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F. Ventura · D. Spano · P. Duce · R. L. Snyder

An evaluation of common evapotranspiration equations

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Abstract A comparison is made between the Pruitt and Doorenbos version of an hourly Penman-type equation, the Food and Agriculture Organization (FAO) hourly Penman-Monteith equation, and an independent measure of reference evapotranspiration (ET_0) from lysimeter data. Reducing the canopy resistance improved the hourly FAO Penman-Monteith estimates. Daytime soil heat flux density is estimated as 10% of net radiation in the FAO hourly Penman-Monteith equation; however, the measured soil heat flux density under grass that was never shorter than 0.10 m in this study was between 3% and 5% of net radiation. The daytime totals of hourly ET_0 from the hourly Penman-Monteith and Pruitt-Doorenbos equations and ET_0 from the 24-h FAO Penman-Monteith equation were computed using data from five Italian and five Californian stations. A comparison showed that all of the equations gave acceptable results. The Pruitt-Doorenbos equation may slightly over-estimate ET_0 in conditions of summertime cold air advection.

Introduction

Reference evapotranspiration ET_0 is often defined as the evapotranspiration (ET) of a broad expanse of 0.10- to 0.15-m-tall, cool-season (C3 species) grass when the ET is not limited by soil water content (Doorenbos and Pruitt 1977). ET_0 is used to quantify evaporative demand within a region and to estimate crop ET when the ET_0 is multiplied by a crop coefficient (K_c) factor to account for differences between the grass and crop ET. California and other Mediterranean climatic regions around the world have a large range of evaporative demand conditions. Consequently, it is desirable to use a reference evapotranspiration (ET_0) equation that consistently gives good results.

When the California Irrigation Management Information System (CIMIS), an automated weather station network, was established between 1982 and 1985, the Pruitt and Doorenbos (1977) version of the Penman (1948, 1963) equation was selected for calculating ET_0 (Snyder and Pruitt 1992). The Pruitt and Doorenbos (PD) equation was developed by calibrating a wind function using micrometeorological data and grass (not less than 0.1 m tall) ET from a 6.1-m-diameter lysimeter. Recently, Allen et al. (1994) recommended using a modified hourly Penman-Monteith (PM) equation (Monteith 1965) for estimating ET_0; thus, a comparison seems worthwhile. Allen et al. also recommended a modified 24-h PM equation for estimating ET_0. Internationally, the modified 24-h PM equation, which was first presented by Allen et al. (1989), has received widespread acceptance for estimating ET_0. This equation is currently recommended by the United Nations Food and Agriculture Organization (FAO) and by the World Meteorological Organization (WMO), and it is used in the FAO CROPWAT irrigation scheduling software (Smith 1993). Because the modification was developed for use by FAO, it will be referred to as the "hourly FAO Penman-Monteith" equation in this paper. The equation that uses 24-h data will be referred to as the 24-h FAO PM equation.

The accuracy of the PD and PM equations was assessed using a data set containing hourly micrometeorological and lysimeter data (Table 1) from Pruitt and Lourence (1965) for summer conditions. Hourly weather data from different seasons and a wide range of climatic conditions were used to calculate the daily sum of ET_0 from the PD and PM hourly calculations assuming that the ET_0 is zero at night. ET_0 estimates using the 24-h FAO PM equation (Allen et al. 1994) were also compared with the summed hourly values.

F. Ventura · D. Spano
University of Sassari, Italy

P. Duce
CNR-IMAes, Sassari, Italy

R. L. Snyder (✉)
University of California, Davis, CA 95616, USA

Materials and methods

ET_0 equations

PD equation

Pruitt and Doorenbos (1977) calibrated the wind function of the Penman (1948, 1963) equation using micrometeorological and lysimeter data to obtain an hourly estimate of ET_0.

$$\mathrm{PD}_i = \frac{\Delta_i}{\Delta_i + \gamma_i}(R_{ni}) + \lambda_i \frac{\gamma_i}{\Delta_i + \gamma_i}(e_{ai} - e_{di})\, F(u_i) \tag{1}$$

PD_i = ET_0 (for the ith hour) $\mathrm{W\ m^{-2}}$
R_{ni} = net radiation $\mathrm{W\ m^{-2}}$
Δ_i = slope of the saturation vapor pressure curve at T_i $\mathrm{kPa\ ^\circ C^{-1}}$
γ_i = psychrometric constant $\mathrm{kPa\ ^\circ C^{-1}}$
e_{ai} = saturation vapor pressure at air temperature kPa
e_{di} = measured vapor pressure kPa
$F(u_i)$ = wind function $\mathrm{mm\ kPa^{-1}\ h^{-1}}$

The latent heat of vaporization (λ_i) in $\mathrm{W\ m^{-2}\ mm^{-1}\ h}$ is from Fritschen and Gay (1979).

$$\lambda_i = 694.5\,(1 - 0.000946\,T_i) \tag{2}$$

The slope of saturation vapor pressure (Δ_i), the psychrometric constant (γ_i), the saturation vapor pressure (e_{ai}), and the wind function ($F(u_i)$) are calculated using the following equations:

$\Delta_i = (e_{ai}/T_{ki})\,(6790.5/T_{ki} - 5.028)$ $\mathrm{kPa\ ^\circ C^{-1}}$
$\gamma_i \approx 0.000646\,(1 + 0.000946\,T_i)\,P$ $\mathrm{kPa\ ^\circ C^{-1}}$
$e_{ai} = 0.1608 \exp[(17.27\,T_i)/(T_i + 237.3)]$ kPa
$F(u_i) = 0.030 + 0.0576\,u_i$ if $Rn_i > 0$ $\mathrm{mm\ kPa^{-1}\ h^{-1}}$
$F(u_i) = 0.125 + 0.0439\,u_i$ if $Rn_i \le 0$ $\mathrm{mm\ kPa^{-1}\ h^{-1}}$
T_{ki} = absolute air temperature K
T_i = air temperature °C
P = barometric pressure kPa
u_i = wind speed at 2.0 m $\mathrm{m\ s^{-1}}$

The wind function was developed by calibration against lysimeter measurements taken from a large field of unstressed cool-season grass. The grass was frequently cut to a height not less than 0.1 m. Daytime and night-time wind functions differ because the grass stomata close at night to inhibit transpiration. Barometric pressure (P) in kPa is estimated from the elevation (z) in meters above sea level using an equation from Doorenbos and Pruitt (1977):

$$P = 101.3 - 0.01152\,z + 5.44 \times 10^{-7}\,z^2 \tag{3}$$

The difference between the equation for P presented here and the equation presented by Allen et al. (1994) is insignificant. The daily reference evapotranspiration (PD_i') in $\mathrm{mm\ day^{-1}}$ is calculated as the sum of PD_i in $\mathrm{W\ m^{-2}}$ over 24 h divided by λ_i.

$$\mathrm{PD}_i' = \sum_{i=1}^{24} \mathrm{PD}_i / \lambda_i \tag{4}$$

However, the night-time values for PD_i (when $R_{ni} < 0$) were assumed to equal zero in this paper. This decision was made because transpiration is near zero at night and because significant evaporation from the surface is only likely if the grass and soil are wet and there is considerable warm air advection. In this case the evaporation would be from a free water surface rather than from a non-transpiring grass reference crop and the measurements would not represent ET_0.

FAO hourly PM equation

The PM equation is a modification of the Penman (1963) equation. The main difference is that the PM equation includes the effect of canopy resistance on evapotranspiration. The crop controls the evapotranspiration by closing stomata, which inhibit vapor transfer from the leaves to the ambient air. This control is quantified as the canopy resistance or r_c that is found in the PM_i equation described below. The PM_i equation to estimate ET_0 was modified from Allen et al. (1994) by multiplying both sides of the equation by the latent heat of vaporization (λ_i) in $\mathrm{W\ m^{-2}\ mm^{-1}\ h}$ (Eq. 2). Rn_i and G_i are input in $\mathrm{W\ m^{-2}}$ to give PM_i in $\mathrm{W\ m^{-2}}$.

$$\mathrm{PM}_i = \frac{\Delta_i (R\,n_i - G_i) + \gamma_i\,\lambda_i\,\dfrac{37}{T + 273}\,u_i\,(e_{a_i} - e_{d_i})}{\Delta + \gamma_i^*} \tag{5}$$

Here, $\gamma_i^* = \gamma_i(1 + r_c/r_a)$ and r_c and r_a are the canopy and aerodynamic resistance values ($\mathrm{s\ m^{-1}}$). According to Allen et al. (1994), the aerodynamic resistance is approximately $r_a = 208/u_i$ for a 0.12-m-tall grass canopy when the wind speed is measured at a height of 2 m and temperature and humidity are measured at a height of 1.5 or 2.0 m. The value for r_a is slightly different when the temperature and humidity are measured at a height of 1.5 m. However, Allen et al. (1994) recommended using values from a height of 2.0 m to standardize calculations. They estimated the canopy resistance at $r_c = 70\ \mathrm{s\ m^{-1}}$. By substitution, the modified psychrometric constant is:

$$\gamma_i^* = \gamma_i\left(1 + \frac{r_c}{r_a}\right) \approx \gamma_i\left(1 + \frac{70}{208}\,u_i\right) = \gamma_i\,(1 + 0.34\,u_i) \tag{6}$$

Although the canopy resistance of $r_c = 70\ \mathrm{s\ m^{-1}}$ has been reported to give good estimates of ET_0 when used in the 24-h PM equation (Jensen et al. 1990), it is well known that canopy resistance changes during the day and it might not be correct for hourly calculations. The daytime total (PM_i') in $\mathrm{mm\ day^{-1}}$ is calculated as the sum of the 24-h values (with $\mathrm{PM}_i = 0$ whenever $R_{ni} < 0$) divided by λ_i.

$$\mathrm{PM}_i' = \sum_{i=1}^{24} \mathrm{PM}_i / \lambda_i \tag{7}$$

Twenty-four-hour FAO PM equation

The 24-h FAO PM (PM_d) equation is commonly used to estimate ET_0 when only daily weather data are available. The PM_d equation to estimate ET_0 in $\mathrm{mm\ day^{-1}}$ (Allen et al. 1994) is:

$$\mathrm{PM}_d = \frac{0.408\,\Delta(R_n - G) + \gamma\,\dfrac{900}{T + 273}\,u(e_a - e_d')}{\Delta + \gamma^*} \tag{8}$$

in which: $1/\lambda = 0.408$.

$\lambda \approx 2.45$ $\mathrm{MJ\ kg^{-1}}$
Δ = slope of the saturation vapor pressure curve at mean air temp $\mathrm{kPa\ ^\circ C^{-1}}$
R_n = 24-h net radiation $\mathrm{MJ\ m^{-2}\ day^{-1}}$
G = 24-h soil heat flux density ≈ 0 $\mathrm{MJ\ m^{-2}\ day^{-1}}$
e_a = saturation vapor pressure kPa
e_d' = actual vapor pressure kPa
γ^* = modified psychrometric constant $\mathrm{kPa\ ^\circ C^{-1}}$
u = mean 24-h wind speed at 2 m height $\mathrm{m\ s^{-1}}$

For a 0.12-m-tall grass reference crop and wind speed measured at a height of 2.0 m, γ^* is expressed as:

$$\gamma^* = \gamma\left(1 + \frac{r_c}{r_a}\right) \approx \gamma\left(1 + \frac{70}{208}\,u\right) = \gamma(1 + 0.34\,u) \tag{9}$$

γ is the psychrometric constant in $\mathrm{kPa\ ^\circ C^{-1}}$.

$$\gamma \approx 0.00163\,\frac{P}{\lambda} \tag{10}$$

Δ is the slope of the saturation vapor pressure curve at T_m in $\mathrm{kPa\ ^\circ C^{-1}}$.

$$\Delta \approx (4099\,e_a)/(T_m + 237.3)^2 \tag{11}$$

in which:

T_m = $(T_x+T_n)/2$ = mean 24-h temperature °C
T_x = maximum air temperature °C
T_n = minimum air temperature °C
e_a = $0.5\,(e_{ax}+e_{an})$ = saturation vapor pressure kPa
e_{ax} = $0.6108 \exp[(17.27 \cdot T_x)/(T_x+237.3)]$ kPa
e_{an} = $0.6108 \exp[(17.27 \cdot T_n)/(T_n+237.3)]$ kPa
e_d' = $0.5\,(e_{dx}+e_{dn})$ = actual vapor pressure kPa
e_{dx} = $e_{ax}(RH_n/100)$ = actual vapor pressure at T_x kPa
e_{dn} = $e_{an}(RH_x/100)$ = actual vapor pressure at T_n kPa
RH_x = maximum 24-h relative humidity %
RH_n = minimum 24-h relative humidity %

Experimental data

Hourly data

Six partial days of micrometeorological and lysimeter data (Table 1) were used to check the accuracy of the PD_i and PM_i equations. The data were reported by Pruitt and Lourence (1965). A crop of perennial ryegrass was grown in a 6.1-m-diameter weighing lysimeter, with approximately 200 m of fetch in the predominant upwind direction, at the Campbell Tract research site in Davis, California. Pruitt and Angus (1960) have described the lysimeter characteristics and management. Data were recorded on an automatic printer to the nearest 0.9 kg ≈ 5.2 $\mathrm{W\ m^{-2}}$, which is about 1% of a typical summer $\mathrm{ET_0}$ rate. The grass was cut every 7–10 days but never to a height below 0.10 m. A large field of grass cut to the same height surrounded the lysimeter in all directions. The lysimeter and immediate area around the lysimeter were irrigated approximately weekly to avoid a significant drop in ET due to low soil water content. The large field around the lysimeter area was irrigated during the following day and night. Sufficient water was applied to return the soil to field capacity. Data were collected between 24 and 96 h after irrigation depending on the weather (W. O. Pruitt, personal communication). Data were collected at half-hour intervals, but hourly averages are used in this study. The lysimeter evaporation (LE_i) data and $\mathrm{ET_0}$ estimates from the equations were expressed in energy flux density units ($\mathrm{W\ m^{-2}}$) to make comparisons. There were few night-time data provided, so only calculations during daylight hours were analyzed. The LE_i data were measured in kg of weight loss from the lysimeter and converted to energy flux density units. The conversion to energy flux density is temperature dependent, but a 1.0 $\mathrm{kg\ h^{-1}}$ of weight loss from the 6.1-m-diameter lysimeter is equivalent to 0.008554 $\mathrm{mm\ h^{-1}}$ or 5.80 $\mathrm{W\ m^{-2}}$ at 25 °C. Therefore, a high evapotranspiration rate of 0.9 $\mathrm{mm\ h^{-1}}$ is roughly equal to 610 $\mathrm{W\ m^{-2}}$.

Although the purpose was to test the PD_i equation and the PM_i equation using r_c = 70 $\mathrm{s\ m^{-1}}$, the PM equation was also tested using r_c = 70 $\mathrm{s\ m^{-1}}$, but without hourly soil heat flux density (G_i). In addition, the best value for canopy resistance, with and without the soil heat flux density, was determined by trial and error. Therefore, four PM equations and the PD_i equation were tested against the lysimeter (LE_i) data. The equations tested are listed below.

PD_i Pruitt and Doorenbos (1977) modified Penman (1963) equation
PM_i Allen et al. (1994) modified Penman-Monteith (Monteith 1965) equation assuming $G_i = 0.1 \times R_{ni}$ and r_c = 70 $\mathrm{s\ m^{-1}}$
PM_j Allen et al. (1994) modified Penman-Monteith (Monteith 1965) equation assuming $G_i = 0$ and r_c = 70 $\mathrm{s\ m^{-1}}$
PM_k Allen et al. (1994) modified Penman-Monteith (Monteith 1965) equation assuming $G_i = 0$ and r_c = 59 $\mathrm{s\ m^{-1}}$
PM_l Allen et al. (1994) modified Penman-Monteith (Monteith 1965) equation assuming $G_i = 0.1 \times R_{ni}$ and r_c = 42 $\mathrm{s\ m^{-1}}$

Daily data

To assess the effect of climate and season on the $\mathrm{ET_0}$ equations, additional hourly data from five Californian and five Italian weather stations were used. There was no independent measure of $\mathrm{ET_0}$ at these stations, so the other equation results were compared with $\mathrm{ET_0}$ determined using the PM_l equation, which had the lowest Root Mean-Square Error (RMSE) when compared to lysimeter readings. The Californian data came from CIMIS, an automated agricultural weather network that is operated by the California Department of Water Resources (Snyder and Pruitt 1992). The CIMIS data were quality tested using the procedures reported by Snyder et al. (1985). The Italian data came from the Sardinian Agrometeorological Network, which is operated by the Servizio Agrometeorologico Regionale (SAR). It is an automated weather station network of 50 stations on the island of Sardinia (Italy), which is located in the Mediterranean Sea west of the Italian mainland (Duce et al. 1996). The data were quality tested based on procedures reported by Meek and Hatfield (1994).

In California, net radiation (R_{ni}) is calculated using the procedure described in Dong et al. (1992). R_{ni} is calculated using a fundamental radiation balance equation (Monteith 1973) that accounts for net short and long wave radiation balance. Estimating the long wave radiation downward from clouds is problematic because it depends on the cloud base temperature, which is unknown. Using screen temperature to estimate the cloud base temperature leads to errors because the cloud base is generally colder. The difference in temperature varies depending on cloud type and cloud base height. Because cloud type is similar in any given month of the year, Monteith (1973) recommended calibrating the long wave downward radiation from clouds by month. Dong et al. (1992) determined these monthly calibration factors for California to account for the temperature difference. The net radiation values used in this paper were computed using the Dong et al. (1992) method and the monthly calibration factors for cloud effects on long wave radiation.

The weather data were used to calculate hourly $\mathrm{ET_0}$ using the PM_l, PD_i and PM_i equations. Night-time hourly $\mathrm{ET_0}$ values, when $R_n<0$, were assumed to be insignificant and were set equal to zero. This is a fair assumption because transpiration by grass is negligible at night, and most of the heat flux density from the soil and air at night is used to replace the net radiation energy loss rather than for evaporation. Appreciable night-time evaporation would be unlikely unless the grass field was wetted by something other than dew formation and there was considerable warm air advection. Sums of the hourly $\mathrm{ET_0}$ for $R_n>0$ were calculated to make comparisons. In addition, daily weather data were used to calculate the PM_d values for $\mathrm{ET_0}$. For the climate difference comparisons, the following equations were used:

$$\mathrm{PD}_i' = \sum_{i=1}^{24} \mathrm{PD}_i \quad \text{with} \quad \mathrm{PD}_i = 0 \quad \text{when} \quad R_{ni} < 0$$

$$\mathrm{PM}_i' = \sum_{i=1}^{24} \mathrm{PM}_i \quad \text{with} \quad \mathrm{PM}_i = 0 \quad \text{when} \quad R_{ni} < 0$$
$$\text{assuming} \quad G_i = 0.1 \times R_{ni} \quad \text{and} \quad r_c = 70\ \mathrm{s\ m^{-1}}$$

$$\mathrm{PM}_l' = \sum_{i=1}^{24} \mathrm{PM}_l \quad \text{with} \quad \mathrm{PM}_l = 0 \quad \text{when}\ R_{ni} < 0$$
$$\text{assuming} \quad G_i = 0.1 \times R_{ni} \quad \text{and} \quad r_c = 42\ \mathrm{s\ m^{-1}}$$

$$\mathrm{PM}_d = 24\text{-h FAO Penman-Monteith}$$
$$\text{assuming } G_i = 0 \text{ and } r_c = 70\ \mathrm{s\ m^{-1}}$$

For each of the ten stations, the first 7 days of hourly data for the months February, May, August, and November 1995 were selected to obtain a range of climatic conditions during the year. Because there were considerable missing data during some of the selected periods, a different week of data was used in some cases. Table 2 lists the stations and their climate characteristics. The variables used in the analysis were:

Air temperature at 1.5 m (CIMIS) and 2.0 m (SAR)	°C
Water vapor pressure at 1.5 m (CIMIS) and 2.0 m (SAR)	kPa
Wind speed at 2.0 m	$\mathrm{m\ s^{-1}}$
Net radiation (estimated)	$\mathrm{W\ m^{-2}}$

The RMSE statistic was used to compare the hourly equations with the lysimeter measurements and to compare the daily $\mathrm{ET_0}$ estimates.

Because it is an indication of both bias and variance from the 1 : 1 line, the RMSE provides a good measure of how closely two independent data sets match. The RMSE values were calculated as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\mathrm{PE}_i - \mathrm{OE}_i)^2} \tag{12}$$

where PE_i = predicted ET_0, OE_i = independent measure of ET_0, and n = number of observations.

For the hourly data, the OE_i values were the lysimeter data. For the 24-h comparisons, the OE_i values were the PM_l' calculations.

Results

Hourly equations versus lysimeter ET_0

The micrometeorological data from Davis (Table 1) were used to calculate ET_0 (W m^{-2}) using the PD_i and several PM equations. The net radiation term, canopy resistance, and RMSE values are shown below.

Equation	R_n term	r_c	RMSE (W m^{-2})
PD_i			47
PM_i	$R_n - G$	70	44
PM_j	R_n	70	30
PM_k	R_n	59	26
PM_l	$R_n - G$	42	23

Figure 1 shows the plots of PM_l, PM_i, and PD_i versus LE_i. Except for a few outliers when the ET_0 is high, the points for all three equations are evenly distributed about the 1 : 1 line. Based on the authors' experience using aerodynamic methods to measure ET, a RMSE value less than 50 W m^{-2} is good, so all of the equations give acceptable estimates of lysimeter-measured ET_0. The PM_k and PM_l equations were slightly better than the others at matching LE_i, and the PM_l equation performed best.

In the FAO hourly PM equation, the daytime soil heat flux density is estimated as the product $G_i = 0.1 \times R_{ni}$. However, the measured G_i in the Pruitt and Lourence (1965) data was about $G_i = 0.03 \times R_{ni}$ (Fig. 2). In fact, G_i was measured as the mean of three heat flux plates buried at 0.01 m depth in the soil. At the time of their experiment that was standard practice. However, today it is recommended that G_i measured at some depth be adjusted for changes in stored heat above the flux plates to obtain a more accurate estimate of G_i at the surface. Pruitt and Lourence (1965) reported soil temperature data at 0.01 m depth on only 2 of the 6 days. Using those data and assuming 1200 kg m^{-3} for the soil bulk density, the adjusted surface G_i was about 12% to 15% higher for volumetric water contents of 0.2–0.3. Therefore, for those water contents, correcting for the heat storage will increase the surface G_i to between 3.6% to 4.5% of R_{ni}. For these data, it is clearly less than the 10% suggested by Allen et al. (1994). Based on the authors' field experience, the $G_i = 0.1 \times R_{ni}$ is typical of shorter (0.05–0.10 m tall) turfgrass where sunlight is better able to transmit to the ground. Therefore, using a smaller G_i seems reasonable for the taller (0.10–0.15 m tall) grass.

Table 1 Micrometeorological data for the previous hour measured over 0.10- to 0.15-m-tall, cool-season grass (from Pruitt and Lourence, 1965)

Date	Time PST	T_i °C	u_i M s^{-1}	e_i kPa	R_{ni} W m^{-2}	G_i W m^{-2}	H_i W m^{-2}	LE_i W m^{-2}
30 July 1962	15	29.2	4.3	1.24	536	14	–7	528
	16	29.1	4.8	1.22	405	8	–36	432
	17	28.5	4.4	1.30	217	3	–86	299
31 July 1962	7	13.2	1.5	1.03	65	–6	40	31
	8	15.2	1.5	0.53	208	–1	90	119
	11	23.3	1.6	1.35	586	19	178	389
	12	25.5	2.2	1.38	647	24	151	472
	13	27.2	3.1	1.37	666	24	120	522
	14	28.7	4.1	1.28	628	19	68	540
	15	29.8	4.5	1.20	537	14	–4	527
	16	29.8	4.6	1.31	409	10	–36	435
	17	28.4	4.7	1.35	260	5	–65	320
	18	27.1	4.0	1.28	105	2	–103	205
31 August 1962	8	13.8	1.9	1.32	139	–5	55	89
	9	17.9	1.2	1.39	296	1	143	151
	10	20.8	1.0	1.45	432	8	169	254
	11	23.9	0.9	1.50	541	15	195	332
	12	27.3	0.9	1.56	597	19	178	401
	13	29.8	0.9	1.49	604	21	141	442
	15	33.1	0.9	1.29	453	16	68	369
	16	33.6	1.1	1.27	316	13	16	287
	17	33.4	1.3	1.31	163	9	–24	179
6 June 1963	11	23.2	8.5	0.91	654	12	114	528
	12	24.4	7.7	0.94	699	17	120	563
	13	25.3	6.3	0.97	689	20	67	602
	14	26.0	5.6	0.96	640	20	38	582
	15	26.6	4.6	1.00	539	18	5	516
	16	26.7	3.4	0.98	415	15	–16	416
14 August 1963	8	17.9	2.6	1.38	144	–3	36	112
	9	21.3	2.6	1.42	299	3	63	234
	10	24.9	2.4	1.41	435	9	87	339
	11	27.3	2.8	1.38	554	14	87	452
	12	29.2	2.9	1.34	629	18	84	526
	13	30.8	2.4	1.26	618	22	66	529
	14	31.9	2.2	1.18	574	24	37	514
	15	32.7	1.5	1.13	480	22	–9	467
	16	33.1	1.4	1.16	351	19	–37	369
	17	33.9	1.0	1.20	194	15	–51	231
	18	33.5	0.8	1.23	54	11	–71	114
15 August 1963	8	21.9	2.2	1.30	154	–2	–12	168
	9	26.0	3.3	1.25	311	4	22	285
	10	28.3	4.8	1.27	459	8	14	437
	11	30.1	4.7	1.36	567	11	44	513
	12	32.1	3.8	1.34	624	16	63	545
	13	34.2	2.1	1.33	621	22	49	549
	14	34.9	1.4	1.26	564	26	19	519
	15	35.3	1.3	1.29	467	23	–19	463
	16	35.8	1.0	1.27	337	20	–25	342
	17	35.7	1.0	1.15	184	16	–61	229
	18	32.8	2.2	1.26	46	11	–113	148

Daily PM_l', PD_i', PM_i', and PM_d comparison

Using the hourly and 24-h data from the five CIMIS and five SAR weather stations, ET_0 was estimated using the PM_l', PD_i', PM_i', and PM_d equations. The California and Italy data were analyzed separately and there were a total of n = 140 days of data for each data set.

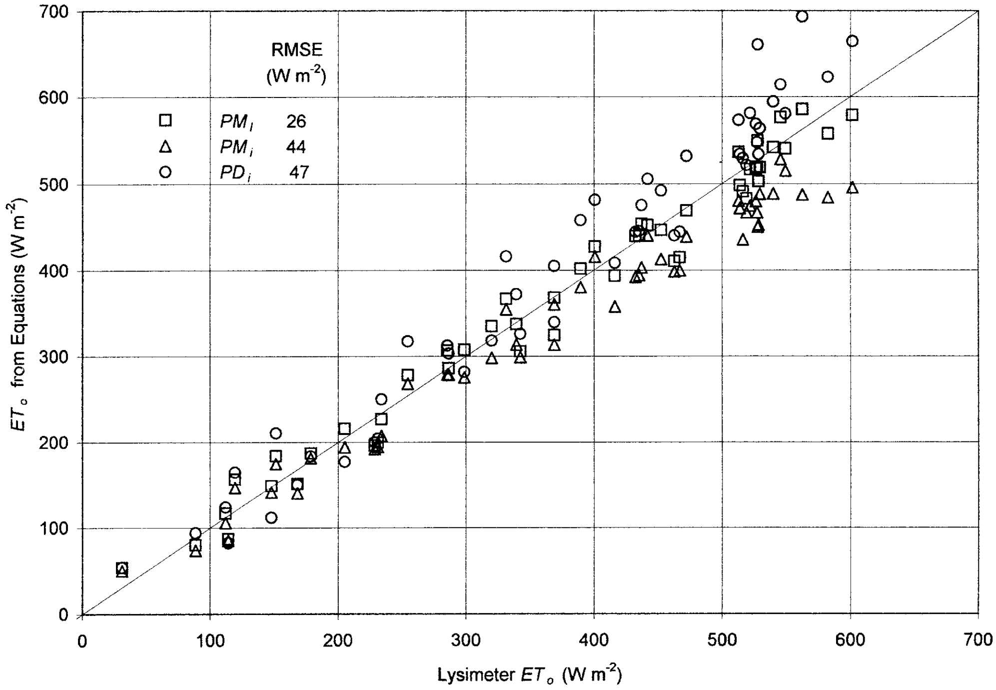

Fig. 1 A plot of ET$_0$ from the hourly FAO Penman-Monteith equation assuming $G_i = 0.1\times R_{ni}$ and $r_c = 70$ s m^{-1} (PM$_i$), the hourly Penman-Monteith equation assuming $G_i = 0.1\times R_{ni}$ and $r_c = 42$ s m^{-1} (PM$_l$), and the Pruitt-Doorenbos equation (PD$_i$) versus lysimeter-measured ET$_0$

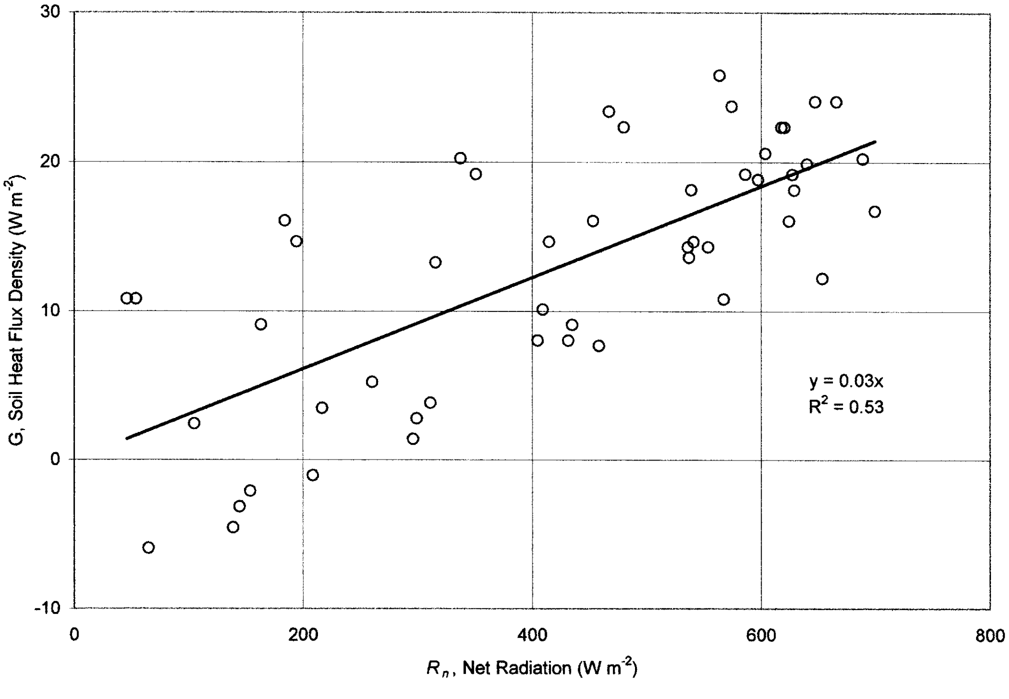

Fig. 2 A plot of hourly soil heat flux density (G_i) measurements in W m^{-2} versus net radiation (R_{ni}) measurements in W m^{-2} using the data from Table 1

For the Italy data (Fig. 3), the PD$_i'$, PM$_i'$, and PM$_d$ results are plotted versus the PM$_l'$ data. The PD$_i'$ were mostly above the 1:1 line and the PM$_i'$, and PM$_d$ calculations were mostly below the 1:1 line. The RMSE values were all smaller than 0.42 mm day^{-1}, so the expected error for all of the equations is likely to be less than 10% during the main growing season in Sardinia. The PM$_i'$ results were closest to PM$_l'$.

The California data (Fig. 4) were similar to the Italy data in that the RMSE was less than 0.43 mm day^{-1} for all equations. Again, this implies that any of the equations is suitable for estimating ET$_0$. The PD$_i'$ values in the range of 3–5 mm day^{-1} were higher than the ET$_0$ values from PM$_l'$. The discrepancy mainly arises in the summer data from Salinas, which is characterized by strong winds that blow cold air from the Pacific Ocean possibly creating an unstable (lapse) condition. The PD$_i$ wind function was calibrated in Davis where warm air advection and stable conditions are common over irrigated grass during windy periods. During warm air advection, an increase in ET$_0$ is ex-

Table 2 Weather station descriptions

Station	Elevation (m)	Latitude	Longitude	Description
Davis, CA	18	38°32′N	121°46′W	A central valley location near Sacramento. Clear, hot, and dry with calm winds until late afternoon in summer. Moderate SW winds in late afternoon. Moderate and variable spring and fall conditions. Cool and foggy winter.
Parlier, CA	102	36°35′N	119°30′W	A central valley location south of Fresno. Clear, hot, and dry with calm winds in summer. Moderate and variable spring and fall conditions. Cool and foggy winter.
Calipatria, CA	–33	33°02′N	115°24′W	A below sea level desert location. Very hot, dry and sometimes windy conditions in summer. Mostly clear to partly cloudy. Mild, partly cloudy winters with transitions in the spring and fall.
McArthur, CA	1006	41°03′N	121°27′W	Northern mountain valley. Variable cloudy conditions much of the year. Warm dry summers and cool to cold winters with snow.
Salinas, CA	36	37°37′N	121°32′W	A central coast location south of San Francisco. Cool, foggy mornings followed by clear windy afternoons during summer. Moderate winters with variable clouds and moderate rainfall.
Atzara, I	620	40°00′N	9°05′E	A central mountain location characterized by sub-humid climate. Hot and humid in summer. Mostly clear to partly cloudy. Spring and fall rainy conditions, cool to cold winter with heavy rain.
Marrubiu, I	38	39°47′N	8°39′E	A central western coastal location (Campidano plane) characterized by mild-hot climate. Hot and humid in summer. Moderate and variable spring and fall condition. Cool and rainy winter.
Olmedo, I	32	40°39′N	8°21′E	A northwestern coastal location (Nurra plane) characterized by mild-hot climate. Clear, hot and humid with calm winds until midday in summer. Moderate and variable spring and fall condition. Cool and rainy winter.
Ozieri, I	228	40°37′N	8°52′E	A north central hilly location with mild-hot climate and sometimes windy conditions in summer. Moderate and variable spring and fall condition. Cool and rainy winter.
Villasalto, I	555	39°28′N	9°21′E	A southeastern hilly location characterized by sub-humid climate. Very hot and humid in summer. Moderate and variable spring and fall condition. Cool and rainy winter.

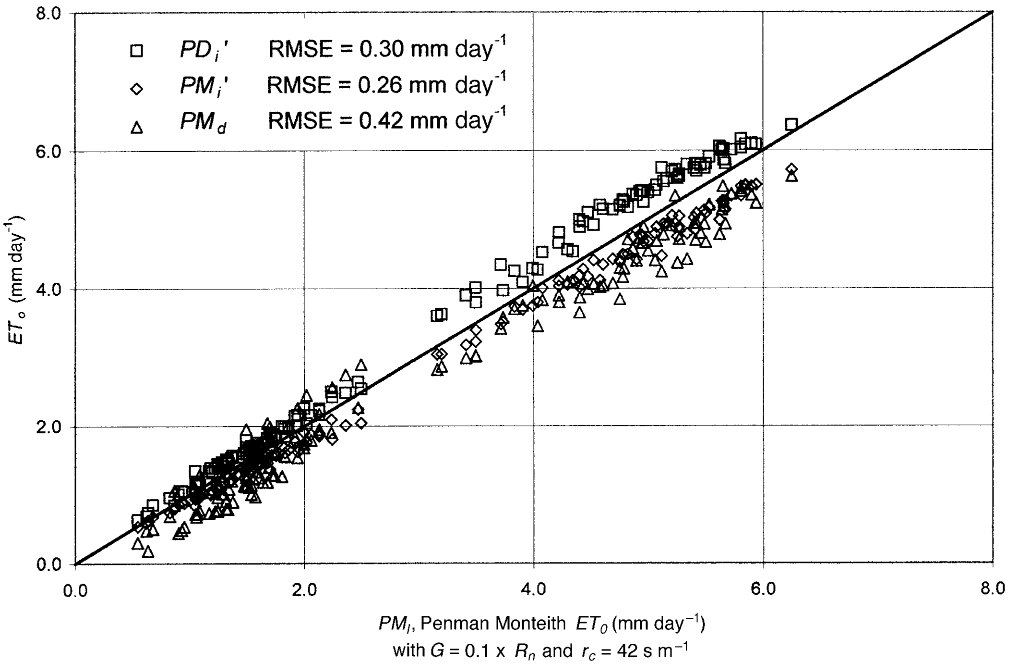

Fig. 3 A plot of (1) hourly FAO Penman-Monteith ET$_0$ summed over daylight hours (PM$_i'$), (2) 24-h FAO Penman-Monteith (PM$_d$), and (3) hourly Pruitt-Doorenbos ET$_0$ summed over daylight hours (PD$_l'$) versus the hourly FAO Penman-Monteith equation using r_c = 42 s m^{-1} summed over daylight hours (PM$_l'$). Four weeks of data from different seasons and five Italian weather stations in differing climate zones were used

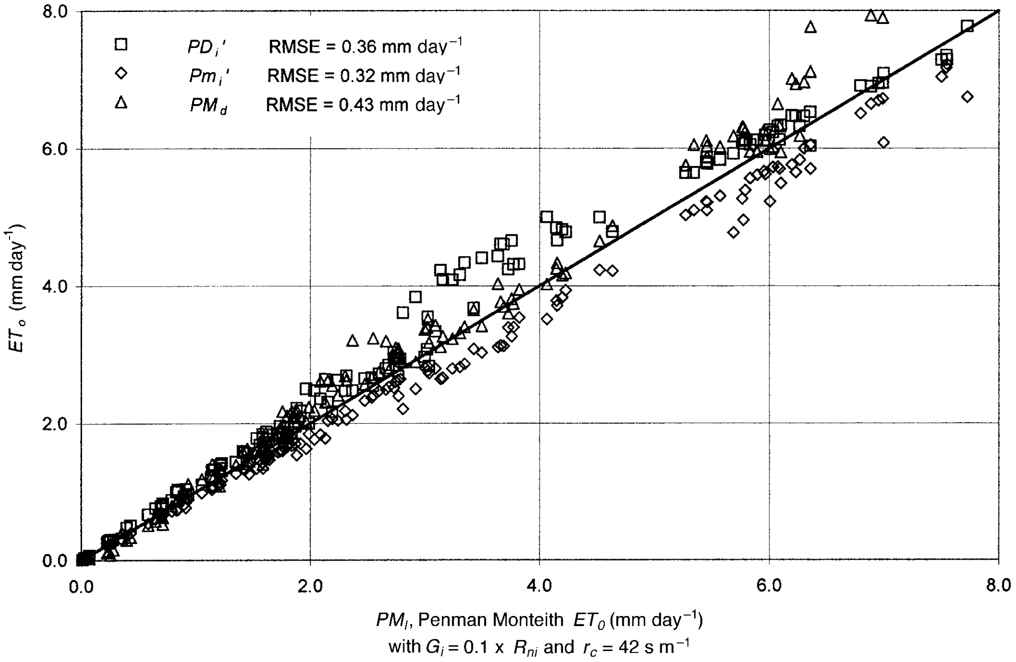

Fig. 4 A plot of (1) hourly FAO Penman-Monteith ET_0 summed over daylight hours (PM_i'), (2) 24-h FAO Penman-Monteith (PM_d), and (3) hourly Pruitt-Doorenbos ET_0 summed over daylight hours (PD_l') versus the hourly FAO Penman-Monteith equation using r_c = 42 s m^{-1} summed over daylight hours (PM_l'). Four weeks of data from different seasons and five Californian weather stations in differing climate zones were used

pected at higher wind speed. However, with cold air advection an increase in wind speed will not have the same effect on ET_0. This possibly explains why Penman-type equations having calibrated wind functions often fail in locations with different climate than where they were calibrated. The PM equation should be less affected by this phenomenon because the canopy resistance rather than a wind function is calibrated.

Conclusions

Several modifications of the FAO PM equation and the PD equation for estimating hourly ET_0 were tested against daytime lysimeter data. Using a soil heat flux density (G_i) equal to 10% of net radiation and a canopy resistance (r_c) equal to 42 s m^{-1}, the PM equation best matched measured ET_0. The next best equation was the PM equation assuming G_i = 0 and r_c = 70 s m^{-1}. The FAO recommended the PM equation assuming $G_i = 0.1 \times R_n$ and r_c = 70 s m^{-1} and the PD (1977) equation performed less well, but the results were acceptable for estimating ET_0.

Daily sums of hourly ET_0 (neglecting night-time values) were calculated from weekly data sets from the four seasons for five locations in Italy and five locations in California to assess difference between the equations in various climates. The equations used include (1) the FAO hourly PM equation assuming $G_i = 0.1 \times R_{ni}$ and r_c = 70 s m^{-1}, (2) the PD hourly equation, and (3) the 24-h FAO PM equation. The results of the calculations were compared with estimates from the PM equation assuming G_i = 0 and r_c = 42 s m^{-1}, which performed best against the lysimeter data.

For the Italy data, the two PM equations gave results slightly below the 1:1 line and the PD equation gave values slightly above the 1:1 line. However, any of the equations provide acceptable ET_0 estimates. For the California data, the results were similar. The PD equation slightly over-estimated ET_0 in the range of 3.5–5.0 mm day^{-1}. However, the data in this range were from the Salinas Valley where cold air advection occurs in summer. The over-prediction may occur because the wind function was calibrated in Davis, California where cold air advection is uncommon in the summer. These results might partially explain why calibrated Penman-type wind function equations sometimes fail when used in different climates.

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