Fig. 3. Regressions between ET_O estimates and ET_O measured by lysimeter using (**a**) the FAO-PM equation with the optimized fixed $\boldsymbol{r}_c$, and (**b**) the KP-PM approach with the locally calibrated parameters *a* and *b*

common ground. The results of the best fitting are shown in Fig. 3. The local calibration greatly improved the results of ET estimate by the KP-PM (Fig. 3b), which were not significantly different from the TD-PM method (Fig. 2c) without any calibration. The FAO-PM method (Fig. 3a), instead, showed to be almost insensitive to the local calibration.

The statistics of these regressions are reported in Table 2, along with the new values of *a*, *b* and $\boldsymbol{r}_c$. The best-fitted $\boldsymbol{r}_c$ was essentially the same value ($71.3\,s\,m^{-1}$) as the constant $\boldsymbol{r}_c$ adopted by the FAO-PM method, confirming its robustness and consistency. However, the FAO-PM equation showed overestimation at low ET_O values as compared to the two other methods. Inversely, at high ET_O values, the underestimation by the FAO-PM is larger than that obtained by the TD-PM and KP-PM methods.

Based on the results presented so far, it can be stated that the ET_O estimates using a variable $\boldsymbol{r}_c$ are relatively superior to the ET_O estimates obtained with a fixed $\boldsymbol{r}_c$. However, when the parameters of Eq. (9) are locally calibrated (KP-PM method), the gain is quite limited since the KP-PM method showed to be very sensitive to small changes in the parameters *a* and *b*. For example, performing a simple sensitivity analysis, by keeping *b* fixed at 1 and varying *a*, a variation of about 2% and 2.6% in slope and intercept, respectively, was observed for each 1% variation in *a*. Similarly, by keeping *a* fixed at 0.1 and varying *b*, a variation of about 0.7% in slope and 0.8% in intercept was observed for each 1% variation in *b*. This indicates that the KP-PM method is more sensitive to the variations in *a* than in *b*. Furthermore, in absolute terms, the impact of the variation of the parameters on the slope is much higher than on the intercept.

It is expected that these parameters also vary significantly from year to year depending on the quality of collected data and their distribution throughout the seasons within the same year. The variation of the parameters *a* and *b* for each year separately is presented in Table 3 along with the results of the regression analysis. In a similar fashion, the best fitting of $\boldsymbol{r}_c$ was derived from the FAO-PM in each year and the results are reported in Table 4. These results show a relatively larger $\boldsymbol{r}_c$ variation, from year to year, than the *a* and *b* parameters. Nevertheless, the FAO-PM showed to be less sensitive to variation in $\boldsymbol{r}_c$ than the KP-PM to the variation in *a* and *b*.

The most relevant inference drawn from this analysis is that both FAO-PM and KP-PM methods

Table 2. Root mean square error (RMSE) of ET_O estimate and intercept, slope and coefficient of determination (r^2) of the regressions presented in Fig. 3. The $\boldsymbol{r}_c$ of the FAO-PM equation and the parameters *a* and *b* used in the KP-PM equation are derived by the least square method in fitting the ET_O estimates to the ET_O measured by lysimeter

Equation	*a*	*b*	r_c (s m^{-1})	Intercept	Slope	r^2	RMSE
FAO-PM	–	–	71.3	0.542	0.877	0.903	0.652
KP-PM	0.180	0.918	–	0.181	0.942	0.913	0.615

Table 3. Root mean square error (RMSE) of ET_O estimate and intercept, slope and coefficient of determination (r^2) of the yearly regressions between ET_O estimates by the KP-PM equation and the ET_O measured by lysimeter. The parameters *a* and *b* are derived by the least square method in fitting the ET_O estimates to the ET_O measured by lysimeter (AVG = average and STD = standard deviation)

Years	*a*	*b*	Intercept	Slope	r^2	RMSE
1981	0.225	0.907	0.284	0.927	0.888	0.766
1982	0.183	0.947	0.366	0.906	0.922	0.614
1983	0.188	0.850	0.158	0.938	0.894	0.612
1984	0.192	0.921	0.158	0.949	0.926	0.512
1985	0.160	0.945	0.017	0.982	0.946	0.503
1986	0.158	0.916	0.089	0.967	0.932	0.537
1987	0.176	0.892	0.066	0.966	0.906	0.596
AVG	0.183	0.911	0.163	0.948	0.916	0.591
STD	0.023	0.033	0.124	0.026	0.021	0.090

Table 5. Root mean square error (RMSE) of ETo estimate and intercept, slope and coefficient of determination (r^2) of the yearly regressions between ET_O estimates by the TD-PM method and the ET_O measured by lysimeter. The $\boldsymbol{r}_c$ values are averaged on yearly basis and they are derived by the method developed by Todorovic. (AVG = average and STD = standard deviation)

Years	r_c (s m^{-1})	Intercept	Slope	r^2	RMSE
1981	93.4	0.344	0.859	0.8898	0.816
1982	105.6	0.488	0.863	0.9217	0.630
1983	99.4	0.254	0.961	0.8931	0.638
1984	98.2	0.177	0.925	0.9226	0.530
1985	94.2	0.020	1.002	0.945	0.517
1986	96.1	0.149	0.993	0.9313	0.564
1987	84.9	0.0831	0.986	0.9073	0.599
AVG	95.971	0.211	0.941	0.916	0.613
STD	6.348	0.169	0.060	0.020	0.101

Table 4. Root mean square error (RMSE) of ET_O estimate and intercept, slope and coefficient of determination (r^2) of the yearly regressions between ET_O estimates by the FAO-PM equation and the ET_O measured by lysimeter. The $\boldsymbol{r}_c$ of the FAO-PM equation is derived by the least square method in fitting the ET_O estimates to the ET_O measured by lysimeter (AVG = average and STD = standard deviation)

Years	r_c (s m^{-1})	Intercept	Slope	r^2	RMSE
1981	44.7	0.777	0.849	0.883	0.788
1982	71.5	0.827	0.813	0.915	0.695
1983	92.8	0.502	0.868	0.887	0.630
1984	64.3	0.489	0.882	0.925	0.524
1985	70.7	0.232	0.948	0.936	0.541
1986	91.3	0.379	0.912	0.941	0.500
1987	62.5	0.368	0.930	0.877	0.682
AVG	71.1	0.511	0.886	0.909	0.623
STD	16.8	0.219	0.047	0.027	0.106

are very sensitive to local conditions, which in turn limits the extent of their generalization.

The results of ET_O estimates by the TD-PM method for each year separately are presented in Table 5. The results are in the same range of those obtained by the KP-PM method when using the new parameters derived for each single year (Table 3) and by FAO-PM when using a fixed $\boldsymbol{r}_c$ optimized for each single year (Table 4). The $\boldsymbol{r}_c$ calculated by TD-PM method does not show great variation when it is averaged over the years (Table 5). Therefore, with this method the relationship between $\boldsymbol{r}_c$ and weather variables is sufficiently accounted for.

4. Conclusions

The results of the investigation show that the FAO-PM method (Allen et al., 1998) remains the most feasible to estimate daily ET_O when using a constant canopy resistance. Nevertheless, the constant $\boldsymbol{r}_c$ does not allow to account for the non-physiological component of $\boldsymbol{r}_c$ that varies with the variation in the prevailing climatic conditions. The consequence of using the FAO-PM is, then, the tendency to over-predict ET_O during winter time (when ET_O is low) and, most critical, to under-predict during summer time (when ET_O is high). This underestimate is particularly remarkable in arid and semi-arid regions of the Mediterranean.

To overcome the limitations of the FAO-PM, it is necessary to introduce an $\boldsymbol{r}_c$ that would vary according to the main climatic conditions get established over the canopy.

The Katerji-Perrier (1983) approach introduces an $\boldsymbol{r}_c$ variable as function of a *critical* resistance ($\boldsymbol{r}^*$) dependent on climatic conditions through empirical parameters. However, the results of this investigation shows that the KP-PM performed worse than the FAO-PM when using the standard parameters suggested by Rana et al. (1994), while it performed better than the FAO-PM when the parameters were locally calibrated. This finding suggests that the parameters of the KP-PM method are not so generalizable as suggested, and that their actual variability in time and space necessarily requires a local calibration. This makes the KP-PM equation of limited advantage.

The approach of Todorovic (1999) introduces a variable $\boldsymbol{r}_c$ modeled as a mechanistic function of climatic variables, without additional input variables than those required by the FAO-PM method, nor calibration. The results of this investigation shows the TD-PM method to give the best performance of all methods in estimating daily ET_O using either the dataset as a whole (seven years) or the single years.

From all the above, we can draw two main conclusions: (i) it should be recognized that $\boldsymbol{r}_c$ carries over the impact of the climatic conditions and, consequently, should be considered as variable to improve the daily ET_O estimates; (ii) if a variable $\boldsymbol{r}_c$ has to be conceived in the daily ET_O estimates through the PM equation, the mechanistic approach proposed by Todorovic (1999) is expected to be the most reliable one.

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