Evaluation of 13 Empirical Reference Potential Evapotranspiration Equations on the Island of Crete in Southern Greece

Fotios Xystrakis, Ph.D.[1]; and Andreas Matzarakis[2]

Abstract: Knowledge of reference potential evapotranspiration (PET_{ref}) conditions is important for a number of vegetation- and hydrological-related applications. Direct estimations of PET_{ref} are difficult and require sophisticated instrumentation. The Food and Agriculture Organization (FAO), therefore, proposed a method for the estimation of PET_{ref} using only meteorological data. This equation has been widely accepted as the standard method for the estimation of PET_{ref} because of its good fit with measured values. Nevertheless, it requires several meteorological variables (e.g., wind speed), which are rarely available. Where such data are not available, its application is hampered. To overcome this problem, a number of simpler, empirical equations requiring only a fraction of the meteorological input variables required by the FAO PET_{ref} have been developed. Before using these equations, it is important to evaluate their performance and choose the equation that will have the lowest possible bias in the estimation of PET_{ref}. Using daily meteorological observations obtained from seven meteorological stations on the island of Crete (southern Greece), the performance of 13 empirical equations (radiation- and temperature-based) for the estimation of PET_{ref} has been evaluated against the estimations of PET_{ref} using the FAO equation. Performance was evaluated on a daily and a monthly basis, and five different measures of goodness of fit were used. The results showed that when the use of the FAO equation is not possible because of the unavailability of data, some empirical methods can serve as appropriate alternatives. The radiation-based equations generally performed better than those that included only temperature-related input variables. The equations proposed by Hansen and Turc were the most useful because they had an average monthly absolute error ranging from 5.7 to 17.7 mm and 5.5 to 19.2 mm, respectively.
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Introduction

Potential evapotranspiration (PET) is defined as the amount of water that can potentially evaporate and transpire from a vegetated surface with no restrictions other than the atmospheric demand (Lu et al. 2005). PET provides a good representation of the maximum possible water loss to the atmosphere. Knowledge of PET rates is essential for a variety of applications, including hydrological modeling, irrigation planning, geobotanical studies, and estimation of sensitive-to-climatic change aridity indexes. Although the PET concept is applied in a wide spectrum of applications, the term is considered a source of confusion because of the vague definition of "vegetated surface." To overcome this problem, the term PET has gradually been replaced by "reference potential evapotranspiration" (PET_{ref}), for which the characteristics of the vegetated surface have been standardized. The Food and Agriculture Organization (FAO) Expert Consultation of Revision of FAO Methodologies of Crop Water Requirements accepted the following definition of the reference surface: "A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s/m, and an albedo of 0.23" (Allen et al. 1998). Consequently, PET_{ref} is defined as the amount of water that can potentially evaporate and transpire from a reference crop with no restrictions other than the atmospheric demand.

PET_{ref} can be obtained using specific devices, through measurements of various physical parameters, or on the basis of the soil water balance using lysimeters. These methods are expensive, demanding in terms of accuracy of measurements, and require well-trained research personnel (Allen et al. 1998). Perhaps the easiest way to calculate PET_{ref} values is with the FAO Penman-Monteith method, which according to an expert consultation held in May 1990, is now the recommended standard method for the definition and computation of PET_{ref}. The form of this equation, revised from Allen et al. (1998), is

$$PET_{FAO} = \frac{0.408\cdot\Delta\cdot(R_n - G) + \gamma\cdot(900/T_{mean} + 273)\cdot U_2\cdot(e_s - e_a)}{\Delta + \gamma\cdot(91 + 0.34\cdot U_2)} \quad (1)$$

where Δ = slope of saturation vapor pressure curve at air temperature T ($kPa \cdot °C^{-1}$); R_n = net radiation ($MJ \cdot m^{-2}$); G = soil heat flux ($MJ \cdot m^{-2}$) (0 for daily periods); γ = psychrometric constant ($kPa \cdot °C^{-1}$); T_{mean} = daily mean air temperature at 2 m height (°C); U_2 = wind speed at 2 m height ($m \cdot s^{-1}$); e_s = saturation vapor pressure (kPa); and e_a = actual vapor pressure (kPa).

[1]Institute of Silviculture, Albert-Ludwigs Univ. of Freiburg, Tennenbacherstr 4, D-79106, Freiburg. I Br., Germany (corresponding author). E-mail: xystrakis.fotis@waldbau.uni-freiburg.de

[2]Professor, Meteorological Institute, Albert-Ludwigs Univ. of Freiburg, Werthmannstr 10, D-79085, Freiburg I Br., Germany. E-mail: andreas.matzarakis@meteo.uni-freiburg.de

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This physically based equation, involving all the meteorological variables controlling evapotranspiration, is deemed to provide the best estimates of PET_{ref} values over a wide range of climates and is widely used as a standard for the evaluation of other empirical PET_{ref} formulas (Droogers and Allen 2002; Gavilán et al. 2006; Nandagiri and Kovoor 2006; Popova et al. 2006; Trajkovic 2005; Xu and Singh 2002).

However, the equation requires a variety of meteorological input variables that the vast majority of meteorological stations do not record. For this reason, in most operational applications PET_{ref} is estimated by means of various simpler, empirical equations that are less demanding in terms of input variables. Depending on the necessary input data, these equations, can be classified as either temperature-based, radiation-based, or combined methods. The number of empirical equations is rather high and the output may be inconsistent and prone to bias because of the different underlying assumptions and the corresponding input data requirements or because they were developed for specific climatic regions (Allen et al. 1998; Grismer et al. 2002). To ensure accuracy, it is essential that the performance of these empirical equations for the estimation of PET_{ref} be evaluated prior to their use, either by using existing observations of evapo(transpi)ration or PET_{ref} values calculated with one of the more sophisticated methods (energy balance, lysimeters, etc.) in the region of interest.

To this end, daily values of PET_{ref}, estimated by using 13 empirical equations obtained from a review of the existing literature, were compared with the respective output of the PET_{FAO} equation using data obtained from seven meteorological stations in Crete, which has a typical semiarid, Mediterranean climate. The risk of desertification is high (Croke et al. 2000; Grove and Rackham 1993; Vardavas et al. 1997) and sustainable irrigation planning for drought mitigation and adaptation is essential (Lambrakis and Kallergis 2001; Tsakiris and Tigkas 2007; Tsakiris et al. 2007; Vardavas et al. 1997). The evaluation of the empirical equations in this region is of major interest. PET_{ref} estimates exist for Crete (for example, Naoum and Tsanis 2003; Tsanis and Naoum 2003), but a current evaluation of empirical equations is lacking.

Various measures of goodness of fit were applied to assess the accuracy of the empirical PET_{ref} equations. The results of this study provide insight into the choice of the most suitable empirical PET_{ref} equation when the unavailability of data prevents the application of the PET_{FAO} equation in Crete and in other regions with similar climatic conditions.

Methods

Climate Data and Location of Meteorological Stations

Daily values of meteorological data obtained from seven weather stations in Crete were used in the study. The meteorological data included the variables shown in Table 1. The observation period and other variables of the weather stations are presented in Table 2. The locations of the meteorological stations are depicted in Fig. 1.

These meteorological variables build the input data used for the estimation of the daily values of PET_{ref} in all of the equations. Days with at least one meteorological variable missing were excluded from the analyses. The long observation period allowed for the extraction of safe conclusions over the performance of the PET_{ref} equations for both daily and monthly analyses. The global (total) solar radiation data, not measured by any of the meteorological stations in Crete, were estimated using the RayMan model (Matzarakis and Rutz 2007; Matzarakis et al. 2007), taking into consideration the cloud cover, the latitude, and the elevation of the meteorological stations. To estimate the extraterrestrial radiation (R_a) and net radiation (R_n) the method described by Allen et al. (1998) was followed. An albedo value of 0.23 was used (Allen et al. 1998) in the calculation of R_n for the reference crop.

Table 1. Meteorological Variables Collected by Weather Stations in Study Area; Values Include Daily Observations

Variable	Description
T_{mean}	Daily mean air temperature at 2 m above ground (°C)
T_{min}	Minimum air temperature (°C)
T_{max}	Maximum air temperature (°C)
T_d	Dew-point temperature (°C)
RH	Relative humidity (%)
U_2	Wind velocity at 2 m above ground ($m \cdot s^{-1}$)
Cl	Cloud cover (octas)

Table 2. Location and Observation Period of Weather Stations; Geographic Coordinates Are in Decimal Degrees; Projection System: WGS84

Station	Latitude	Longitude	Elevation	Observation period
Ierapetra	35.02	25.73	10	1956–2001
Iraklio	35.33	25.18	39.3	1955–2001
Kastelli	35.2	25.33	335	1976–2001
Rethimno	35.35	24.51	5.1	1957–2001
Sitia	35.2	26.1	115.6	1960–2001
Souda	35.55	24.11	151.6	1958–2001
Tymbaki	35	24.75	6.7	1959–2001

Empirical PET_{ref} *Equations*

The empirical equations evaluated include temperature- and radiation-based methods, all of which are presented in the following sections. Because these equations include units from nonuniform systems, unit conversion was necessary for their application. A summary of the definitions and descriptions of the symbols is shown in Table 3. The equations where the input variables should be measured in different units than these reported in Table 3, are noted in the text. The equations include a wide variety of input parameters thus their applicability depends on the data availability. A summary of the different potential evapotranspiration methods included in this paper is presented in Table 4.

Temperature-Based Methods

- Hargreave's equation (Allen et al. 1998; Oudin et al. 2005; Xu and Singh 2002)

$$PET_{Har} = 0.0023 \cdot (R_a/\lambda) \cdot \sqrt{(T_{max} - T_{min})} \cdot (T_{mean} + 17.8) \quad (2)$$

- McGuinness-Bordne's equation (Oudin et al. 2005)

$$PET_{McG} = (R_a/\lambda \cdot \rho) \cdot [(T_{mean} + 5)/68] \quad (3)$$

- Romanenko's equation (Oudin et al. 2005)

$$PET_{Rom} = 4.5 \cdot [1 + (T_{mean}/25)]^2 \cdot (1 - e_a/e_s) \quad (4)$$

Fig. 1. Location of meteorological stations in Crete, Greece

Table 3. Definitions of and Procedures for Calculation of Units Used in PET_{ref} Equations

Symbol	Definition	Unit	Calculation	Reference
R_a	Extraterrestrial radiation	MJ/m^2	Depends on latitude and Julian day	Allen et al. (1998)
R_s	Global (total) radiation	MJ/m^2	RayMan	Matzarakis and Rutz (2007)
R_n	Net radiation	MJ/m^2	Based on R_s, albedo and longwave radiation. Computational details in Allen et al. (1998)	Allen et al. (1998)
T_{mean}	Mean air temperature	°C	—	—
T_{max}	Maximum air temperature	°C	—	—
T_{min}	Minimum air temperature	°C	—	—
DL	Day length	hours	Function of latitude, RayMan	Matzarakis and Rutz (2007)
e_o	Generalized equation of saturation vapor pressure	kPa	$e_o = 0.6108\cdot\exp[(17.27\cdot T)/(T+237.3)]$	Allen et al. (1998)
e_s[a]	Mean saturation vapor pressure	kPa	$e_s = (e_{T_{max}} + e_{T_{min}})/2$	
e_a	Actual vapor pressure	kPa	$e_a = 0.6108\cdot\exp[(17.27\cdot T_{dew})/(T_{dew}+237.3)]$	
SVD[a]	Saturated vapor density at mean air temperature	g/m^3	$SVD = 216.7\cdot[e_s/(T_{mean}+273.3)]$	Lu et al. (2005); Rosenberry et al. (2004)
RH	Relative air humidity	%	—	—
Δ	Slope of saturation vapor pressure curve	kPa/°C	$\Delta = 4098\cdot\left[0.6108\cdot\exp\frac{17.27\cdot T_{mean}}{T_{mean}+237.3}\right]/(T_{mean}+237.3)^2$	Allen et al. (1998)
γ[b]	Psychrometric constant	kPa/°C	$\gamma = (C_p\cdot P)/(\varepsilon\cdot\lambda) = 0.665\cdot 10^{-3}\cdot P$	Allen et al. (1998)
ρ	Water density	$1000(kg/m^3)$	Allen et al. (1998)	
λ	Latent heat of vaporization	MJ/kg	$\lambda = 2.501 - (2.361\cdot 10^{-3})\cdot T_{mean}$	Allen et al. (1998)

Note: Because of nonlinearity, the mean saturation vapor pressure is estimated as the average of the saturation vapor pressure (e_o) at T_{max} and the saturation vapor pressure at T_{min}. For computation details, refer to Allen et al. (1998).
[a] e_s is measured in mb.
[b] For unit descriptions and calculation procedures, refer to Allen et al. (1998).

Table 4. Summary of the Input Data Requirements of PET_{ref} Equations

	T_{mean}	T_{min}	T_{max}	T_{dew}	RH	Wind speed	DL	R_s	R_a	R_n
PET_{FAO}	✓	✓	✓	✓		✓				✓
PET_{Cap}	✓							✓		
PET_{deB}	✓									✓
PET_{Ham1}	✓	✓	✓				✓			
PET_{Ham2}	✓						✓			
PET_{Ham3}	✓	✓	✓				✓			
PET_{Han}	✓							✓		
PET_{Har}	✓	✓	✓						✓	
PET_{Jen}	✓							✓		
PET_{Mak}	✓							✓		
PET_{McC}	✓									
PET_{McG}	✓								✓	
PET_{Rom}	✓	✓	✓	✓						
PET_{Tur}	✓				✓			✓		

- Hammon's equation (Lu et al. 2005)

$$\mathrm{PET_{Ham1}} = 0.1651 \cdot (DL/12) \cdot [216.7 \cdot e_s/(T_{\mathrm{mean}} + 273.3)] \cdot a \quad (5)$$

where $a = \text{constant} = 1.2$; and e_s in mb.

- Hammon's equation (Oudin et al. 2005)

$$\mathrm{PET_{Ham2}} = (DL/12)^2 \cdot \exp(T_{mean}/16) \quad (6)$$

- Hammon's equation (Rosenberry et al. 2004)

$$\mathrm{PET_{Ham3}} = 0.55 \cdot (DL/12)^2 \cdot (SVD/100) \cdot 25.4 \quad (7)$$

- McCloud's equation (Irmak et al. 2003; Jacobs and Satti 2001)

$$\mathrm{PET_{McC}} = a \cdot b^{(T_{\mathrm{mean}} - 32)} \quad (8)$$

where PET (is in in.); $a = \text{constant} = 1.07$; and $b = \text{constant} = 0.01$.

Radiation-Based and Combination Methods

- Hansen's equation (Hansen 1984; Xu and Singh 2002)

$$\mathrm{PET_{Han}} = 0.7 \cdot [\Delta/(\Delta + \gamma)] \cdot (R_s/\lambda) \quad (9)$$

where R_s is in $\mathrm{cal \cdot cm^{-2}}$; Δ and γ are in $\mathrm{mb \cdot {}^\circ C^{-1}}$; and λ is in $\mathrm{cal \cdot g^{-1}}$.

- Caprio's equation (Caprio 1974) (source: http://www.wsl.ch/staff/niklaus.zimmermann/programs/aml3_2.html)

$$\mathrm{PET_{Cap}} = (6.1/10^6) \cdot R_s \cdot (1.8 \cdot T_{\mathrm{mean}} + 1.0) \quad (10)$$

where R_s is in $\mathrm{kJ \cdot m^{-2}}$.

- Jensen-Haise's equation [exact form is from Rosenberg et al. (1983), but forms presented in Jensen and Haise (1963) and Rosenberry et al. (200)4 were also tested]

$$\mathrm{PET_{Jen}} = (R_s/\lambda) \cdot (0.025 \cdot T_{\mathrm{mean}} + 0.08) \quad (11)$$

- Turc's equation (Jacobs and Satti 2001; Lu et al. 2005). For RH $< 50\%$:

$$\mathrm{PET_{Turc}} = 0.013 \cdot [T_{\mathrm{mean}}/(T_{\mathrm{mean}} + 15)] \cdot (R_s \cdot 23.8846 + 50) \cdot [1 + (50 - \mathrm{RH})/70] \quad (12a)$$

For RH $> 50\%$:

$$\mathrm{PET_{Turc}} = 0.013 \cdot [T_{\mathrm{mean}}/(T_{\mathrm{mean}} + 15)] \cdot (R_s \cdot 23.8846 + 50) \quad (12b)$$

- Makkink's equation [from Rosenberry et al. (2004); forms cited in Xu and Singh (2000, 2002) were also tested]

$$\mathrm{PET_{Mak}} = [0.61 \cdot (\Delta/\Delta + \gamma) \cdot (R_s/\lambda) - 0.012] \cdot 10 \quad (13)$$

where R_s is in $\mathrm{cal \cdot cm^{-2}}$; Δ and γ are in $\mathrm{mb \cdot {}^\circ C^{-1}}$; and λ is in $\mathrm{cal \cdot g^{-1}}$.

- De Bruin's equation (de Bruin and Keijman 1979; Rosenberry et al. 2004)

$$\mathrm{PET_{deB}} = \{[\Delta/(0.85 \cdot \Delta + 0.63 \cdot \gamma)] \cdot (R_n/\lambda)\} \cdot 10 \quad (14)$$

where R_n is in $\mathrm{cal \cdot cm^{-2}}$; Δ and γ are in $\mathrm{mb \cdot {}^\circ C^{-1}}$; and λ is in $\mathrm{cal \cdot g^{-1}}$.

Evaluation of PET$_{\mathrm{ref}}$ *Equations*

The performance of the empirical equations was assessed by using the calculations from several goodness-of-fit statistics (StatSoft 2007). The measures applied to evaluate the performance of the empirical equations were:

- Mean square error (MSE):

$$\frac{\sum_{i=1}^{N} (E_i - O_i)^2}{N - 1} \quad (15)$$

- Mean absolute error (MAE):

$$\frac{\sum_{i=1}^{N} |E_i - O_i|}{N - 1} \quad (16)$$

- Relative mean square error (RMSE):

$$\frac{\sum_{i=1}^{N} (\frac{E_i - O_i}{E_i})^2}{N - 1} \quad (17)$$

- Relative mean absolute error (RMAE):

$$\frac{\sum_{i=1}^{N} \frac{|E_i - O_i|}{E_i}}{N - 1} \quad (18)$$

- Mean bias error (MBE):

$$\frac{\sum_{i}^{N} (E_i - O_i)}{N - 1} \quad (19)$$

- Pearson's correlation coefficient (CC), described in StatSoft (2007).

where N = number of observations; E_i = values from empirical equations; and O_i = respective values from PET$_{\mathrm{FAO}}$ equation.

These (or similar) statistical procedures have been widely discussed in the relevant literature (Jacovides 1998; Jacovides and Kontoyiannis 1995; Knotters and Voshaar 1998; Willmott 1984; Willmott 1982; Willmott et al. 1985) and have proven to be important for the evaluation of the performance of empirical PET$_{\mathrm{ref}}$ equations.

All but the MBE measure of goodness of fit were used for the evaluation of the performance of the empirical equations on a daily and a monthly basis. The daily PET$_{\mathrm{ref}}$ estimates were averaged in monthly totals because it has been demonstrated that any bias in calculation can be reduced when integrated over longer periods and, therefore, the errors were expected to be lower (Hupet and Vanclooster 2001). Additionally, the monthly analysis allows for the suggestion over the use of specific empirical formulas during the different months (different underlying climate conditions). The MBE was used to evaluate the averaged monthly totals of PET$_{\mathrm{ref}}$ estimates.

Prior to the analyses of goodness-of-fit measures, the meteorological stations were ordinated by the weight of each variable in influencing PET$_{\mathrm{ref}}$, allowing for the identification of groups with climatic homogeneity and the detection of possible regional patterns or climatic regions (Comrie and Glenn 1998; Giles et al. 1989; Morin et al. 1979) across the study area. These variables included the mean daily values of T_{mean}, $T_{\max}$, T_d, R_s and wind speed over the observation period recorded at each station. The ordination method used was an *s*-mode principal component analysis (PCA). The type of cross-products matrix was the correlation matrix (data were centered and standardized), which was used to eliminate differences in measurement units between variables. Outlier analysis did not reveal any extreme value at three standard deviations cut-off level. The scores of the variables were calculated using the distance-based biplot method. The analysis was performed with the PCORD software (McCune and Mefford 1999).

Results

Climatic Regions

The ordination diagram shown in Fig. 2 helped identify spatial patterns in the climate data recorded by the meteorological stations.

From the PCA diagram, the stations Tymbaki, Ierapetra, and Sitia form one group, the stations Iraklio and Rethimno form another. While the two remaining stations, Souda and Kastelli, are both located on the left-hand side of the diagram they do not form a distinct group. The first three stations, located in the east and southeast, represent the driest part of Crete (see Fig. 2). The stations Iraklio and Rethimno, situated in northcentral Crete (see Fig. 2), stand out owing to the high wind speed values at these locations. The high wind speed values are positively correlated with high PET_{ref} values, especially in hot and dry climates (Allen et al. 1998). Souda, a lowland station in western Crete, lies between the aforementioned groups and the Kastelli meteorological station, which is situated to the very left of the diagram. Its position is explained by the low values of T_{mean}, T_{max}, T_{dew}, and R_s because its altitude (300 m a.s.l.) is higher than the other stations (see Table 2). The northwest to southeast climatic gradient observed in Crete (Pennas 1977) is also apparent in Fig. 2.

Evaluation of the Empirical PET_{ref} *Equations on a Daily Basis*

The results of the analysis of the daily PET_{ref} values are shown in Table 5. Some equations perform relatively well, whereas others reveal a great bias in the estimation of PET_{ref}. The radiation-based formulas perform better for all meteorological stations except Rethimno and Iraklio. There is great variation with respect to the best temperature-based equations, which contrasts with the clearer pattern observed for the radiation-based equations. Table 5 shows that the RMSE and RMAE of the PET_{Rom}, could not be evaluated because of the calculation procedures. Since the saturation vapor pressure (e_s) is here calculated as $(e_{Tmax} + e_{Tmin})/2$ as proposed from Allen et al. (1998), for some humid and warm days (e.g., for 167 days in Ierapetra), the actual vapor pressure (e_a) is calculated to be lower than the saturation vapor pressure (e_s),

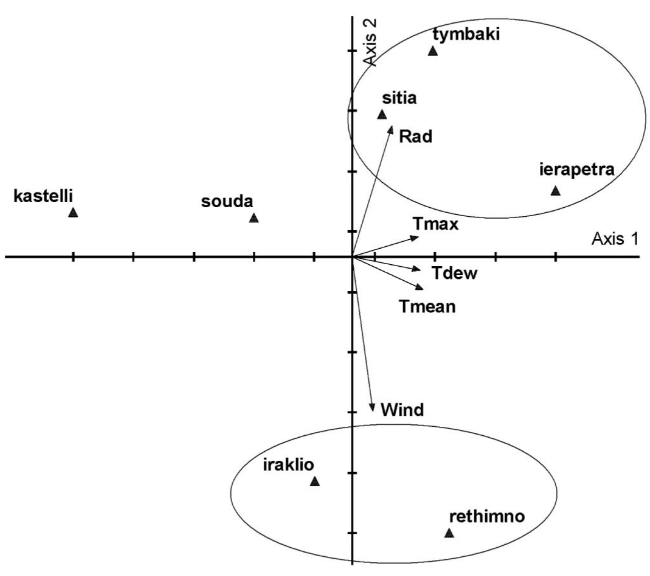

Fig. 2. Axes 1 and 3 of the PCA diagram of meteorological variables recorded by the seven weather stations; cumulative of total variance explained from axes 1 and 2 equals 91.9%

which resulted in negative values of PET_{ref}. For this reason, the evaluation of PET_{Rom} was based only on the MAE, RMAE and the Pearson's CC.

Temperature-Based Equations

The temperature-based equations that exhibited the best fit were PET_{McG}, PET_{Ham2}, and PET_{Ham3}. The minimum values obtained for the MSE, MAE, RMSE, and RMAE (indicating best performance) were for PET_{Ham2} in Kastelli, PET_{Ham2} in Kastelli, PET_{McG} in Sitia, and PET_{Ham2} in Sitia, respectively. The maximum CC value was for PET_{McG} in Kastelli. The PET_{McG} revealed the best fit for the stations Iraklio and Rethimno, where the wind speed values were highest (and PET_{ref}). For the other stations, the MSE and MAE values were much higher. The worst fits were observed for these two stations. PET_{Ham3} was identified as the empirical PET_{ref} equation with the highest Pearson's CC for three stations, but given the results of the remaining goodness-of-fit measures it cannot be considered a suitable equation for the estimation of PET_{ref}.

Radiation-Based Equations

The pattern is clearer for the radiation-based equations. PET_{Turc} stood out clearly from the other empirical equations, followed by PET_{Han} and PET_{deB}. PET_{Mak} also demonstrated good performances because its goodness-of-fit measures were comparable with PET_{Han} and PET_{deB}. As with the temperature-based methods, the worst fits were observed for the stations Iraklio and Rethimno. PET_{Jen} had the best Pearson's CC at the stations Ierapetra and Kastelli. PET_{deB2} was also identified as the best method in terms of RMSE for the stations Souda and Kastelli, whereas PET_{deB} had the best fit in terms of CC for Souda. The minimum values of MSE, MAE, RMSE, and RMAE were for PET_{Tur} in Sitia,; PET_{Tur} in Kastelli; PET_{Tur} in Tymbaki; and PET_{Tur} in Tymbaki, respectively. The maximum value of CC was for PET_{Jen} in Kastelli. As with the temperature-based-equations, the best fits were observed for the stations Kastelli and Sitia, but good fits were also observed for Tymbaki.

Evaluation of the Empirical PET_{ref} *Equations on a Monthly Basis*

The results of the integrated monthly PET_{ref} values are presented in Table 6. It can be seen that some equations clearly stood out for their consistently good fit with the PET_{FAO} equation, whereas others clearly showed a very poor fit. For the daily analysis (see the "Evaluation of the Empirical PET_{ref} Equations on a Daily Basis" section), the radiation-based equations provided better estimates than the temperature-based formulas for all the stations other than Iraklio and Rethimno. In the case of the latter stations, the best temperature-based equations outperformed the best radiation-based equations. Additionally, the relative errors (RMSE and RMAE) for the integrated monthly PET_{ref} values were smaller than the corresponding errors for the daily values.

Temperature-Based Equations

The pattern observed from the study of the integrated monthly values was clearer than that of the daily values (see the "Evaluation of the Empirical PET_{ref} Equations on a Daily Basis" section). PET_{McG} exhibited the best fit for the stations Iraklio and Rethimno, but the performance of the empirical equations was still worse for these stations than elsewhere. For the remaining stations, PET_{Ham2} stood out from all of the other temperature-based equations. The minimum values of MSE, MAE, RMSE, and RMAE were for PET_{Ham} in Sitia; PET_{Ham2} in Sitia; PET_{Ham2}, in Sitia and Souda; and PET_{Ham2} in Sitia, respectively. The maximum value of CC was for PET_{McG} in Souda.

Table 5. Goodness-of-Fit Measures of the Empirical PET Equations when Compared with the PET_{FAO}; Bold Values Indicate Radiation- and Temperature-Based Equations with Best Fits for Each Meteorological Station and for Each Goodness-of-Fit Measure

	Temperature-based							Radiation-based					
	PET_{Har}	PET_{McG}	PET_{Rom}	PET_{Ham1}	PET_{Ham2}	PET_{Ham3}	PET_{McC}	PET_{Mak}	PET_{Han}	PET_{Cap}	PET_{Jen}	PET_{Tur}	PET_{deB}
Ierapetra													
MSE	3.619	1.506	—	1.776	**1.150**	3.635	2.421	1.704	0.959	2.176	2.493	**0.630**	1.412
MAE	1.339	0.996	1.658	1.029	**0.825**	1.474	1.188	0.864	0.703	1.103	1.195	**0.602**	0.867
MRSE	0.396	**0.088**	—	0.117	0.103	0.424	0.500	0.155	0.083	0.158	0.114	**0.067**	0.148
MRAE	0.448	0.242	16.778	0.282	**0.240**	0.527	0.478	0.271	0.202	0.263	0.252	**0.179**	0.260
CC	0.818	0.901	0.871	0.913	0.910	**0.923**	0.848	0.932	0.933	0.944	0.944	**0.953**	0.893
Sitia													
MSE	2.762	0.952	—	0.896	**0.560**	2.141	1.792	0.512	0.400	2.530	2.974	**0.365**	0.673
MAE	1.253	0.779	1.472	0.781	**0.560**	1.208	1.035	0.525	0.497	1.211	1.330	**0.466**	0.657
MRSE	0.507	0.061	—	0.081	**0.061**	0.319	0.507	0.149	0.089	0.215	0.150	**0.070**	0.088
MRAE	0.523	0.199	0.317	0.236	**0.180**	0.471	0.484	0.230	0.185	0.302	0.287	**0.166**	0.201
CC	0.797	**0.944**	0.731	0.916	0.935	0.938	0.839	0.956	0.957	0.961	**0.962**	0.960	0.960
Tymbaki													
MSE	1.342	1.165	—	1.158	**0.815**	2.522	2.197	0.721	0.484	2.766	3.174	**0.444**	0.741
MAE	0.831	0.866	1.958	0.863	**0.671**	1.271	1.089	0.571	0.549	1.226	1.338	**0.522**	0.671
MRSE	0.166	**0.073**	—	0.099	0.079	0.362	0.557	0.110	0.066	0.149	0.111	**0.055**	0.080
MRAE	0.278	0.219	4.801	0.259	**0.207**	0.493	0.498	0.208	0.174	0.272	0.263	**0.162**	0.195
CC	0.884	**0.931**	0.790	0.908	0.927	0.926	0.849	0.950	0.951	0.958	0.959	**0.959**	0.939
Iraklio													
MSE	4.289	**1.263**	—	1.974	1.367	4.256	2.925	2.527	1.804	2.945	3.137	**1.499**	1.895
MAE	1.570	**0.848**	1.284	1.079	0.852	1.725	1.351	1.129	0.920	1.337	1.380	**0.852**	0.987
MRSE	0.970	**0.098**	—	0.160	0.185	0.780	0.916	0.914	0.570	0.881	0.606	**0.378**	0.522
MRAE	0.684	**0.224**	0.255	0.317	0.291	0.733	0.664	0.579	0.429	0.533	0.464	**0.360**	0.426
CC	0.756	0.869	0.831	0.884	0.875	**0.888**	0.825	0.847	0.849	0.868	0.866	**0.873**	0.842
Rethimno													
MSE	3.424	**1.616**	—	1.910	1.635	4.054	2.931	2.765	2.105	3.639	3.845	**1.757**	2.275
MAE	1.368	0.971	1.122	0.998	**0.896**	1.633	1.314	1.112	0.922	1.466	1.510	**0.845**	1.030
MRSE	0.864	**0.113**	—	0.164	0.191	0.783	0.743	0.982	0.623	0.795	0.583	**0.393**	0.607
MRAE	0.586	**0.243**	0.268	0.298	0.283	0.694	0.584	0.573	0.427	0.515	0.458	**0.351**	0.429
CC	0.789	0.838	0.840	0.845	0.837	**0.847**	0.781	0.808	0.809	0.825	0.823	**0.836**	0.802
Souda													
MSE	1.275	1.048	—	0.873	**0.674**	1.955	1.947	0.644	**0.448**	2.555	2.914	0.481	0.535
MAE	0.843	0.819	1.912	0.750	**0.596**	1.115	1.018	0.571	0.502	1.167	1.253	**0.500**	0.562
MRSE	0.178	0.069	—	0.080	**0.062**	0.274	0.550	0.200	0.116	0.360	0.212	0.100	**0.092**
MRAE	0.305	0.213	0.535	0.232	**0.186**	0.432	0.500	0.268	0.203	0.348	0.306	**0.186**	0.191
CC	0.908	**0.944**	0.850	0.922	0.935	0.939	0.847	0.954	0.955	0.957	**0.958**	0.956	0.957
Kastelli													
MSE	1.141	0.845	—	0.920	**0.545**	2.117	2.045	0.494	**0.409**	1.953	2.303	0.421	0.564
MAE	0.781	0.719	1.400	0.759	**0.544**	1.148	1.102	0.476	0.475	1.004	1.098	**0.455**	0.569
MRSE	0.163	0.067	—	0.091	**0.063**	0.320	0.803	0.133	0.084	0.791	0.177	0.305	**0.077**
MRAE	0.290	0.207	4.587	0.251	**0.189**	0.473	0.636	0.210	**0.180**	0.345	0.281	0.180	0.185
CC	0.884	**0.950**	0.850	0.930	0.939	0.943	0.858	0.957	0.958	0.963	**0.964**	0.963	0.955

Radiation-Based Equations

Of the radiation-based equations, the PET_{Han} and PET_{Tur} exhibited the most consistent pattern of best fit, both had comparable goodness-of-fit values. PET_{deB} followed closely, also with comparable results. In spite of the different climatic conditions in Rethimno and Iraklio, no other equation was observed to perform better than these three, although the error measures were 2–3 times higher than for the other stations. The minimum values of MSE, MAE, RMSE, and RMAE were for PET_{Han} in Sitia for all of the aforementioned statistical measures. The highest value of Pearson's CC was for PET_{Han} in Kastelli.

Seasonal Patterns

Additional information was extracted from the analysis of the MBE of the averaged monthly totals of PET_{ref}, presented in Fig. 3. This provided information concerning the over- or underestimation of PET_{ref} by the empirical equations, and can be used as a tool for the choice of the best-fitting empirical formulas during the different seasons and their underlying different climate conditions in the absence of a more thorough analysis of the physical conditions that lead to over- or underestimations on a daily basis.

The graphs reveal that for some equations there is a clear pattern of over- or underestimation for all weather stations, but for some of

Table 6. Goodness-of-Fit Measures of Results of Empirical PET Equations Compared with those of the PET_{FAO} Equation; Basis for Comparison Was the Integrated Monthly Values of PET Not Grouped in Monthly Subsets; Bold Values Indicate Radiation- and Temperature-Based Equations with Best Fits for Each Meteorological Station and for Each Goodness-of-Fit Measure

	Temperature-based							Radiation-based					
	PET_{Har}	PET_{McG}	PET_{Rom}	PET_{Ham1}	PET_{Ham2}	PET_{Ham3}	PET_{McC}	PET_{Mak}	PET_{Han}	PET_{Cap}	PET_{Jen}	PET_{Tur}	PET_{deB}
Ierapetra													
MSE	2154.9	526.1	2017.16	877.06	**209.14**	2586.06	923.56	962.20	268.03	1302.58	1581.63	**129.16**	481.94
MAE	32.962	18.87	37.260	23.188	**11.228**	42.278	24.596	22.791	11.065	26.489	29.632	**8.256**	15.661
MRSE	0.145	0.035	0.084	0.048	**0.018**	0.262	0.205	0.052	0.012	0.034	0.033	**0.008**	0.051
MRAE	0.310	0.155	0.251	0.192	**0.106**	0.480	0.329	0.197	0.087	0.159	0.161	**0.071**	0.163
CC	0.938	0.971	0.948	0.977	0.980	**0.984**	0.939	0.985	0.986	0.990	0.990	**0.991**	0.958
Sitia													
MSE	1905.7	546.63	1614.62	475.41	**131.37**	1647.69	989.23	199.76	**47.02**	1850.76	2238.92	51.43	311.66
MAE	33.722	20.780	34.490	18.560	**8.94**	35.512	24.650	12.215	**5.564**	31.616	34.804	5.749	14.458
MRSE	0.219	0.032	0.103	0.039	**0.014**	0.222	0.274	0.023	**0.005**	0.049	0.046	0.006	0.025
MRAE	0.396	0.163	0.267	0.174	**0.091**	0.442	0.374	0.131	**0.056**	0.193	0.187	0.058	0.127
CC	0.924	**0.989**	0.915	0.969	0.984	0.986	0.915	0.996	**0.996**	0.991	0.992	0.995	0.995
Tymbaki													
MSE	546.1	595.30	3262.3	555.25	**199.23**	1852.99	908.99	334.06	**79.69**	2039.51	2404.09	83.99	256.19
MAE	16.127	20.927	48.488	19.35	**10.70**	36.608	24.038	13.62	**7.19**	32.76	36.21	7.41	12.54
MRSE	0.030	0.036	0.130	0.042	**0.016**	0.229	0.268	0.022	**0.008**	0.048	0.047	0.009	0.023
MRAE	0.138	0.167	0.317	0.178	**0.101**	0.446	0.369	0.125	**0.070**	0.191	0.193	0.073	0.117
CC	0.977	0.983	0.899	0.973	0.984	**0.985**	0.935	0.991	0.991	0.991	0.992	**0.994**	0.982
Iraklio													
MSE	2722.0	**287.69**	1271.58	1031.88	389.54	3097.88	1682.9	1215.77	473.14	1446.50	1572.81	**402.43**	510.95
MAE	45.209	**13.214**	31.054	26.55	16.63	51.835	35.419	33.095	18.822	32.838	32.646	**17.354**	18.888
MRSE	0.404	**0.021**	0.065	0.076	0.080	0.587	0.547	0.309	0.144	0.242	0.156	**0.105**	0.230
MRAE	0.573	**0.112**	0.217	0.241	0.212	0.726	0.572	0.464	0.275	0.370	0.306	**0.238**	0.318
CC	0.922	0.973	0.945	0.968	0.976	**0.978**	0.928	0.982	0.983	0.981	0.982	**0.984**	0.978
Rethimno													
MSE	1888.8	**488.57**	980.73	816.92	518.99	2693.14	1574.97	1238.14	568.87	1815.53	1953.25	**481.53**	670.99
MAE	39.016	**18.265**	26.146	23.88	18.42	48.427	32.622	32.340	19.268	35.310	35.281	**17.700**	21.413
MRSE	0.347	**0.033**	0.054	0.08	0.087	0.583	0.461	0.347	0.172	0.237	0.163	**0.120**	0.265
MRAE	0.505	**0.147**	0.191	0.231	0.213	0.694	0.501	0.468	0.285	0.364	0.310	**0.241**	0.334
CC	0.946	**0.962**	0.923	0.948	0.95	0.959	0.882	0.966	0.966	0.960	0.962	**0.969**	0.961
Souda													
MSE	677.7	581.95	3804.69	406.09	**164.92**	1421.13	903.58	288.28	**57.07**	1809.1	2121.29	87.64	162.33
MAE	19.25	21.579	55.73	16.88	**9.731**	32.215	23.290	14.354	**5.904**	30.454	32.526	7.067	10.305
MRSE	0.052	0.037	0.142	0.037	**0.014**	0.182	0.293	0.038	**0.009**	0.068	0.049	**0.009**	0.023
MRAE	0.190	0.176	0.352	0.165	**0.094**	0.397	0.383	0.166	**0.067**	0.219	0.192	0.073	0.112
CC	0.979	**0.990**	0.956	0.973	0.98	0.987	0.926	0.993	0.993	0.987	0.989	0.992	0.993
Kastelli													
MSE	495.7	464.43	1919.36	517.14	**137.96**	1579.19	1179.33	189.09	**75.39**	1311.21	1610.48	94.96	224.57
MAE	14.91	18.327	35.626	18.25	**8.979**	33.173	27.653	10.440	**6.855**	26.179	28.245	7.348	10.879
MRSE	0.038	0.036	3086.6	0.050	**0.019**	0.239	0.489	0.020	**0.010**	0.070	0.044	0.011	0.018
MRAE	0.149	0.168	3.473	0.194	**0.104**	0.453	0.523	0.113	**0.079**	0.219	0.183	0.081	0.104
CC	0.964	**0.988**	0.932	0.970	0.982	0.983	0.936	0.993	**0.993**	0.985	0.987	**0.993**	0.988

the others such a clear pattern is not apparent. An increase in the MBE values during the summer period is normal due to the increased values of PET_{ref}.

More specifically, of the temperature-based equations, PET_{Har} and PET_{Ham3} constantly underestimated PET_{ref} for all stations and all seasons with a bias that increased during the summer. PET_{Ham2}, which exhibited similar bias to this of the radiation-based equations, slightly underestimated PET_{ref} during winter and overestimated during summer (except at the stations Iraklio and Rethimno), whereas PET_{Ham1} tended to overestimate it during winter and underestimate it during summer. PET_{Ham1}, PET_{Ham2}, and PET_{Ham3} correlated with one another because of the similarity of the equations. Finally, PET_{McG} and PET_{Rom} revealed no constant pattern. At some stations, it performed better during the winter and at others during the summer. The success of this equation in Iraklio and Rethimno must be attributed to the considerably lower bias during the winter period, when all of the other equations severely underestimated PET_{ref}.

Of the radiation-based equations, PET_{Han} and PET_{Tur} revealed the most consistent pattern of good fit (for all stations except Rethimno and Iraklio). Their estimates were always close to PET_{FAO}, and they either slightly under- or overestimated PET_{ref}.

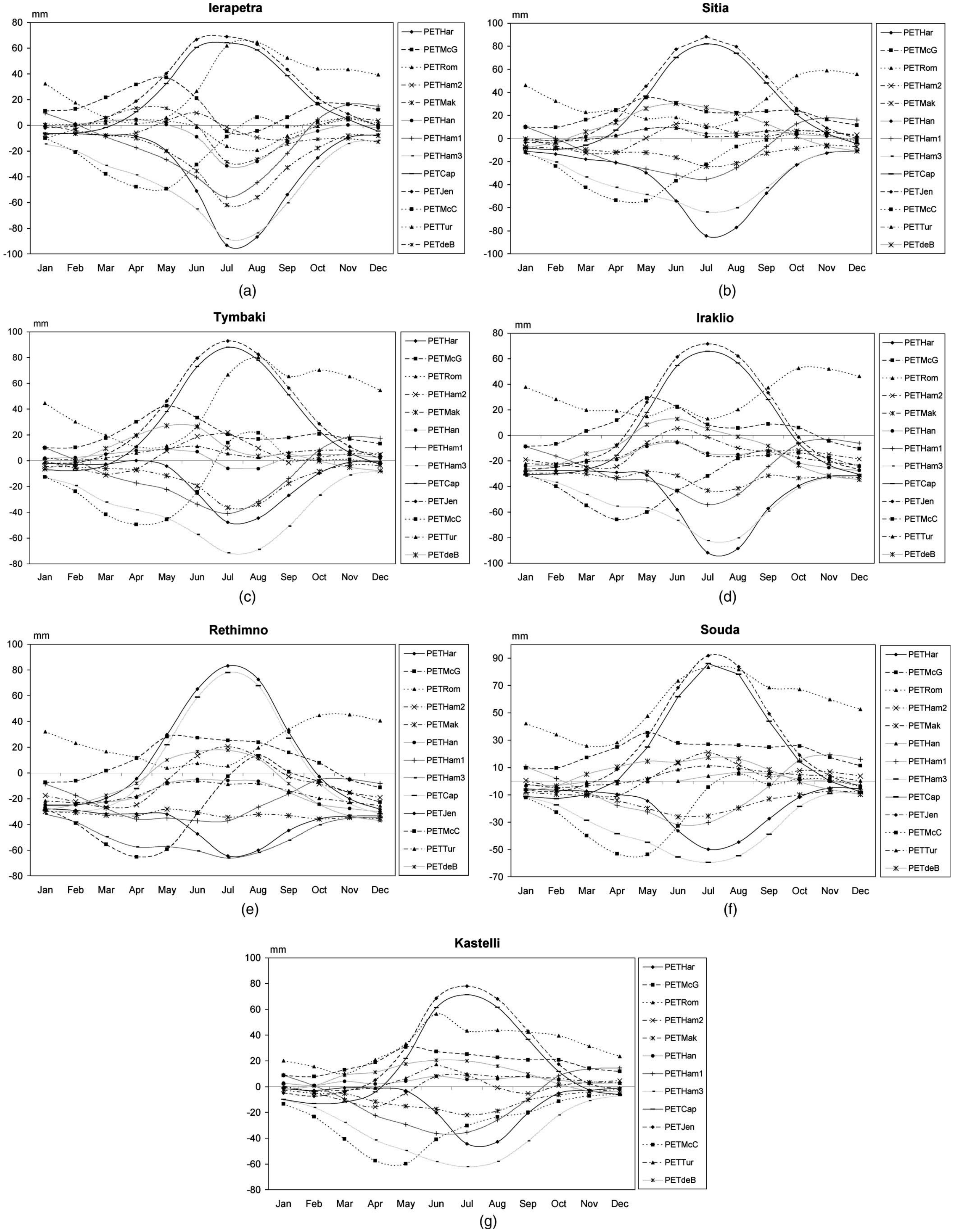

Fig. 3. Mean bias error between the averaged monthly totals of PET_{ref} estimated using empirical equations and the PET_{FAO} equation

The underestimation generally occurred in winter and the overestimation during summer. PET_{Cap} and PET_{Jen}, two very similar equations, revealed great variations in their MBE, with low bias during winter and a slight underestimation of PET_{ref}, and with a very large overestimation during the summer. PET_{McC} exhibited a distinct pattern, with a high underestimation of PET_{ref} during the spring. PET_{Mak} constantly underestimated PET_{ref}, while PET_{deB} tended to overestimate PET_{ref} in summer and underestimate in winter for most stations. This tendency was more pronounced in Iraklio and Rethimno.

Discussion

Radiation- and Temperature-Based Equations

The results revealed that the radiation-based equations generally overperformed the respective temperature-based equations. This is in accordance with a number of similar studies (Lu et al. 2005; Xu and Singh 1998). This pattern is observed for both the daily and monthly based analysis, for all goodness-of-fit measures, and at all weather stations except Iraklio and Rethimno, where the equations of PET_{McG} and PET_{Ham1} are found to be the best alternatives to the PET_{FAO}. The fact that the equations PET_{McG} and PET_{Ham1} provided better estimates for the stations Iraklio and Rethimno should not be attributed solely to the better performance of these equations. The measures of their goodness of fit were relatively poor, indicating that although they provided better results, they did not really perform all that well. That is, all of the other equations performed rather badly. This was obvious from both the very low values of Pearson's CC and the high values of the relative errors. The RMSE and RMAE of, for example, 0.076 and 0.241 associated with PET_{Ham1} for the station Iraklio ascertained for the monthly analyses (see Table 6) were very high when compared with the values of 0.008 and 0.071 for the corresponding measures of the PET_{Tur} in the station Ierapetra. Their success should be attributed to the observed tendency to greatly overestimate PET_{ref}; moreover, of the empirical equations take into account, the high wind speed values actually increase PET_{ref} rates. Their overestimation, observed for all of the other stations, was counterbalanced by the severe underestimation of the PET_{ref} for these two stations by all of the other equations.

The seasonal analysis of PET_{ref} estimates, except for some PET_{ref} equations, did not show a constant under- or overestimation, suggesting that for the different regions, the final choice of the empirical PET_{ref}, beside the consideration of data availability, should be also based on the patterns of performance. For different seasons, different equations should be chosen and this choice should be accompanied with a discussion over the level of under- or overestimation of PET_{ref}. The identified differences in the performance of the equations among seasons also allows for their season-based calibration to obtain more accurate estimates of PET_{ref}. Further research should be carried out to identify the physical conditions that contribute to the over- or underestimation of the empirical PET_{ref} equations, but that is beyond the scope of this paper.

Comparison to Similar Studies

Unfortunately, an extensive evaluation of empirical equations is lacking for Greece. Only a small number of scientific publications dealing with the topic exist and the comparisons made are limited to a small number of empirical equations (Alexandris and Kerkides 2003; Michalopoulou and Papaioannou 1991; Papadopoulou et al. 2003) or to the estimation of free-water surface evaporation (Valiantzas 2006). Therefore, the discussion of the results of this study will be based on a comparison with the results of studies carried out in regions with similar climate conditions.

The results suggested that PET_{Har} can be used as an alternative to the PET_{ref} equation in situations where there is a lack of meteorological data (Allen et al. 1998). PET_{Har} estimates for southern Spain (Gavilán et al. 2008) produced an average daily RMSE of 0.8 mm when compared with the ASCE-Penman-Monteith equation (Gavilán et al. 2008). In Crete, which is at comparable latitude, the result of the comparison with the PET_{FAO} was almost double (1.55 mm). Quantitative differences between this study and Gavilán et al. (2008) should also be attributed to the differences in the method for the estimation of PET_{ref} (integrated daily values from hourly time steps, measure of radiation fluxes, etc.). The highest error measures associated with PET_{Har} were obtained for the stations Iraklio and Rethimno, followed by Ierapetra, Sitia, Tymbaki, Souda, and Kastelli. This pattern indicates that the bias associated with PET_{Har} is positively correlated with the PET_{ref} values, which agrees with Gavilán et al. (2008). The latest can be attributed to the fact that PET_{Har} is not able to account for the effect of high advection phenomena of semiarid environments (Berengena and Gávilan 2005). The fact that the error associated with PET_{Har} increases in areas with high wind speeds (Iraklio and Rethimno) does not correspond to the findings of Martínez-Cob and Tejero-Juste (2004). The reason for this is that in the case of the latter, high wind speeds were related to a lower daily air temperature range [see p. 259 of Martínez-Cob and Tejero-Juste (2004)], thus resulting in reduced PET_{ref} rates, which was not true for this study. Nevertheless, other studies have concluded that PET_{Har} does not perform well or that it requires calibration, in semiarid environments (Alexandris et al. 2006; Droogers and Allen 2002; Gavilán et al. 2006; Jabloun and Sahli 2008; Stöckle et al. 2004). Similarly, this equation was found to underperform in the warm humid climate of the southeastern United States (Lu et al. 2005) and in the humid climate of the western Balkans (Trajkovic and Kolakovic 2009). Alexandris et al. (2008) also indicated a severe underperformance of PET_{Har} in the Balkan region. By contrast, in the semiarid environment of California (Temesgen et al. 2005) and of Iran (DehghaniSanij et al. 2004) the PET_{Har} equation performed well relative to other empirical and physical equations, despite the simplicity of the formula which only requires air temperature data. The accuracy of this equation depends greatly on local climatic conditions (Alexandris et al. 2006; Wang et al. 2009) and, therefore, does not have the performance stability required for it to be considered as a globally accepted method.

The proposed use of PET_{Har} for the estimation of PET_{ref} for periods of 10 days or more (Droogers and Allen 2002; Martínez-Cob 1996) is also underlined by the results of this study, reflected in the large decrease in the error associated with the integrated monthly values table 6.

PET_{McG} was found to perform well when compared with 27 other PET equations tested in various rainfall-runoff models (Oudin et al. 2005) applied in 308 catchments in Australia, France, and the United States. This corresponds with the findings of this study. However, whereas Oudin et al. (2005) found that the results of the PET_{McG} equation were comparable to those produced by the radiation-based equations, in Crete, this equation, like all temperature-based equations, was outperformed by the radiation-based equations at all stations except for Iraklio and Rethimno.

A slightly modified version of the PET_{Rom} equation provided good results in Switzerland (Xu and Singh 1998), as a method to estimate pan evaporation. However, it did not perform well in the regions studied by Oudin et al. (2005). The results of this study demonstrated that, in this semiarid region, this equation should not be chosen for the estimation of PET_{ref}.

PET_{Ham1} was found to produce reasonable results in the warm and humid climates of the northeastern United States (Lu et al. 2005), but it did not perform well in the warm and semiarid climate of Crete. The modification of this equation, herein referred to as PET_{Ham2}, performed quite well not only in Crete but also in the regions studied by Oudin et al. (2005). On the other hand, PET_{Ham3} underestimated PET rates in a wetland prairie in North Dakota (Rosenberry et al. 2004) and was among the temperature-based equations with the largest bias. The same results were obtained for Crete; this equation resulted in even greater underestimations than PET_{Ham1}. Therefore, its use in Crete is not recommended.

Although PET_{McC} is the simplest formula, it did not perform well in evaluations conducted in various climates (Oudin et al. 2005), in Florida (Jacobs and Satti 2001), or in the semiarid climate of Crete. Therefore, its use is not recommended.

PET_{Mak} has been widely used as an empirical equation for estimating PET_{ref}. However, in the southwestern United States (Lu et al. 2005), it did not perform as well as other empirical equations. In Switzerland (Xu and Singh 2000), PET_{Mak} did not perform well for estimating of pan evaporation. PET_{Mak} was only moderately successful in a prairie wetland (Rosenberry et al. 2004), its fit improving with some modifications to its coefficients. Similar results were obtained in a study of the PET_{Mak} equation in a small lake in the northcentral United States (Winter and Rosenberry 1995). Alexandris et al. (2008) reported that PET_{Mak} produced the greatest underestimates of PET_{ref} of the six empirical equations tested in the Balkan Peninsula. Finally, Oudin et al. (2005) found that PET_{Mak} performed better than the PET_{Tur} equation, yet ranked it as being average overall.

Although PET_{Tur} performed well in Crete, the results obtained in other studies were mixed. Jacobs and Satti (2001) found that this equation underestimates PET_{ref} in Florida throughout the year except in summer. Xu and Singh (1998) also found that this equation significantly underestimated evaporation values in Switzerland. Underestimates, albeit small, were also reported by Alexandris et al. (2008) when this equation was applied in the Balkan Peninsula. Oudin et al. (2005) did not recommend the use of this equation for rainfall-runoff models because it failed to perform well. By contrast, Trajkovic and Kolakovic (2009) found that PET_{Tur} performed well in the humid western Balkans. This corresponds with the PET_{Tur} equation that was initially proposed for the estimation of PET_{ref} in the humid climate of western Europe (Turc 1961). Similarly, Douglas et al. (2009) also found that PET_{Tur} provided good results. In arid and semiarid climates in India, PET_{Tur} performed better than other equations (Nandagiri and Kovoor 2006). In the same study, PET_{Har}, which was also compared there, did not perform equally well. Lu et al. (2005) proposed the use of PET_{Tur} for regional use in the southwestern United States. That this equation also performed well in Crete suggests that it is adjustable to the local climatic conditions, most likely because it requires RH data as an input. Although ASCE ranks PET_{Tur} below PET_{Har} for application in semiarid and arid climates (George et al. 2002), PET_{Tur} clearly outperforms PET_{Har} under the climatic conditions prevailing in Crete.

The PET_{Jen} equation performed well for the estimation of integrated monthly evaporation values in the northcentral United States (Winter and Rosenberry 1995) and for evapotranspiration in the prairie wetlands of North Dakota (Rosenberry et al. 2004). Xu and Singh (2000) reported that the uncalibrated PET_{Jen} resulted in a large bias in the estimation of pan evaporation values in Switzerland. However, none of the latter three publications directly corresponds to the estimation of PET_{ref}. According to Oudin et al. (2005), PET_{Jen} was one of the equations that performed best. Given the close relationship between PET_{Jen} and PET_{Cap}, similar results can be expected. Based on the results of this study, the large overestimates of PET_{ref} by these equations should limit their use.

PET_{Han}, a modification of the PET_{Mak} equation (Hansen 1984), was one of the best methods for the estimation of PET_{ref} values in Switzerland (Xu and Singh 2000). In the semiarid environment of Crete, PET_{Han} performed very well, and it is surprising that such good estimates of PET_{ref} were obtained using an equation originally developed and tested in Nordic environments.

Pitfalls and Concerns

There were a number of drawbacks in relation to the methods adopted in this research. The most important was possibly that the radiation-related inputs were not measured but calculated. The estimation of input variables may result in errors in the final estimate of PET_{ref} (Llasat and Snyder 1998; Mahmood and Hubbard 2005) and results can be altered both qualitatively and quantitatively if actual radiation data are used. However, as there is no meteorological station in Crete measuring any form of radiation (global, net, etc.) the only approach available was to estimate incoming solar radiation using other meteorological observations as auxiliary variables.

Additionally, there is a concern that some parameters of the PET_{FAO} equation should be modified prior to its use in semiarid environments (Berengena and Gávilan 2005; Gavilán et al. 2008). These changes refer mainly to the use of different parameters (coefficients) during the day and at night, as proposed by ASCE-EWRI (ASCE-EWRI 2005). These modifications require hourly meteorological observations, which the meteorological stations in Crete do not provide. Nevertheless, for overcoming the lack of daily observations, ASCE-EWRI (2005) also proposed the use of the coefficients provided by Allen et al. (1998), as used in this study. The absence of hourly meteorological observations (low sampling frequency) also contributes to the relatively high bias in the final estimate of several parameters, including solar radiation and PET (Hupet and Vanclooster 2001).

Other pitfalls related mostly to the quality and integrity of meteorological data were summarized by Hargreaves (2003). Several authors proposed the adjustment of meteorological observations in the case of nonreference conditions (Allen 1996; Dinpashoh 2006; Jensen et al. 1997; Temesgen et al. 1999). These procedures require values of relative wetness (precipitation/PET ratio) (Dinpashoh 2006) or other factors (Temesgen et al. 1999) for all stations. Another source of uncertainty concerning the PET_{ref} values was the location of the meteorological stations. Most of them were situated in coastal areas and were, therefore, subject to large variations, especially in humidity-related values, depending on the wind direction. However, through the use of integrated monthly values, these variations are smoothed out. The identification of the sources of bias in the estimation of PET_{ref} requires more detailed information and sophisticated analyses exceeding the aims and the scope of this study, that is, the evaluation of several empirical PET_{ref} equations within an operational framework. The meteorological stations may not reflect optimally the conditions of the reference areas, yet the data they provide are sufficient for a comparative analysis of PET equations. Nevertheless, adjustments may introduce further unpredictable bias into calculations (Howell 2000; Temesgen et al. 1999), thus minimizing possible positive effects.

Unfortunately, all of these pitfalls could not be addressed in this study, owing mainly to the unavailability of the necessary data. Given the restrictions, and in spite of the expected bias, the authors are convinced that the optimum method was followed.

Conclusions

There is no golden rule concerning the optimal equations to estimate PET_{ref} under various climates because even in the same climatic type, different studies have produced mixed results in relation to the performance of the empirical PET_{ref} equations. Additionally, because modifications to the parameters of some equations [see the example of PET_{Han} and PET_{Mak} in Xu and Singh (2002)] result in radically different output, suggests that a regional evaluation and calibration of the empirical PET_{ref} equations prior to their use is needed.

The radiation-based equations generally exhibited better fits than the temperature-based equations. PET_{Han} and PET_{Tur} were the most successful of the radiation-based equations, the latter having a more complicated formula requiring RH data. This additional input variable renders the PET_{Han} a more favorable equation. On the other hand, PET_{Jen}, PET_{Cap}, PET_{Mak}, and PET_{deB} clearly revealed a great bias and, therefore, their use for the estimation of PET_{ref} in the semiarid climate of Crete is not recommended.

With respect to the temperature-based equations, attention should be focused on the PET_{McG} and PET_{Ham2} equations. They proved to be the best of these equations, although they were inferior to the best radiation-based equations for all stations except Iraklio and Rethimno. The latest resulted in a bias comparable with that of the radiation-based equations, rendering it an attractive option owing to its limited requirements in terms of input data. Although the radiation-based equations generally performed better, one should not discount the fact that the temperature-based equations require a lower number of input variables. This is important in situations where meteorological data are missing.

It is also important that the climatic parameters of the meteorological stations should be carefully taken into consideration to choose the best empirical equation. To exemplify, two stations (Rethimno and Iraklio) exhibited high PET_{ref} values as a result of high wind speeds. At these stations, the temperature-based PET_{McG} equation outperformed the other equations yet the bias was high.

Although there were some factors that could possibly result in a bias in the estimation of PET_{ref}, the method followed was robust and efficient and the results of some of the empirical equations, as described in the aforementioned sections, were found to compare reasonably well with those of the PET_{FAO} equation. These formulas can be applied where a lack of data limits the use of PET_{FAO}or where there are no current measurements of PET_{ref}.

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