Sensitivity of the Food and Agriculture Organization Penman–Monteith Evapotranspiration Estimates to Alternative Procedures for Estimation of Parameters

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Abstract: Reference crop evapotranspiration (ET_o) is a key variable in procedures established for estimating evapotranspiration rates of agricultural crops. As per internationally accepted procedures outlined in the United Nations Food and Agriculture Organization's *Irrigation and Drainage Paper No. 56* (FAO-56), using the Penman–Monteith (PM) combination equation is the recommended approach to computing ET_o from ground-based climatological observations. Applying of the PM equation requires converting input climate and site data into a number of parameters, and FAO-56 recommends exact procedures for estimating these parameters. However, a plethora of alternative procedures for estimating parameters exist in literature. As a consequence, it is likely that ambiguous results may be obtained from the FAO-56 PM equation because of the adoption of such alternative (nonrecommended) supporting equations. The purpose of the present study is to evaluate differences that could arise in FAO-56 ET_o estimates if nonrecommended equations are used to compute the parameters. Using historical climate records from 1973 to 1992 of a station located in the humid tropical region of Karnataka State, India, monthly ET_o estimates computed by FAO-56 recommended procedures were statistically compared with those obtained by introducing alternative procedures for estimating parameters. In all, 13 alternative algorithms for ET_o estimation were formulated, involving modified procedures for parameters associated with weighting factors, net radiation, and vapor-pressure-deficit terms of the PM equation. For the 240-month period considered, nine of these algorithms yielded ET_o estimates that were in close correspondence with FAO-56 estimates as indicated by mean absolute relative difference (AMEAN) values within 1% and maximum absolute relative difference (MAXE) values within 2%. The remaining four algorithms, involving nonrecommended procedures for the vapor-pressure-deficit and net-radiation parameters, yielded considerably different ET_o estimates, giving rise to AMEAN values in the range of 2 to 8% and MAXE values ranging between 8 and 28%. The results of this study highlight the need for strict adherence to recommended procedures, especially for estimating of vapor-pressure-deficit and net-radiation parameters if consistent results are to be obtained by the FAO-56 approach.

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Introduction

Estimates of evapotranspiration (ET) flux occurring from cropped land surfaces are essential in studies relating to hydrology, climate, and agricultural water management. The procedure for estimating of ET rates from agricultural crops is well established. As a first step, it involves computing reference crop evapotranspiration (ET_o) by using regularly recorded climatological data. Several equations—broadly classified as temperature-based, radiation-based, and combination-type—have been proposed for ET_o computations. Innumerable studies have evaluated the performances of these equations under different climatological conditions, with Katul et al. (1992), Amatya et al. (1995), Khandelwal et al. (1999), and Mall and Gupta (2002) being a few of the more recent ones. Most of such comparative studies have indicated the superiority of combination-type ET_o equations. In particular, the physically-based Penman–Monteith (PM) combination equation has proved to be the best estimator of ET_o across a wide range of climates (Jensen et al. 1990).

On the basis of such findings, the recent version of the internationally accepted United Nations Food and Agriculture Organi-

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Table 1. Input Data Required to Compute Parameters of Equation (1)

Parameter	Input data
u_2	u_{24}, z_w
e_s	T_{max}, T_{min}
e_a	$T_{max}, T_{min}, RH_{max}, RH_{min}$
Δ	T_{max}, T_{min}
γ	z
R_n	ϕ, time of year, n, z, T_{max}, T_{min}
G	$\overline{T}$

Note: All symbols are explained in notation list.

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zation (FAO) methodology for estimating crop water requirements (Allen et al. 1998), recommends the sole use of the PM equation for ET_o computations. In contrast, the previous version of the FAO methodology (Doorenbos and Pruitt 1977), offered a choice of five equations for computing ET_o.

According to Allen et al. (1998) (called FAO-56 in this paper), the recommended form of the PM equation is

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\dfrac{900}{\overline{T} + 273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where ET_o=reference crop ET (mm/day), defined as the evapotranspiration from 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; R_n=net radiation at crop surface $[\mathrm{MJ/(m^2\,day)}]$; G=soil heat flux density $[\mathrm{MJ/(m^2\,day)}]$; $\overline{T}$=mean air temperature (°C) at 2 m height; u_2=wind speed (m/s) at 2 m height; e_s=saturation vapor pressure (kPa); e_a=actual vapor pressure (kPa); $(e_s - e_a)$=saturation vapor pressure deficit (vpd) (kPa); Δ=slope of vapor pressure versus temperature curve at temperature T (kPa/°C); and γ=psychrometric constant (kPa/°C).

The application of Eq. (1) requires standard ground-based climatological observations of solar radiation or sunshine, air temperature, humidity, and wind speed, as well as site details of latitude and altitude. The structure of Eq. (1) suggests that except for wind speed and air temperature, none of the other inputs appear explicitly in the computation of ET_o. Although air temperature $(\overline{T})$ does appear in the second term of the numerator, other elements of Eq. (1) also depend on temperature. In other words, using Eq. (1) necessarily involves converting measured parameters into a number of estimated parameters. Table 1 shows the relationships among measured climate variables and estimated parameters of Eq. (1). FAO-56 describes the exact procedures to be adopted to compute these parameters and presents numerical examples that demonstrate the use of the recommended methods.

However, several other methods exist for computing the parameters of Eq. (1). Given that some of these parameters are also used in other ET_o equations, a number of methods for their computation from climatological and site inputs are documented in literature (e.g., Doorenbos and Pruitt 1977; Rosenberg et al. 1983; Sharma 1985; Allen et al. 1989; Jensen et al. 1990; Kotsopoulos and Babajimopoulos 1997; Irmak et al. 2003b).

It is important to note that the FAO-56 methodology represented by Eq. (1) is actually an abbreviated form of a complete algorithm comprising several specific supporting equations. However, not all references to the FAO-56 PM approach reproduce the entire algorithm (e.g., Shuttleworth 1992; Irmak et al. 2003a) which may lead to a situation where a user adopts the FAO-56 recommended form of the PM model in Eq. (1), but chooses to use methods other than those recommended by FAO-56 to compute the parameters. How sensitive are ET_o estimates to alternative choices of parameter computation methods? In our opinion, an answer to this question would prevent ambiguous applications of Eq. (1) and thereby support the need for a consistent and standardized procedure for ET_o estimation using the FAO-56 PM model.

The ASCE Task Committee on Standardization of Reference ET (Allen et al. 2000) has recognized, among several other important issues, the need for standardized calculation of parameters. However, few earlier studies seem to have analyzed the issue in detail and provided quantitative estimates of differences in ET_o arising out of alternative choices of parameter computation methods. A noteworthy exception is the study of Sadler and Evans (1989), but they confined themselves to comparing only 15 different methods of computing the saturation vapor deficit parameter $(e_s - e_a)$ in a combination-type ET_o equation and reported differences of −80 to +100% in ET_o estimates across a wide range of environments. Similarly, Howell and Dusek (1995) investigated the accuracy of five different methods of computing the saturation vapor-pressure deficit parameter $(e_s - e_a)$ and documented errors in excess of 25% between deficits measured in Texas and estimated deficits. However, they did not investigate the propagation of such errors into ET_o estimates.

In the present study, a comprehensive evaluation of ET_o estimates that are based on Eq. (1) was taken up with the objective of evaluating differences introduced by selecting alternative methods for computing a number of these parameters. The overall methodology adopted involved retaining the FAO-56 procedure as the reference and documenting differences introduced into ET_o estimates from Eq. (1), by using alternative methods for estimating parameters. For the analysis reported in this paper, we used climatological measurements made at a station located in the humid coastal district of Dakshina Kannada, Karnataka State, India. Eq. (1) can in principle be applied at time steps ranging from less than hourly to monthly, but the monthly time step was adopted in this analysis because of its importance in studies related to watershed modeling and computing crop-irrigation water requirements.

Computation of Parameters

FAO-56 Methods

The FAO-56–recommended equations for computing various parameters of Eq. (1) are described in Annex 2 of Allen et al. (1998) but are reproduced here for the sake of completeness. In this study, we assume the reference crop to be green grass.

Saturation Vapor Pressure (e_s)

An estimate of mean daily e_s is obtained as

$$\underset{(\mathrm{kPa})}{e_s} = \frac{e^o(T_{\max}) + e^o(T_{\min})}{2} \tag{2}$$

where $T_{\max}$ and $T_{\min}$ are maximum and minimum air temperatures (°C), respectively; and saturation vapor pressures (kPa) corresponding to them are obtained from

$$\underset{(\mathrm{kPa})}{e^o(T^*)} = 0.6108 \exp\left[\frac{17.27T^*}{T^* + 237.3}\right] \tag{3}$$

in which T^* (°C) may be either $T_{\max}$ or $T_{\min}$ and $e^o(T^*)$=saturation vapor pressure at air temperature T^* (kPa).

Actual Vapor Pressure (e_a)

$$\underset{(\mathrm{kPa})}{e_a} = \frac{\left[e^o(T_{\min})\dfrac{RH_{\max}}{100} + e^o(T_{\max})\dfrac{RH_{\min}}{100}\right]}{2} \tag{4}$$

where $RH_{\max}$ and $RH_{\min}$ are maximum and minimum values, respectively, of relative humidity (%).

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Slope of Vapor Pressure Curve (Δ)

$$\underset{(\mathrm{kPa/°C})}{\Delta} = \frac{4{,}098\left[0.6108\exp\left(\frac{17.27\bar{T}}{\bar{T}+237.3}\right)\right]}{(\bar{T}+237.3)^2} \tag{5}$$

where $\bar{T}$ = mean air temperature defined as

$$\bar{T} = \frac{T_{\max} + T_{\min}}{2} \tag{6}$$

Psychrometric Constant (γ)

$$\underset{(\mathrm{kPa°C})}{\gamma} = 0.665 \cdot 10^{-3} P \tag{7}$$

where P = atmospheric pressure (kPa), which is obtained from

$$\underset{(\mathrm{kPa})}{P} = 101.3\left[\frac{293 - 0.0065z}{293}\right]^{5.76} \tag{8}$$

where z = elevation of the site above mean sea level (m).

Net Radiation at Crop Surface (R_n)

According to the principle of radiation balance,

$$\underset{[\mathrm{MJ/(m^2\ day)}]}{R_n} = R_{ns} - R_{nl} \tag{9}$$

where R_{ns} = net short-wave solar radiation $[\mathrm{MJ/(m^2\,day)}]$ and R_{nl} = net long-wave radiation $[\mathrm{MJ/(m^2\,day)}]$. Procedures to calculate R_{ns} vary depending on the type of radiation measurements made at the location. In this paper, we concentrate on computing R_{ns} by using measurements of actual sunshine hours (n). Accordingly, the relevant procedure considers the incident and reflected components of incoming short-wave solar radiation (R_s). Net short-wave solar radiation is calculated as

$$\underset{[\mathrm{MJ/(m^2\ day)}]}{R_{ns}} = (1 - \alpha)R_s \tag{10}$$

where α = albedo or canopy reflection coefficient. FAO-56 suggests that for a hypothetical grass reference crop,

$$\alpha = 0.23 \tag{11}$$

Incoming solar radiation $[\mathrm{MJ/(m^2\,day)}]$ is calculated as

$$\underset{[\mathrm{MJ/(m^2\ day)}]}{R_S} = \left(0.25 + 0.5\frac{n}{N}\right)R_a \tag{12}$$

where R_a = extraterrestrial solar radiation at the top of the atmosphere $[\mathrm{MJ/(m^2\,day)}]$; n = actual duration of sunshine (hours); and N = maximum possible duration of sunshine (hours). N is dependent on time of year and latitude and may be obtained as

$$\underset{(\mathrm{hours})}{N} = \frac{24}{\pi}\omega_s \tag{13}$$

where ω_s is sunset-hour angle (radians) and is computed as

$$\underset{(\mathrm{rad})}{\omega_s} = \arccos(-\tan\varphi\tan\delta) \tag{14}$$

and ϕ = latitude of the place (radians); and δ = solar declination (radians), which, for any day number of the year (J) may be calculated as,

$$\underset{(\mathrm{rad})}{\delta} = 0.409\sin\left(\frac{2\pi J}{365} - 1.39\right) \tag{15}$$

Extraterrestrial solar radiation (R_a) is also related to time of year (J and δ) and latitude (ϕ) through the relationship

$$\underset{[\mathrm{MJ/(m^2\ day)}]}{R_a} = \frac{24(60)}{\pi}G_{sc}d_r[\omega_s\sin\varphi\sin\delta + \cos\varphi\cos\delta\sin\omega_s] \tag{16}$$

where G_{sc} = solar constant $[=0.0820\ \mathrm{MJ/(m^2\,min)}]$; and d_r, the inverse relative distance from Earth to Sun may be obtained from

$$d_r = 1 + 0.033\cos\left(\frac{2\pi J}{365}\right) \tag{17}$$

Net long-wave solar radiation (R_{nl}) in Eq. (9) is computed as

$$\underset{[\mathrm{MJ/(m^2\ day)}]}{R_{nl}} = \sigma\left(\frac{T^4_{\max k} + T^4_{\min k}}{2}\right)(0.34 - 0.14\sqrt{e_a})\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \tag{18}$$

where σ = Stephan–Boltzmann constant $[=4.903 \cdot 10^{-9}\ \mathrm{MJ/(K^4\,m^2\,day)}]$; $T_{\max k}$ = maximum temperature in (K); $T_{\min k}$ = minimum temperature (K); and clear-sky short-wave radiation (R_{so}) may be calculated using

$$\underset{[\mathrm{MJ/(m^2\ day)}]}{R_{so}} = (0.75 + 2 \cdot 10^{-5}z)R_a \tag{19}$$

Wind Speed at 2.0 m above Ground Surface (u_2)

The FAO-56 procedure uses wind speed (u_2) measured at 2 m above the ground surface and suggests the following equation to convert wind speed (u_z) measured at any other height (z_w) into equivalent u_2 values:

$$\underset{(\mathrm{m/s})}{u_2} = u_z\frac{4.87}{\ln[67.8z_w - 5.42]} \tag{20}$$

Soil Heat Flux Density (G)

According to FAO-56, soil heat flux (G) needs to be calculated only when ET_o is computed by using mean monthly climatological records. The recommended equation for G is

$$\underset{[\mathrm{MJ/(m^2\ day)}]}{G_{\mathrm{month},i}} = 0.14(T_{\mathrm{month}.i} - T_{\mathrm{month},i-1}) \tag{21}$$

where $T_{\mathrm{month},i}$ = mean air temperature for month i and $T_{\mathrm{month},i-1}$ = mean air temperature for month $i-1$.

Day Number (J)

For monthly calculations, J at the middle of the month is found to give satisfactory results and is calculated by

$$J = \mathrm{INTEGER}(30.4 \cdot J_1 - 15) \tag{22}$$

where J_1 is the number of the month ($J_1 = 1, 2, \ldots, 12$).

The algorithm implementing the use of Eqs. (2)–(22) for computation of ET_o of grass reference crop by Eq. (1) is summarized in Box 11, Chapter 4, of Allen et al. (1998). A computer program that is based on this algorithm was developed in this study to derive estimates of all parameters and PM ET_o using monthly mean climatological data and other relevant inputs. The program was validated by using the numerical example given in Example 17 (Chapter 4, Page 5) of FAO-56 and reproduced exactly the same results with respect to all parameters and ET_o estimates.

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Alternative Methods

Vast amounts of literature exists on methods to estimate many of the parameters that appear in Eq. (1). Since it would be nearly impossible to include all available methods in our comparative analysis, we concentrated on the more recent and in some cases the more widely cited works on the topic of ET_o estimation. The list of alternative methods for estimating parameters that appears in this section of the paper is by no means complete or even exhaustive, yet enough alternatives are included to fulfill the objectives of the study. Also, the equations are reproduced here in their original form; consequently, many of them possess units that are not consistent with the requirements of Eq. (1). However, the necessary conversion of units was performed before including them in the comparative analysis.

Saturation Vapor Pressure (e_s)

A significant anomaly in computing saturation vapor pressure is the manner in which the saturation vapor pressure function is applied to the input climatic data—air temperature (T). FAO-56 defines saturation vapor pressure (e_s) as the average of $e^o(T_{\max})$ and $e^o(T_{\min})$ [Eq. (2)]. Among the three alternative methods for computing saturation vapor pressure considered in the present study, two methods apply the saturation vapor pressure function to the mean temperature as

$$e_s = e^o(\overline{T}) \tag{23}$$

Doorenbos and Pruitt (1977) provide a table showing e_s values for various values of T. Nandagiri (1993) found favorable comparison between values tabulated in Doorenbos and Pruitt (1977) and estimates obtained by using the following polynomial equation suggested by Lowe (1977):

$$\underset{(\text{mbar})}{e^o(\overline{T})} = k_0 + \overline{T}(k_1 + \overline{T}(k_2 + \overline{T}(k_3 + \overline{T}(k_4 + \overline{T}(k_5 + k_6\overline{T}))))) \tag{24}$$

where $\overline{T}$ = mean air temperature given by Eq. (6);

$$k_0 = 6.1077961; \quad k_1 = 4.436518521 \cdot 10^{-1}$$

$$k_2 = 1.428945805 \cdot 10^{-2}; \quad k_3 = 2.650648471 \cdot 10^{-4}$$

$$k_4 = 3.031240396 \cdot 10^{-6}; \quad k_5 = 2.034080948 \cdot 10^{-8}$$

and

$$k_6 = 6.13682092910^{-11}$$

On the basis of a comparison with four other equations for estimating e_s from mean air temperature $\overline{T}$, Kotsopoulos and Babajimopoulos (1997) recommended a new improved expression of the form

$$\underset{(\text{mbar})}{e^o(\overline{T})} = 6.1051 \exp\left(\frac{18.0788\overline{T} - 0.00254\overline{T}^2}{248.57 + \overline{T}}\right) \tag{25}$$

Allen et al. (1989) and Jensen et al. (1990), however, recommended the following equation for e_s, in which saturation vapor pressure is computed as the average of $e^o(T_{\max})$ and $e^o(T_{\min})$

$$\underset{(\text{kPa})}{e^o(T^*)} = \exp\left[\frac{16.78T^* - 117}{T^* + 237.3}\right] \tag{26}$$

Actual Vapor Pressure (e_a)

Actual vapor pressure is defined by Doorenbos and Pruitt (1977) as

$$e_a = e_s \cdot \frac{RH_{\text{mean}}}{100} \tag{27}$$

where mean relative humidity (%) is

$$RH_{\text{mean}} = \frac{(RH_{\max} + RH_{\min})}{2} \tag{28}$$

The e_s in Eq. (27) is to be obtained by combining Eq. (23) with either Eqs. (24) or (25).

Slope of Vapor Pressure Curve (Δ)

An expression for the slope of the vapor pressure curve may be obtained by differentiating Eq. (24) with respect to T to yield

$$\underset{(\text{mbar°C}^{-1})}{\Delta} = k_1 + \overline{T}(2k_2 + \overline{T}(3k_3 + \overline{T}(4k_4 + \overline{T}(5k_5 + 6k_6\overline{T})))) \tag{29}$$

with coefficients k_1 to k_6 being as defined in Eq. (24).

Kotsopoulos and Babajimopoulos (1997) proposed

$$\underset{(\text{mbar°C}^{-1})}{\Delta} = e_s\left[\frac{4{,}650.79}{(\overline{T} + 248.7)^2} - 0.00254\right] \tag{30}$$

whereas Allen et al. (1989) and Jensen et al. (1990) proposed

$$\underset{(\text{kPa°C})}{\Delta} = \frac{4{,}098 \exp\left[\dfrac{16.78\overline{T} - 117}{\overline{T} + 237.3}\right]}{(\overline{T} + 237.2)^2} \tag{31}$$

Psychrometric Constant (γ)

Doorenbos and Pruitt (1977) recommended the following equation for γ:

$$\underset{(\text{mbar°C}^{-1})}{\gamma} = 0.671[1 - 1.14 \cdot 10^{-4}z + 5.37 \cdot 10^{-9}z^2] \tag{32}$$

Allen et al. (1989) and Jensen et al. (1990) proposed an equation for γ that is somewhat similar to that used in FAO-56:

$$\underset{(\text{kPa°C})}{\gamma} = \frac{C_pP}{\varepsilon\lambda} \tag{33}$$

where C_p = specific heat of moist air at constant pressure [$=1.03 \cdot 10^{-3}$ MJ/(kg°C)]; ε = ratio of molecular weight of air to water (=0.622); and λ = latent heat of vaporization ($=2.50 - (2.361 \cdot 10^{-3})\overline{T}$).

However, atmospheric pressure (P) at elevation z (m) is given by

$$\underset{(\text{kPa})}{P} = P_0\left[\frac{T_0 - \beta(z - z_0)}{T_0}\right]^{g/(\alpha R)} \tag{34}$$

where P_0 = atmospheric pressure at sea level (=101.3 kPa); T_0 = absolute temperature at sea level (=288 K); z_0 = mean sea level (0.00); β = constant adiabatic lapse rate (=0.0065 K/m); g = acceleration due to gravity ($=9.8$ m s^{-2}); and R = specific gas constant for dry air (=286.9 J/kg K).

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Net Radiation (R_n)

For the sake of clarity, the equations that are alternatives to Eq. (9) for the computation of R_n are listed under subheadings corresponding to the two components, net short-wave radiation (R_{ns}) and net long-wave radiation (R_{nl}).

Net Short-Wave Radiation (R_{ns}). Net short-wave radiation R_{ns} as given by Eq. (10) involves parameters α and R_s. Doorenbos and Pruitt (1977) recommended that for most green crops,

$$\alpha = 0.25 \tag{35}$$

Allen et al. (1989) suggested that the value of α for green plants varies from 0.23 to 0.30. To investigate the effect of a higher value of α, the upper limit of this range was used in this study:

$$\alpha = 0.30 \tag{36}$$

Although R_s in general is defined by Eq. (12), various methods other than that proposed by FAO-56 exist for computing the parameters involved, N and R_a. For instance, Kreider (1979), while using Eq. (13) for the calculation of N, proposed the following equation to derive extraterrestrial solar radiation (R_a).

$$\underset{(\mathrm{mm/day})}{R_a} = \frac{24}{\pi} I_{sc} d_r [\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s] \tag{37}$$

in which I_{sc}=solar constant (2 mm/hr) and ω_s and d_r are given by Eqs. (14) and (17), respectively; but solar declination δ required in its calculation is given by

$$\underset{(\mathrm{rad})}{\delta} = \sin(-23.45°)\cos\left[\frac{360(10.5+J)}{365.25}\right] \tag{38}$$

Allen et al. (1989) propose the use of Eqs. (13), (14), and (16) for N, ω_s, and R_a, respectively, but suggest a slightly different expression for δ,

$$\underset{(\mathrm{rad})}{\delta} = 0.4093 \sin\left[\frac{2\pi(284\ J)}{365}\right] \tag{39}$$

Kotsopoulos and Babajimopoulos (1997), however, departed from conventional procedures and proposed new, simple expressions derived from nonlinear regression analysis. Their equations for monthly values of N and R_a are as follows:

$$\underset{(\mathrm{hours})}{N} = M + C_1 \cos\left(\frac{2\pi J_1}{12} + C_2\right) \tag{40}$$

where $M = 12.073 + 0.00284 \cdot L_a$; $C_1 = 0.0434 \cdot L_a + 0.00075 \cdot L_a^2$; and $C_2 = 3.0376$;

$$\underset{(\mathrm{mm/day})}{R_a} = M_1 + C_3 \cos\left(\frac{2\pi J_1}{12} + C_4\right) + C_5 \cos\left(\frac{4\pi J_1}{12} + C_6\right) \tag{41}$$

where $M_1 = 14.9425 - 0.0098 L_a - 0.00175 L_a^2$; $C_3 = -0.5801 + 0.1834 L_a - 0.00066 L_a^2$; $C_4 = 3.1365 - 0.00489 L_a + 0.000061 L_a^2$; $C_5 = 0.597 - 5.36 \cdot 10^{-6} L_a^3$; and $C_6 = 2.9588 - 0.00909 L_a + 0.00024 L_a^2$, where L_a=latitude of the place in degrees and J_1 =month number ($J_1 = 1, \ldots, 12$).

Net Long-Wave Radiation (R_{nl}) Doorenbos and Pruitt (1977) recommended the following equation for computing net long-wave radiation (R_{nl}),

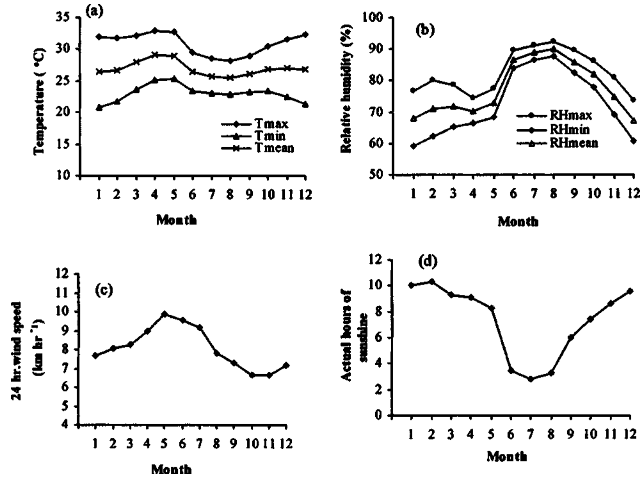

Fig. 1. Observed monthly mean climatic variables averaged over 20-year period

$$\underset{(\mathrm{mm/day})}{R_{nl}} = \sigma_1(\overline{T}+273)^4(0.34 - 0.044\sqrt{e_{al}})\left(0.1 + 0.9\frac{n}{N}\right) \tag{42}$$

where σ_1=Stephan–Boltzmann constant [$=1.985 \cdot 10^{-9}$ mm/(day K^4)]; and e_{al}=actual vapor pressure (mbar) obtained from Eqs. (23), (24), and (27).

Irmak et al. (2003b) while addressing the issue of net radiation calculations with limited data, proposed a direct equation for R_n as

$$\underset{[\mathrm{MJ/(m^2\ day)}]}{R_n} = (-0.09 T_{\max}) + (0.203 T_{\min}) - (0.101 RH_{\mathrm{mean}}) + (0.687 R_s) + 3.97 \tag{43}$$

where incoming solar radiation (R_s) may be predicted by using

$$\underset{[\mathrm{MJ/(m^2\ day)}]}{R_s} = (KT) R_a (TD)^{0.5} \tag{44}$$

where R_a is computed by Eq. (16) using parameters ω_s, δ, and d_r defined by Eqs. (14), (15), and (17), respectively;

$$TD = T_{\max} - T_{\min} \tag{45}$$

where TD=difference between maximum and minimum air temperature.

To account for proximity to a large body of water and elevation effects on the volumetric heat capacity of the atmosphere, the coefficient KT for coastal regions is given by Irmak et al. (2003b) as

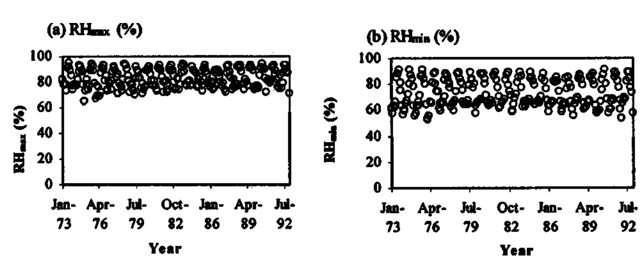

Fig. 2. Integrity checks for climate data set used: (a) $RH_{\max}$; and (b) $RH_{\min}$

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Table 2. Interdependence of Parameters

Parameter changed	Parameters influenced
Δ	Δ
γ	γ
e_s,e_a	e_s,e_a,R_{nl},R_n
δ	δ,R_a,N,R_{ns},R_{nl},R_n
R_a	R_a,R_{ns},R_{nl},R_n
N	N,R_s,R_{ns},R_{nl},R_n
α	α,R_{ns},R_n
R_{so}	R_{nl},R_n
R_{nl}	R_{nl},R_n

$$KT = 0.2\left(\frac{P}{P_0}\right)^{0.5} \tag{46}$$

where P=mean monthly atmospheric pressure of the site given by Eq. (8); and P_0 is mean monthly atmospheric pressure at sea level (=101.3 kPa).

Table 3. Details of RET Algorithms Used

Algorithm number	Equation number: Defined by FAO-56	Equation number: Replaced by	For parameters
RET 0	1 to 22	—	—
RET 1	5	29	Δ
RET 2	5	30	Δ
RET 3	5	31	Δ
RET 4	7	32	γ
RET 5	7,8	34,33	P,γ
RET 6	3,2,4	24,23,27	e^o,e_s,e_a
RET 7	3,2,4	25,23,27	e^o,e_s,e_a
RET 8	3	26	e^o
RET 9	15,16	38,37	δ,R_a
RET 10	16,13	41,40	R_a,N
RET 11	16	39	δ
RET 12	11,18	35,42	α,R_{nl}
RET 13	12,9	44,43	R_s,R_n

Materials and Methods

Climate Data

Climate data pertaining to Panambur station (latitude 12°57′ N, longitude 74°53′ E, altitude 114.0 m), located in Dakshina Kannada district, Karnataka State, India, was used in the present study. The station is one of more than 550 surface observatories operated and maintained by the India Meteorological Department (IMD), Government of India. The district is flanked by the Arabian Sea on the west and on the east by the Western Ghats mountains, which are located an average distance of about 100 km from the coastline. The climate of the region according to Thornthwaite's classification, is humid tropical. The average annual rainfall of the district is about 4,100 mm, with the bulk (93%) of the rain occurring during the months of June through September because of the southwest monsoon phenomenon. The entire region is characterized by luxuriant growth of vegetation consisting mainly of deciduous trees, shrubs, mangroves, coconut and arecanut palms, and patches of rain-fed paddy fields.

The climate station is equipped with mercury and alcohol thermometers, a cup anemometer, a Campbell sunshine recorder, and a wet-bulb thermometer. Records from a more recently installed automatic hair hygrometer are used to validate relative humidity estimates made from wet-bulb depression. Climatological records for the period 1973–1992 (20 years) were procured from IMD and used in the present analysis. Data comprised daily values of the following variables averaged over each calendar month: $T_{\max}$ (°C), $T_{\min}$ (°C), $RH_{\max}$ (%), $RH_{\min}$ (%), u_2 (km/h), and n (hours). The 24-h wind speed was recorded in km/h and the necessary correction was applied to convert it to m/s to conform to its application in Eq. (1).

Fig. 1, plotted using monthly means averaged over the 20-year period, depicts the typical intraannual variations of these climate variables. Maximum and minimum air temperatures both display very small variations over the year, and the low values of the daily temperature range are typical of tropical humid climates. Relative humidity, however, while remaining fairly constant over a day, displays considerable monthly variations. Extremely high humidity levels (close to saturation) are common on days during the monsoon season. Wind speeds peak at the time of onset of monsoon rains (June), whereas sunshine hours drop off from dry-season highs (10 h) to extremely low values (2 h) during the rainy season.

Although IMD carries out routine quality checks on data before supplying it, integrity checks were carried out on the air temperatures and relative humidity data used in this study. Monthly $T_{\max}$, $T_{\min}$, and $\overline{T}$ values for individual years were compared with the long-term averages shown in Fig. 1(a) and did not indicate any major deviations. Also, as Fig. 2 indicates, $RH_{\max}$ values during the 20-year period are consistently greater than 70%, and $RH_{\min}$ values are greater than 50%, variations that are typical of a humid climate.

Methodology

As a first step, the computer program developed to calculate PM ET_o values as per FAO-56 procedures described by Eqs. (1)–(21) was used to derive 240 (N_1=20×12) monthly mean estimates of daily ET_o. Estimates of all parameters of Eq. (1) and all intermediate parameters required in their computation were extracted from this computer run. The results of ET_o and parameter values

Table 4. Monthly Mean and Coefficients of Variation of ET_o Estimated by Using FAO-56 Procedures

Month	January	February	March	April	May	June	July	August	September	October	November	December
Mean ET_o (mm/day)	4.79	5.11	5.33	5.70	5.46	3.37	2.99	3.01	3.74	4.04	4.26	4.56
C_v (%)	4.43	3.51	3.35	3.45	8.85	12.39	15.01	10.60	7.46	5.46	8.94	5.86

Note: Coefficient of variation (C_v)=standard deviation/mean.

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Table 5. Results of Statistical Comparisons between Monthly ET_o Estimated by Various Algorithms with Those Estimated by Using Reference FAO-56 Algorithm

Algorithm	AMEAN (%)	MAXE (%)	*NE*	*S*	*I*	R^2
RET 1	0.009	0.405	0	0.9999	0.0005	1.0000
RET 2	0.009	0.405	0	0.9999	0.0005	1.0000
RET 3	0.003	0.287	0	1.0001	−0.0002	1.0000
RET 4	0.043	0.405	0	0.9993	0.0047	1.0000
RET 5	0.016	0.358	0	1.0001	−0.0013	1.0000
RET 6	2.141	8.302	100	0.9545	0.0989	0.9966
RET 7	2.138	8.302	99	0.9545	0.0988	0.9966
RET 8	0.01	0.287	0	1.0004	−0.0010	1.0000
RET 9	0.335	0.717	0	1.0007	−0.0065	0.9997
RET 10	0.958	2	0	1.0021	0.0313	0.9997
RET 11	0.03	0.405	0	0.9993	0.0030	1.0000
RET 12	4.604	10.377	240	0.9331	0.0852	0.9966
RET 13	7.745	28.118	202	0.9595	−0.0509	0.8866

Note: $N_1 = 240$ for all cases; and all symbols are explained in notation list.

obtained for each month of the 20-year record using the FAO-56 algorithm comprised our so-called reference against which all other calculation procedures were compared.

Evaluating the sensitivity of ET_o estimates obtained from Eq. (1) to changes in parameters is not straightforward because of the interdependencies that exist among many of the parameters. For instance, a change in e_s produces changes in e_a, $(e_s - e_a)$, R_{nl}, and R_n. All such interdependencies that exist for the parameters for which alternative methods are being considered are listed in Table 2. This information formed the basis upon which alternative PM ET_o algorithms were formulated to meet the objectives of this study. Considering one parameter at a time, one alternative method for its computation was introduced while retaining the FAO-56 procedures for all other parameters. In this manner, 13 different algorithms, in addition to the reference (FAO-56) algorithm, were established for computing of PM ET_o estimates by using Eq. (1). Table 3 exhibits details of these algorithms (RET1 to RET13) indicating the changes introduced relative to the FAO-56 algorithm (RET0). The climate data (described previously) were used with each of these algorithms to yield output of PM ET_o for each month of the 20-year period. Differences between monthly ET_o estimates from each algorithm relative to the FAO-56 algorithm were quantified by using the following statistics:

- AMEAN is the mean absolute relative difference (%) given by $\text{AMEAN} = ((|c_s - c_t|/c_t) \cdot 100)/N_1$, where c_t denotes estimates from FAO-56 algorithm; c_s denotes estimates from the different algorithms; and N_1 = total numberof data points.
- MAXE is the maximum absolute relative difference (%) given by $\text{MAXE} = \text{MAX}[(|c_s - c_t|/c_t) \cdot 100]$.
- *NE* is the number of absolute relative differences greater than or equal to 2%.
- *S* and *I* are the slope and intercept, respectively, of linear fit between estimated and reference values.
- R^2 is the coefficient of determination of the linear fit.

These statistics were also used to evaluate differences in parameter estimates.

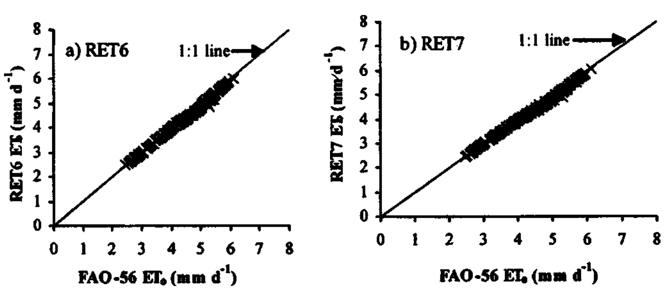

Fig. 3. Comparison of monthly FAO-56 ET_o estimates with those estimated: (a) using algorithm RET6; and (b) using algorithm RET7

Results and Discussion

Monthly means and coefficients of variation (C_v = standard deviation/mean) of ET_o obtained by using the FAO-56 algorithm (RET0) with the 20-year climate data are shown in

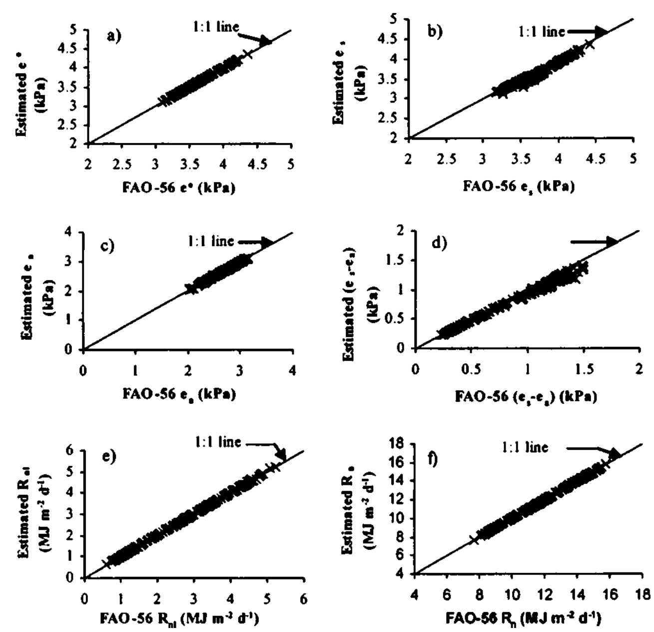

Fig. 4. Comparison of FAO-56 parameter estimates with those estimated by using algorithm RET6

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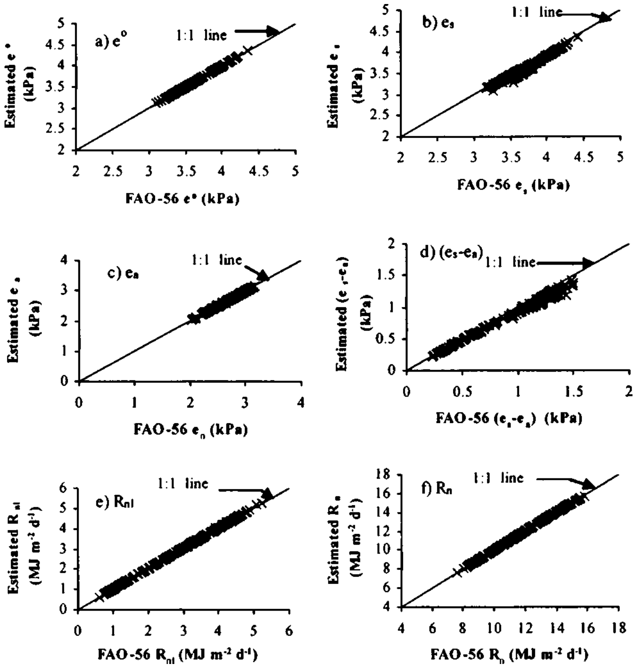

Fig. 5. Comparison of FAO-56 parameter estimates with those estimated by using algorithm RET7

Table 4. ET_o varies from a low of 3.0 mm/day during the monsoon months of July and August to a high of 5.7 mm/day during the summer month of April. The C_v values indicate higher interannual variations during the monsoon months in comparison with other months.

Results of the statistical comparisons of ET_o estimated by using the RET0 algorithm and each of the other 13 algorithms (RET1 to RET13) are summarized in Table 5. It is apparent that algorithms RET1, RET2, RET3, RET4, RET5, RET8, RET9, RET10, and RET11 produce ET_o estimates that are in close correspondence to FAO-56 estimates, whereas the others yield considerable differences, as indicated by values of MAXE ranging between 8 and 28%.

Algorithms RET1, RET2, and RET3 involve alternative methods for parameter Δ; and from the performance statistics shown in Table 5, it may be concluded that the equations for Δ suggested by Lowe (1977), Kotsopoulos and Babajimopoulos (1997), and Allen et al. (1989) may be used instead of the FAO-56–recommended Eq. (5) without loss of much accuracy. As regards algorithms RET4 and RET5, which involve changes in the psychrometric constant (γ), differences are no doubt small (Table 5), but we found that ET estimates are extremely sensitive to this parameter. The statistics shown in Table 5 for these two algorithms are a consequence of differences in the third decimal of estimated γ values.

Algorithms RET6, RET7, and RET8 address the sensitivity of ET_o estimates to changes in parameters e_s and e_a. Differences in ET_o can arise depending on the choice of equations for e^o, e_s, and e_a. Also, these changes affect ET_o in a complex manner because of changes brought about in the radiation components (Table 2). The combined effect of the preceding sources of differences on ET_o are shown in Table 5, from which it can be seen that the alternative equations for e^o, e_s, and e_a suggested by Allen et al. (1989) (RET8) are in close agreement with corresponding FAO-56 equations. However, the other two algorithms (RET6 and RET7) yield some differences, as indicated by statistics shown in Table 5 and the graphical comparisons shown in Fig. 3. In an effort to identify the likely causes for these differences in ET_o estimates, we evaluated the differences in estimates of all parameters that were affected by introducting alternative equations. Accordingly, comparisons of parameter estimates for RET0 versus RET6 are shown in Fig. 4 and for RET0 versus RET7 in Fig. 5. Statistical measures quantifying differences in parameter estimates are shown in Table 6 for both algorithms. From these results, it is evident that alternative methods produce very a accurate estimate of e^o, as indicated in Figs. 4(a) and 5(a), but discrepancies arise when these are converted into estimates of e_s by using Eq. (23). Similar differences when using $T_{\max}$ and $T_{\min}$ instead of $\overline{T}$ in computing e_s have been noted by Howell and Dusek (1995). Although these differences are compensated to a large extent in the computation of e_a by using RH_{mean} [Eq. (27)], as seen in Figs. 4(c) and 5(c) and the statistics shown in Table 6, considerable differences persist in the $(e_s - e_a)$ parameter as indi-

Table 6. Results of Statistical Comparisons between Parameters Estimated by Using FAO-56 Algorithm and Those Estimated by Using Algorithms RET 6 and RET 7

		Statistics					
Algorithm	Parameter	AMEAN (%)	MAXE (%)	*NE*	*S*	*I*	R^2
RET6	e^o	0.016	0.032	0	1.0002	−0.0013	1.0000
	e_s	2.467	7.627	126	0.9447	0.1113	0.9703
	e_a	0.776	2.652	5	0.9886	0.0112	0.9967
	$e_s - e_a$	7.188	17.483	240	0.8917	0.0255	0.9927
	R_{nl}	0.841	2.813	4	1.0043	0.0086	0.9997
	R_n	0.187	0.876	0	0.9986	−0.0041	0.9999
RET7	e^o	0.009	0.032	0	1.0003	−0.0015	1.0000
	e_s	2.463	7.627	126	0.9453	0.1095	0.9703
	e_a	0.767	2.652	5	0.9888	0.0107	0.9967
	$e_s - e_a$	7.178	17.483	240	0.8921	0.0253	0.9926
	R_{nl}	0.836	2.813	4	1.0043	0.0087	0.9997
	R_n	0.185	0.876	0	0.9985	−0.0031	0.9999

Note: All symbols are explained in notation list.

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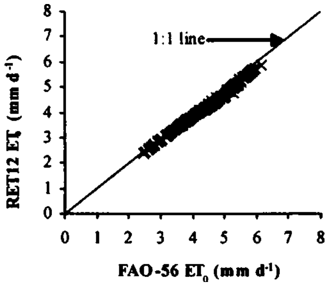

Fig. 6. Comparison of monthly FAO-56 ET_o estimates with those estimated by using algorithm RET12

cated in Figs. 4(d) and 5(d). Using e_a estimated by alternative equations in the FAO-56 expression for R_{nl} in Eq. (18) produces negligible differences as indicated in Figs. 4(e) and 5(e), which are propagated into the R_n term as indicated in Figs. 4(f) and 5(f). In view of these findings, we recommend that irrespective of which equation is used to compute e^o, caution must be exercised in using Eqs. (23) and (27) instead of Eqs. (2) and (4), recommended in FAO-56. To support this conclusion, we found that the value of MAXE in ET_o differences reduced to 0.3% when the alternative equations for e^o were used with Eqs. (2) and (4).

The influence of alternative methods for computing R_a was assessed in algorithms RET9, RET10, and RET11. RET9 uses equations proposed by Kreider (1979) for R_a and δ, which give rise to AMEAN=0.33% and MAXE=0.72% (Table 5). In comparison, algorithm RET10, which implements nonlinear regression equations derived by Kotsopoulos and Babajimopoulos (1997) for R_a and N, yields slightly larger differences (AMEAN =0.96%, MAXE=2.00%). Algorithm RET11, which incorporates an alternative expression for δ proposed by Allen et al. (1989), more or less conforms to the FAO-56 procedure and gives rise to small differences in ET_o estimates (Table 5).

Algorithm RET12 uses recommendations made by Doorenbos and Pruitt (1977) for albedo for green crops ($\alpha=0.25$) and their expression for R_{nl} in Eq. (42). Table 5 shows that using these recommendations in place of FAO-56 procedures results in considerably large differences in ET_o estimates. All 240 estimates of ET_o produce relative differences ⩾2%, with AMEAN being 4.6% and MAXE being as high as 10.4%. Fig. 6 shows a graphical comparison of ET_o estimates obtained by using RET12 and the RET0 algorithms; Fig. 7 compares the differences in the affected parameters R_{ns}, R_{nl}, and R_n; and Table 7 quantifies these differences in terms of statistics. The results of this algorithm, in particular, highlight the magnitude of differences likely to be encountered by an unwary user who uses the PM model of FAO-56, given in Eq. (1) but computes the parameters according to the previous version of the FAO methodology (Doorenbos and Pruitt 1977).

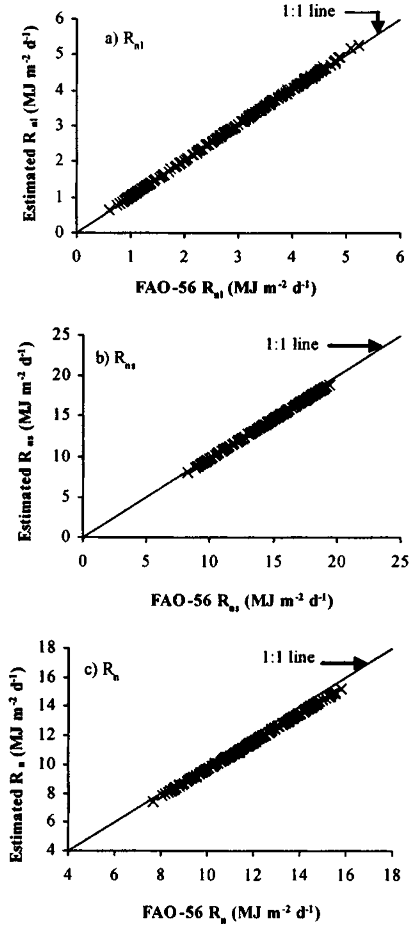

Fig. 7. Comparison of FAO-56 parameter estimates with those estimated by using algorithm RET12

The last algorithm evaluated in this study, RET13, implements a simplified procedure developed by Irmak et al. (2003b) to predict R_n as indicated in Eqs. (43) and (46), in situations in which measured values of R_s are unavailable. From Table 5 and Fig. 8, it can be seen that this algorithm yields ET_o values that deviate the most from the FAO-56 algorithm, with MAXE going up to 28.1%. Although Irmak et al. (2003b) proposed their procedure for computations of daily R_n, these equations have been used herein to estimate monthly mean R_n. To investigate whether using monthly mean R_n instead of daily R_n could have been the cause of

Table 7. Results of Statistical Comparisons between Parameters Estimated by Using FAO-56 Algorithm and Those Estimated by Using Algorithms RET12 and RET13

Algorithm	Parameter	AMEAN (%)	MAXE (%)	NE	S	I	R^2
		Statistics					
RET12	R_{ns}	2.594	2.685	240	0.9741	0.0000	1.0000
	R_{nl}	1.550	3.584	68	1.0048	0.0250	0.9997
	R_n	3.521	4.643	240	0.9611	0.0424	0.9997
RET13	R_s	12.601	65.672	218	0.3538	12.3128	0.5438
	R_n	10.259	34.895	213	0.7108	2.6301	0.5980

Note: All symbols are explained in notation list.

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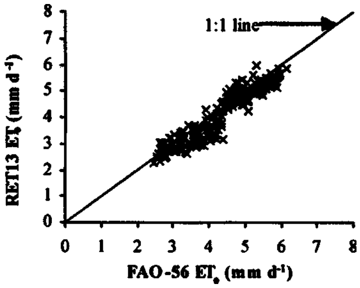

Fig. 8. Comparison of monthly FAO-56 ET_o estimates with those estimated by using algorithm RET13

large differences encountered in ET_o predictions, monthly mean R_s and R_n values estimated by their equations were plotted against those estimated by FAO-56 procedures in Eqs. (9)–(19) with the Panambur climate data. The comparison for R_n is shown in Fig. 9(b), and the linear fit gave values of slope $(S)=0.7108$, intercept $(I)=2.6301$, and coefficient of determination $(R^2)=0.598$. Irmak et al. (2003b) carried out similar statistical comparisons at several locations but with daily estimates of R_n; and they report S values in the range 0.680–0.833, I values between 1.645 and 2.989, and R^2 values of 0.68 to 0.86. Since our monthly comparison yields coefficients within these ranges, one may conclude that using their equations for monthly calculations is not the cause of large differences in ET_o. However, it is extremely interesting to note that Irmak et al. (2003b) found Eqs. (43)–(45) to yield better comparisons with measured values of R_n than the FAO-56 equations in several climates across the United States. Findings such as these underline the need for reexamining some of the FAO-56 procedures on the basis of direct measurements of the parameters in various climatic conditions.

Summary and Conclusions

FAO-56 recommends the sole use of the Penman–Monteith equation for estimating reference crop evapotranspiration, which is a key variable in modeling evapotranspiration flux from cropped land surfaces. Using the PM equation involves converting input climatological and location data into a number of parameters that appear in the equation. The exact procedures for estimating these parameters are described by FAO-56. However, the literature offers several alternative equations for computing these parameters, resulting in the possibility of users adopting the FAO-56 PM equation but computing the parameters with alternative (nonrecommended) equations. In this study, an evaluation of the differences that could arise in such situations has been carried out.

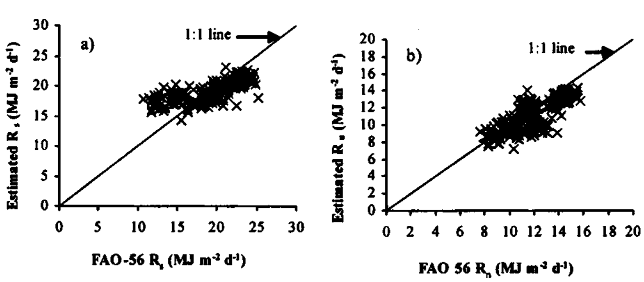

Fig. 9. Comparison of FAO-56 parameter estimates with those estimated by using algorithm RET13

While assuming FAO-56 ET_o estimates as the reference, alternative equations for a number of parameters are introduced, and the resulting differences in estimated ET_o have been quantified. The analysis was carried out by using historical (1973–1992) monthly climate data of a humid tropical location in Karnataka State, India. Statistical comparison of monthly ET_o estimates $(N=240)$ obtained by FAO-56 recommended procedures with those obtained by introducing alternative equations for one parameter at a time was carried out. Overall results indicated that although some of the alternative parameter estimation methods yielded ET_o estimates in close agreement with FAO-56 estimates, others gave rise to considerable differences, with the maximum absolute relative difference varying between 2 and 28%. Significant differences were particularly associated with estimation procedures for the vapor pressure deficit parameter (e_s-e_a) and the parameters involved in computing net radiation (R_n).

While accepting the fact that our results are representative in particular to the climate data set used and in general to humid climates, we reiterate the need for similar evaluations in other climates. Also, the magnitude of differences in ET_o estimates could be different for time steps other than the monthly step used in this analysis. Given the widespread use of FAO-56 procedures, our study highlights the need for strict adherence to standardized procedures of parameter estimation, thereby preventing ambiguous results from being obtained with the PM equation.

Acknowledgment

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Notation

The following symbols are used in this paper:

AMEAN = mean absolute relative difference (%);
C_p = specific heat of moist air at constant pressure [$=1.03\cdot10^{-3}$ MJ/(kg °C)];
C_v = coefficient of variation (standard deviation/mean);
d_r = inverse relative distance between Earth and Sun;
ET_o = reference crop ET (mm/day);
$e^o(T^*)$ = saturation vapor pressure at air temperature T^* (kPa);
$e^o(\overline{T})$ = saturation vapor pressure at air temperature $\overline{T}$ (mbar);
e_a = actual vapor pressure (kPa);
e_{al} = actual vapor pressure (mb);
e_s = saturation vapor pressure (kPa);
G = soil heat flux density [MJ/(m^2 day)];
$G_{\text{month},i}$ = soil heat flux density for month i, [MJ/(m^2 day)];
G_{sc} = solar constant [=0.0820 MJ/(m^2 min)];
g = acceleration due to gravity (=9.8 m/s^2);
I = intercept of linear fit between estimated and reference values;

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I_{sc} = solar constant (2 mm/hr);
J = day number of the year;
J_1 = month number;
KT = coefficient to account for effects of proximity to large body of water and elevation on volumetric heat capacity of atmosphere;
L_a = latitude (degrees);
MAXE = maximum absolute relative difference (%);
N = maximum possible duration of sunshine (hours);
NE = number of absolute relative differences $\geqslant$2%;
N_1 = number of data;
n = actual duration of sunshine (hours);
P = atmospheric pressure (kPa);
P_0 = atmospheric pressure at sea level (=101.3 kPa);
R = specific gas constant for dry air [=286.9 J/(kg K)];
R^2 = coefficient of determination of the linear fit;
R_a = extraterrestrial solar radiation at the top of the atmosphere [MJ/(m^2 day)];
$RH_{\max}$ = maximum relative humidity (%);
RH_{mean} = mean relative humidity (%);
$RH_{\min}$ = minimum relative humidity (%);
R_n = net radiation at crop surface [MJ/(m^2 day)];
R_{nl} = net long-wave radiation [MJ/(m^2 day)];
R_{ns} = net short-wave solar radiation [MJ/(m^2 day)];
R_s = solar or short-wave radiation [MJ/(m^2 day)];
R_{s0} = clear-sky short-wave radiation [MJ/(m^2 day)];
S = slope of linear fit between estimated and reference values;
TD = difference between maximum and minimum air temperature;
T_{dew} = dew-point temperature (°C);
$T_{\max}$ = maximum air temperature (°C);
$T_{\max k}$ = maximum temperature (K);
$T_{\min}$ = minimum air temperature (°C);
$T_{\min k}$ = minimum temperature (K);
$T_{\mathrm{month},i}$ = mean air temperature for month i;
$T_{\mathrm{month},i-1}$ = mean air temperature for month $i-1$;
T_0 = absolute temperature at sea level (=288 K);
T^* = either $T_{\max}$ or $T_{\min}$;
$\overline{T}$ = mean air temperature at 2 m height (°C);
u_2 = wind speed at 2 m height (m/s);
vpd = vapor pressure deficit (vpd) (kPa);
z = elevation of site above mean sea level (m);
z_0 = mean sea level (0.00);
z_w = height of wind measurement (m);
α = albedo or canopy reflection coefficient;
β = constant adiabatic lapse rate (=0.0065 K/m);
γ = psychrometric constant (kPa/°C);
Δ = slope of vapor pressure versus temperature curve at temperature T (k Pa/°C);
δ = solar declination (radians);
ε = ratio of molecular weight of air to water (=0.622);
λ = latent heat of vaporization $(=2.50-(2.361\cdot 10-3)\overline{T})$;
σ = Stephan–Boltzmann constant [=$4.903\cdot 10^{-9}$ MJ/(K^4 m^2 day)];
σ_1 = Stephan–Boltzmann constant [=$1.985\cdot 10^{-9}$ mm/(day K^4)];
ϕ = latitude of the place (radians); and
ω_s = sunset-hour angle (radians).

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