Analysis of Evaporative Flux Data for Various Climates

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Abstract: Estimation of evapotranspiration is a key requirement of hydrologic balance studies and climate analysis. The study reported involved collection of precise weighing lysimeter and meteorological data from three sites representing distinct climates. The combined data set for daily amounts of evapotranspiration and meteorological variables covers a total of 19 years on either an annual or growing season basis. The pan evaporation, Priestley-Taylor, original Penman, and Penman-Monteith evapotranspiration estimating methods are compared with lysimeter measurements using a moving average of 1–30 days. The results indicate the applicability of the various methods as a function of climate regime and the reduction in standard error of the estimate and increase in the coefficient of determination as a function of length of the moving average period. The results can be used both to determine which methods are most applicable for different climates and the expected magnitude of the error as a function of the estimating interval. This study indicates that a 5–10-day moving average can reduce the standard error of the estimate and increase the coefficient of determination significantly between estimated and measured reference evapotranspiration for several estimating methods for various climates.

Introduction

Estimates of evapotranspiration are important in irrigation planning, scheduling, hydrologic balance studies, onsite wastewater treatment, and watershed hydrology. More recently, sensitivity studies with general circulation models (GCMs) have demonstrated the strong interdependence between land surface processes and the atmosphere (Mintz 1984). The potential evapotranspiration component in the GCM models has been demonstrated to play a controlling role in the likelihood of droughts (Rind et al. 1990), the increased vigor of the hydrologic cycle, and the diurnal range of surface temperatures over deserts (Warrilow and Buckley 1989).

Evapotranspiration from a crop surface is commonly estimated from reference evapotranspiration and crop coefficient values. Using this approach, the accurate estimation of reference evapotranspiration is essential to accurate quantification of actual evapotranspiration. In general, reference evapotranspiration can be estimated from meteorological data or pan evaporation data for several time intervals. The time scale for estimating reference evapotranspiration can range from less than 20 min to several months.

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Daily to weekly interval estimates of evapotranspiration are desirable in several agricultural, climatic, civil engineering, and other hydrologic applications. For daily reference evapotranspiration, atmospheric stability can play an important role in the ability of the atmosphere to transport vapor (Mahrt and Ek 1984; Katul and Parlange 1991). Over longer averaging periods, this effect is generally attenuated, and accurately modeling the ability of the atmosphere to transport vapor can be relaxed.

This paper compares the gain in accuracy by using longer averaging intervals for several daily reference evapotranspiration estimating methods under different climatic conditions. The reference evapotranspiration methods considered vary from simple pan evaporation to combination equations that include stomatal control parameters. The climates considered range from humid to semiarid to arid. The three sites chosen to represent these climates were Versailles, France (humid), Davis, California (semiarid), and Kimberly, Idaho (arid). The sites were chosen because of the availability of long-term lysimeter data. The Davis data set included measured reference evapotranspiration from 1965 to 1971. The Kimberly set included lysimeter data from 1969 to 1971. The Versailles set included lysimeter data from 1968 to 1976. The estimating methods tested were the pan evaporation method, the Priestley-Taylor (1972) method, the original Penman (1948) method, and the Penman-Monteith (1965) method. These methods are physically distinct and were not calibrated at the aforementioned sites.

Experimental Setup

Measurements of reference evapotranspiration were performed by lysimeters. The lysimeters used in this study could determine reference evapotranspiration to an accuracy of less than 0.1 mm equivalent water depth. The reference evapotranspiration data came from lysimeters at Davis, California, Kimberly, Idaho, and Versailles, France. The Davis lysimeter was installed 1958–59 at the University of California at Davis within a 5.2 ha grass plot (Pruitt and Angus 1960). The lysimeter is circular, 6.1 m in diameter, 29 m^2 in area, and 0.91 m deep. The circular design resulted in a smaller ratio of perimeter to the area of the lysimeter, which served to reduce wall effects. The construction of the soil tank and upper retaining wall was a fiberglass-reinforced polyester resin to reduce the thermal transfer difference between field and lysimeter soil. The balance system used for determining the weight was a counterbalance mechanical system with a capacity of 45 metric tons. The balance dial and recording system could read the weight of the lysimeter every four minutes to the nearest pound (0.454 kg). The soil in and around the lysimeter was a disturbed Yolo loam with no change in structure and a uniform horizon in the first meter. The lysimeter cover was an Alta fescue grass mowed weekly during summer months to a height of 8–10 cm with regrowth reaching 12–15 cm. Irrigations were scheduled at 50% depletion of moisture content. Soil water potential was also monitored with tensiometers at various depths. The lysimeter design included 300 porous ceramic drainage tiles 30 cm long at the bottom to provide up to −0.1 bar soil water potential. Another system provided for drainage by gravity to discharge excessive water in the case of prolonged and intensive precipitation. The lysimeter proved to be reliable in determining evapotranspiration to 0.03 mm of equivalent depth of water.

The lysimeter at Kimberly was installed in 1968 in a 2.8 ha alfalfa plot (Wright and Jensen 1972; Wright 1982). The lysimeter soil bin was 1.83 m square and 1.22 m deep. The original design of the lysimeter was developed by Ritchie and Burnett (1968) in Texas. The lysimeter was supported on a sensitive mechanical platform scale equipped with a counterbalance mechanism. Net weight of the tank was transferred to an electronic load cell. Weight changes resulting from evapotranspiration, precipitation, or irrigation were recorded with an automatic data system throughout the growing season. The soil water potential within the lysimeter and the surrounding field was monitored with tensiometers. Irrigations were generally applied so that water availability within the crop root zone would not limit transpiration. To insure that water would not be limiting, the field was irrigated when the tensiometers at 45 cm depth exceeded 0.6 atm tension. The precision of the lysimeter was ±0.05 mm equivalent water depth (Wright and Jensen 1972). The lysimeter crop was alfalfa managed for alfalfa hay production with three harvests per season (Wright 1988). Crop evapotranspiration data were selected from periods when the alfalfa crop was well watered, actively growing, and at least 30 cm tall, so that measured evapotranspiration was essentially at the maximum expected level for the existing meteorological conditions.

Since it was desirable to have data representative of a consistent reference crop for this study, the measured alfalfa evapotranspiration at Kimberly was converted to equivalent grass evapotranspiration using (1)

$$ET_0 = \frac{ETr_{\text{alfalfa}}}{K_c} \qquad (1)$$

where ETr_{alfalfa} = measured evapotranspiration from the alfalfa lysimeter; K_c = a crop coefficient; and ET_0 = evapotranspiration for a grass reference as defined by Doorenbos and Pruitt (1977). The crop coefficient is a function of relative humidity, wind speed, and harvesting interval. Doorenbos and Pruitt (1977) presented tabular peak values of K_c for different values of air relative humidity, wind speed, and harvest periods.

Peak values for K_c were used in this study, since the alfalfa crop was in a reference state transpiring water at its maximum rate. The typical K_c value for humid sites with relative humidity exceeding 70% and wind speed not exceeding 5 ms^{-1} is 1.05. For dry climates with relative humidity not exceeding 20% and light to moderate wind speeds, the value fo K_c is 1.15. For wind speeds exceeding 5 ms^{-1}, the value of K_c is 1.25. Linear interpolation was used to obtain the K_c value for intermediate conditions at Kimberly.

The lysimeter at Versailles is a strain gage type installed and tested 1964–65. The lysimeter is circular in shape with a surface area of 5 m^2, and a diameter of 2.5 m. The depth of the lysimeter is 0.6 m resulting in a volume of 2.84 m^3. The change in lysimeter weight caused a change strain compression and signals were recorded on a 115 volt electronic potentiometer to an accuracy of 0.13 mm (Aboukhaled et al. 1982). At the bottom of the lysimeter, a drainage chamber was constructed with a drilled portion of a sphere covered with 0.15 m gravel and 0.1 m fine sand. The soil was placed above the fine sand layer. A vertical conduit was placed in the drainage chamber for pumping excess water out. The advantages of the Versailles lysimeter include a buffer for lysimeter overloading and minimization of temperature effects on the measurement system. The lysimeter cover was well-irrigated grass.

Pan evaporation data were available at Davis and Kimberly. The standard National Weather Service class A pan was used in this study. The class A pan at Davis was manufactured from unpainted galvanized iron, 122 cm in diameter, and 25.4 cm in depth. The class A pan at Kimberly was manufactured from unpainted monel metal with dimensions similar to the pan at Davis. The pans at Davis and Kimberly were surrounded by grass maintained in a reference condition with the wooden frame of the pan set at 15 cm above the ground cover. The pan at Davis was situated in a 50 m by 30 m well-irrigated grass field. The pan was situated closer to the eastern edge of the field since the predominant wind direction at Davis is from the southwest. The pan in Kimberly was situated at the center of a 45 m by 36 m grass plot. The grass was irrigated from April to October. The fetch distance estimated for Davis was 40 m, and the fetch distance estimated for Kimberly was 20 m (Katul 1990).

Daily meteorological observations were available for the full year for Davis from 1965–71. Daily meteorological observations for Kimberly were obtained from the National Weather Service climatological station located about 1 km from the lysimeter field site. This station had an irrigated clipped grass surface, 45 m by 36 m in size, and was surrounded by irrigated field plots planted to various crops each year. Data were utilized for the normal growing season, April–October, for 1969–71. Daily observations for Versailles for 1968–76 were also available. The meteorological variables of interest and the original units of measurements are summarized in Table 1. No class A pan evaporation data were available in Versailles for the study period.

Because relative humidity measurements were not available for Kimberly, an approximation was necessary. Using the dewpoint temperature that was measured at 0700 hours, the maximum and minimum relative humidity were estimated (Cuenca 1989) by

$$\mathrm{RH} = \left(\frac{112 - 0.1 \times T + T_d}{112 + 0.9 \times T}\right)^8 \qquad (2)$$

where RH = air relative humidity (%); T = air temperature in °C; and T_d = dewpoint temperature (°C). The maximum relative humidity for the day was computed using the minimum and the dewpoint temperatures. The minimum relative humidity was computed using the maximum air temperature and the dewpoint temperature for the day. The average relative humidity was computed using the average air temperature and dewpoint temperature.

TABLE 1. Description of Available Data with Original Units

Variables (1)	Davis (2)	Kimberly (3)	Versailles (4)
Maximum temperature	°C	°F	°C
Minimum temperature	°C	°F	°C
Dewpoint temperature	—	°F	°C
Maximum relative humidity	%	—	%
Minimum relative humidity	%	—	%
Wind run	km	mil C (at 3.66 m)	km
Pan evaporation	mm	in.	—
Evapotranspiration	mm	in.	mm
Solar radiation	Ly d^{-1}	Ly d^{-1}	Ly d^{-1}

Equations for Computing Reference Evapotranspiration

The methods used to estimate reference evapotranspiration included the pan evaporation method, the Priestley-Taylor method, the original Penman method, and the Penman-Monteith combination method. This section discusses briefly the equations and the assumptions employed in the context of this study.

The relation between pan evaporation and reference evapotranspiration can be described by (3)

$$ET_0 = K_p \times E_{pan} \qquad (3)$$

where ET_0 = reference evapotranspiration (mm d^{-1}); E_{pan} = pan evaporation (mm d^{-1}); and K_p = class A pan coefficient.

Tabulated values for the pan coefficient as a function of pan environment are presented in Jensen (1974), Doorenbos and Pruitt (1977), Cuenca (1989), and Jensen et al. (1990). Cuenca and Jensen developed a simplified regression equation, suitable for computerized applications to approximate the tabulated results. Eq. (4) was used to obtain the pan coefficient for the growing season at Kimberly and the full year at Davis. The wind speed, relative humidity, and fetch distance were averaged for the full year at Davis and the growing season at Kimberly, and an average pan coefficient was obtained. This coefficient varied from season to season at Kimberly and from year to year at Davis. It was decided not to vary the pan coefficient on a daily basis since fetch data on a daily basis were not available. For class A pan data, the pan coefficient, taken from Cuenca (1989) is

$$K_p = 0.475 - 0.24 \times 10^{-3} \times U_{2m} + 0.00516 \times \mathrm{RH} + 0.00118 \times d - 0.16 \times 10^{-4} \times \mathrm{RH}^2 - 0.101 \times 10^{-5} \times d^2 - 0.8 \times 10^{-6} \times \mathrm{RH}^2 \times U_{2m} - 1.0 \times 10^{-6} \times \mathrm{RH}^2 \times d \qquad (4)$$

where U_{2m} = wind speed at 2 m height (km d^{-1}); RH = air relative humidity (%); and d = fetch distance of green crop (m).

The Priestley-Taylor equation states that evaporation from a saturated surface of a large region is proportional to the equilibrium evaporation. Eq. (5) presents the Priestley-Taylor formulation

$$ET_0 = \alpha \times \frac{\Delta}{\Delta + \gamma} \times (R_n - G) \qquad (5)$$

where α = proportionality constant; γ = psychrometric constant (mb $°C^{-1}$); Δ = slop of the saturation vapor pressure versus temperature curve, mb $°C^{-1}$; and R_n and G = net radiation and the soil heat flux, respectively (mm d^{-1}).

For saturated sufaces, Priestley and Taylor (1972) noted that the proportionality constant was 1.26. The fact that the proportionality constant is greater than unity indicates that the advection-free conditions in the sense of Slatyer and McIlroy (1961) hardly occur, and large-scale advection over saturated surfaces can amount to 22% of the evaporation rate. The proportionality constant α obtained by Priestley and Taylor (1972) assumes minimal horizontal advection, and the vertical transport of vapor through turbulent diffusion is 26% of the net available energy.

The combination method developed by Penman is represented in (6)

$$ET_r = \frac{\Delta}{\Delta + \gamma} \times (R_n - G) + \frac{\gamma}{\Delta + \gamma} \times [f(u) \times (e_s - e_a)] \quad (6)$$

where e_s = saturation vapor pressure (mb); e_a = actual vapor pressure (mb); and $f(u)$ = a wind function (mm d^{-1} mb^{-1}). All other terms were defined in (5).

The wind function of the combination equation represents the vapor transport mechanism, which is very complicated, since it involves turbulent transport phenomena above a permeable rough surface with the roughness at the boundary surface changing with the surface shear stress. The simplest case is to assume the vapor removal mechanism is dependent on the mean air flow above the rough surface and, therefore, dependent on mean horizontal wind speed at a certain height (2 m in this study). This assumption is very crude if the time scale is very short (on the order of 30 min) since atmospheric stability becomes very important in the transport of water vapor (Brutsaert 1982).

In the original publication of Penman (1948), the wind function was defined as follows (Allen 1986):

$$f(u) = 0.263 \times (a_w + b_w \times u) \quad (7)$$

where u = horizontal wind speed at 2 m height in mi d^{-1}. Penman (1948) used the values of 1 and 0.537 for a_w and b_w, respectively, for a short grass cover. The original equation of Penman neglected the soil heat flux G for daily estimates of reference evapotranspiration and computed net radiation as shown in (8)

$$R_n = (1 - \alpha_s) \times R_s - \sigma \times T^4 \times [0.56 - 0.092 \times (e_a)^{1/2}] \times \left(0.1 + 0.9 \times \frac{n}{N}\right) \quad (8)$$

where R_n = net radiation, mm d^{-1}; α_s = surface albedo; R_s = incoming short-wave radiation, mm d^{-1}; σ = Stefan-Boltzman constant, mm d^{-1} K^{-4}; T = mean air temperature, K; n = actual sunshine hours for the day; N = maximum possible sunshine hours; and e_a = actual vapor pressure determined from relative humidity and saturation vapor pressure.

Eq. (8) was also used to compute net radiation for the Priestley-Taylor and the Penman equations. The surface albedo for grass was assumed constant and equal to 0.25. The equations were applied directly with the meteorological data from Kimberly. Therefore, the estimated reference evapotranspiration was grass reference evapotranspiration.

Monteith (1965) discussed the concepts and theoretical relationships of aerodynamic and canopy resistance in the evaporative process and incorporated his results into a Penman-type combination equation as discussed by Allen (1986)

$$ET_r = \frac{\Delta}{\Delta + \gamma^*} \times (R_n - G) + \frac{\gamma}{\Delta + \gamma^*} E_a \quad (9)$$

where γ^* = modified psychrometeric constant (mb °C^{-1}); and E_a = aerodynamic vapor transport term, mm d^{-1}.

The modified psychrometric constant incorporates the resistance terms r_{avg} and r_c and is related to the psychrometric constant as shown in (10)

$$\gamma^* = \gamma \times \left(1 + \frac{r_c}{r_{avg}}\right) \quad (10)$$

where r_{avg} = aerodynamic resistance term (s m^{-1}); and r_c = canopy resistance (s m^{-1}).

The r_{avg} term is a function of wind speed at height z, surface roughness length for the transport of momentum and vapor, and the zero plane displacement height within the vegetative surface. The relation between these variables is given by (11)

$$r_{avg} = \frac{\ln\left(\frac{z - d_o}{z_{om}}\right) \times \ln\left(\frac{z - d_o}{z_{ov}}\right)}{k^2 U_z} \quad (11)$$

where z = wind, air temperature, and vapor measurement height, mm; d = zero plane displacement height within the vegetation (mm); z_{om} = surface roughness length for momentum transport, mm; z_{ov} = surface roughness length for vapor transport, mm; k = von Kármán constant of proportionality, 0.41; and U_z = average daily wind speed at height z, m s^{-1}. Note that (11) does not account for atmospheric stability and assumes average neutral conditions. Since this study is dealing with daily estimates of evaporation, atmospheric stability corrections are neglected.

The bulk canopy stomatal resistance term is estimated from the leaf area index (LAI) as shown in (12)

$$r_c = \frac{100}{0.5 \times \text{LAI}} \quad (12)$$

If d_o, z_{om}, and z_{ov} are not measured, empirical relations presented in (13)–(15) can be used to obtain an estimate of these quantities (Tanner and Pelton 1960; Brutsaert 1982; Allen 1986)

$$d_o = 0.67 \times h_c \quad (13)$$

$$z_{om} = 0.123 \times h_c \quad (14)$$

$$z_{ov} = 0.1 \times z_{om} \quad (15)$$

The mean canopy height h_c (mm), can be easily estimated or measured. It should be noted that the vapor roughness height is dependent on the Reynolds number of the mean air flow (Brutsaert 1982). However, for the purpose of this study, it was assumed as 10% of the momentum roughness height.

The aerodynamic term of the Penman-Monteith equation can be estimated using (Allen 1986)

$$E_a = 8.64 \times 10^7 \times \frac{\rho \times C_p \times (e_s - e_a)}{L \times \gamma \times r_{avg}} \quad (16)$$

where E_a = aerodynamic transport term (mm d^{-1}); C_p = specific heat of dry air (J kg^{-1} K^{-1}); ρ = air density (kg m^{-3}); and L = latent heat of vaporization (J kg^{-1}). In the context of (16), the air density can be estimated using (17)

$$\rho_1 = \frac{0.0003484 \times (P + \varepsilon \times e_o)}{T \times \left(1 + \frac{e_d}{P}\right)} \qquad (17)$$

where P = atmospheric pressure (mb); ε = mass ratio of water vapor to dry air (0.62198); T = mean air temperature (K); and e_d = vapor pressure at dewpoint temperature (mb). Since the Penman-Monteith equation is dependent on crop properties as well as meteorological data, the calculations for Kimberly were performed based on the alfalfa crop and the results were converted to grass using (1).

Allen (1986) recommends the use of the 1972 Kimberly-Penman equation developed by Wright and Jensen (1972) and modified by Wright (1982) to compute the net radiation, soil heat flux, and the albedo for the Kimberly site. The net radiation for the Penman-Monteith equation at Kimberly was computed using (18)

$$R_n = (1 - \alpha_s) \times R_s - 0.5 \times \sigma \times (T^4_{\max} + T^4_{\min}) \times \left(a \times \frac{R_s}{R_{so}} + b\right) \qquad (18)$$

where a and b = empirical coefficients obtained from tables (Jensen 1974; Doorenbos and Pruitt 1977; Wright 1982; Cuenca 1989; Jensen et al. 1990).

The soil heat flux can be estimated from the average air temperature and the specific heat of the soil (Wright 1982; Allen 1986; Cuenca 1989) using (19)

$$G = C_s \times (T - T_{3pd}) \qquad (19)$$

where G = soil heat flux (mm d^{-1}); C_s = specific heat of the soil (mm °C^{-1}); T = the air temperature (°C); and T_{3pd} = mean air temperature for the prior three days (°C).

The albedo for the Penman-Monteith equation at Kimberly was assumed to be a function of the incident shortwave radiation, the clear sky shortwave radiation, the month, and the day of month (Cuenca 1989; Allen 1986) as shown in (20)

$$\alpha_s = 0.29 + 0.06 \sin[30 \times (M + 0.0333 \times N_m + 2.25)] \qquad (20)$$

where M = month; and N_m = day of the month. The sine argument is in degrees. Eq. (20) is used if the incoming shortwave radiation does not exceed 70% of the total clear-sky shortwave radiation. If the incoming short-wave radiation exceeds 70% of the clear-sky shortwave radiation, the albedo is assumed constant and equal to 0.3. For Kimberly, the reference evapotranspiration using the Penman-Monteith equation was computed based on the alfalfa crop and then converted to grass evapotranspiration as discussed using (1). Crop information for Davis and Kimberly (Allen 1986) are summarized in Table 2. The data in Table 2 were used to estimate the aerodynamic component of the Penman-Monteith equation at Davis and Kimberly. It should be noted that the leaf area index (LAI) for alfalfa was assumed constant during the growing season in Kimberly and the LAI for grass at Davis was assumed constant for the full year. Moreover, the crop height was assumed constant for the alfalfa and grass. The errors introduced by these assumption are not significant, since data for about 21 days after the alfalfa harvest were not employed in the analysis (Katul 1990). Only

TABLE 2. Crop and Roughness Information Used in Estimation of Aerodynamic Term of Penman-Monteith Equation

Location (1)	Variables: Estimated mean crop height (mm) (2)	Estimated zero plane displacement height (mm) (3)	Estimated z_{om} (mm) (4)	Estimated z_{ov} (mm) (5)	Estimated leaf area index (6)	Estimated canopy resistance during peak periods r_c (s m^{-1}) (7)
Davis, California	120	80	15	1.5	2.8	70
Kimberly, Idaho	570	380	70	7.0	5.0	40

days when the alfalfa exceeded 30 cm in height were used. Grass at the Davis site was maintained between 8 cm and 15 cm in height; therefore, using an average value of 12 cm was a reasonable assumption. The saturation vapor pressure, the slope of the saturation vapor pressure versus temperature curve, and the psychrometeric constant are nonspecific parameters and are independent of crop type. The calulation of the saturation vapor pressure is presented in (21) (Snyder et al. 1987)

$$e_s = 6.1078 \times \exp\left(\frac{17.27 \times T}{T + 237.3}\right) \qquad (21)$$

where T = air temperature, °C; and e_s = saturation vapor pressure, mb.

The slope of the saturation vapor pressure versus temperature curve can be obtained by taking the derivative of (21) with respect to temperature resulting in (22)

$$\Delta = \frac{24639.48}{(T + 237.3)^2} \times \exp\left(\frac{17.27 \times T}{T + 237.3}\right) \qquad (22)$$

The psychrometeric constant is estimated using (23)

$$\gamma = \frac{C_p \times P}{L \times \varepsilon} \qquad (23)$$

where C_p = specific heat of dry air (J °C gm^{-1}); P = atmospheric pressure (mb); L = latent heat of vaporization (J gm^{-1}); and ε = mass ratio of water vapor to dry air.

If the specific heat at constant pressure of dry air is assumed constant and equal to 1.0035 kJ kg^{-1} °C^{-1}, and the ratio of mass of water vapor to mass of dry air constant and equal to 0.62198, then (23) reduces to equation (24)

$$\gamma = 1.6134 \times \frac{P}{L} \qquad (24)$$

A simplified linear relation between standard atmospheric pressure and site elevation is given in Cuenca (1989) as shown in (25)

$$P = 1013 - 0.1055 \times E \quad (25)$$

where P = atmospheric pressure (mb); and E = site elevation (m).

The latent heat of vaporization can be expressed as a function of wet bulb and dry bulb temperature. However, Cuenca (1989), presented a simplified linear relation between dry bulb temperature and latent heat of vaporization that is sufficiently accurate for evapotranspiration studies. This relation is reproduced in (26)

$$L = 2{,}500.78 - 2.3601 \times T \quad (26)$$

where L = latent heat of vaporization (J gm^{-1}); and T = air temperature (°C). The equations presented in this section were used to estimate daily reference evapotranspiration by the various estimating methods at the three sites.

Results of Moving Average Analysis

Moving average analyses were performed for periods of 1, 2, 3, 5, 7, 10, 15, 20, and 30 days to evaluate the reduction in the standard error of the estimate (SEE) and the increase in the coefficient of determination, r^2. The moving average analysis is identical to a low pass filter in which the points within a certain specified window length are averaged, and then the window translates a unit time length (e.g., 1 day) with the same averaging process repeated within the window. For example, a moving average of period 3 days applied to a given time series averages the first three points in the set, then averages the second, third, and fourth points, then the third, fourth, and fifth points, until the end of the data set. The results are presented in Table 3 for Davis, Table 4 for Kimberly, and Table 5 for Versailles. Moving average analysis tends to attenuate local peaks (low-pass filter) that may arise due to error in measurements or extreme weather conditions. This type of analysis can be useful for determining an averaging interval for a specified standard error criteria for a particular method and climate.

The SEE, which is a measure of the scatter of the estimated reference evapotranspiration around the observed reference evapotranspiration, was computed using (27)

TABLE 3. Moving Average Results for Davis (1965–71)

Days aver-age	Pan Evaporation Method (PAN)		Priestley-Taylor Method (P-T)		Penman Method (PEN)		Penman-Montieth Method (P-M)	
(1)	SEE (2)	r^2 (3)	SEE (4)	r^2 (5)	SEE (6)	r^2 (7)	SEE (8)	r^2 (9)
1	0.76	0.89	1.17	0.77	0.98	0.85	0.84	0.87
2	0.61	0.93	0.96	0.83	0.80	0.90	0.68	0.91
3	0.54	0.94	0.83	0.89	0.75	0.92	0.57	0.93
5	0.45	0.96	0.67	0.93	0.61	0.95	0.44	0.96
7	0.42	0.96	0.63	0.94	0.58	0.96	0.40	0.97
10	0.39	0.97	0.59	0.95	0.56	0.96	0.36	0.97
15	0.35	0.98	0.55	0.96	0.54	0.96	0.33	0.98
20	0.33	0.98	0.54	0.96	0.53	0.96	0.31	0.98
30	0.30	0.98	0.53	0.97	0.51	0.97	0.29	0.98

TABLE 4. Moving Average Results for Kimberly (1969–71)

Days aver-age	Pan Evaporation Method (PAN)		Priestley-Taylor Method (P-T)		Penman Method (PEN)		Penman-Montieth Method (P-M)	
(1)	SEE (2)	r^2 (3)	SEE (4)	r^2 (5)	SEE (6)	r^2 (7)	SEE (8)	r^2 (9)
1	1.25	0.74	1.78	0.70	1.18	0.80	1.23	0.76
2	1.14	0.80	1.69	0.74	1.07	0.85	1.12	0.81
3	1.09	0.82	1.65	0.78	1.02	0.87	1.07	0.84
5	1.03	0.86	1.60	0.78	0.97	0.89	1.02	0.88
7	1.01	0.87	1.58	0.78	0.95	0.90	1.00	0.90
10	1.00	0.89	1.56	0.79	0.94	0.91	0.99	0.93
15	0.97	0.90	1.53	0.81	0.91	0.92	0.97	0.96
20	0.95	0.92	1.51	0.82	0.89	0.93	0.96	0.96
30	0.90	0.94	1.47	0.83	0.85	0.95	0.93	0.97

TABLE 5. Moving Average Results for Versailles (1968–76)

Days average	Priestley-Taylor Method (P-T)		Penman Method (PEN)	
(1)	SEE (2)	r^2 (3)	SEE (4)	r^2 (5)
1	0.77	0.80	0.89	0.81
2	0.64	0.84	0.79	0.83
3	0.58	0.87	0.75	0.84
5	0.49	0.89	0.70	0.85
7	0.46	0.90	0.68	0.86
10	0.44	0.91	0.66	0.86
15	0.41	0.91	0.64	0.87
20	0.40	0.92	0.63	0.87
30	0.38	0.92	0.62	0.87

$$\mathrm{SEE} = \sqrt{\frac{\Sigma\,(ETr_{\mathrm{lys}} - ETr_{\mathrm{computed}})^2}{n - 2}} \quad (27)$$

Note that $(n - 2)$ was used instead of n, since the two variables ETr_{lys} and ETr_{computed} were assumed to be responding to the same causative factors. The coefficient of determination was obtained using linear regression analysis between the daily lysimeter measurements and the computed reference evapotranspiration. The coefficient of determination is an indication of the degree of the correlation between the measured and estimated reference evapotranspiration. The linear regression was forced through the origin when the coefficient of determination was computed. The forcing of the regression through the origin tends to offset any consistent underprediction or overprediction by the estimating method that might appear in the constant of the regression line. Forcing the regression through the origin tends to yield a smaller coefficient of determination. Since pan evaporation data and crop data were not available at the humid site of Versailles, the analysis for that site was restricted to the Priestley-Taylor and the original Penman method.

For Davis, the standard error of the estimate was reduced as the number of days averaged was increased as shown in Fig. 1. The decrease was most pronounced in the first five days for all methods. On a daily basis, the simple

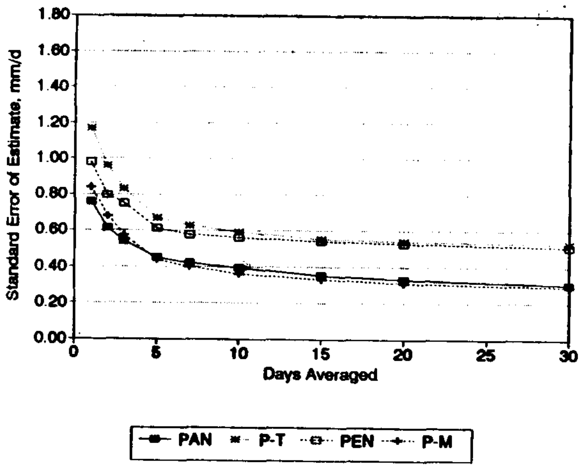

FIG. 1. Standard Error of Estimate (SEE) versus Number of Days Averaged for Davis (1965–71), for Entire Year (PAN = Pan Evaporation; PEN = Penman Method; P-T = Priestley-Taylor Method; P-M = Penman-Monteith Method)

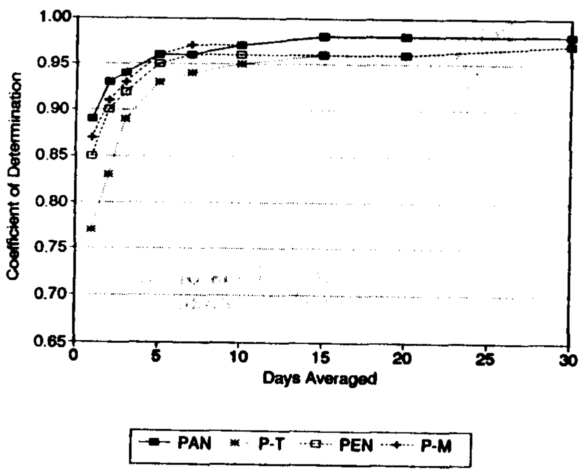

FIG. 2. Coefficient of Determination versus Number of Days Averaged for Davis (1965–71), for Entire Year

pan evaporation method had the smallest standard error. After a 5-day period, two sets of curves were noted. The lower curve set was made up of the pan evaporation and the Penman-Monteith methods, and the upper curves were defined by the energy-based Priestley-Taylor and the original Penman combination equation. After five days, all methods considered at Davis have a standard error of estimate less than 0.7 mm d^{-1} and a coefficient of determination exceeding 0.92. The coefficient of determination increased rapidly in the first five days, increased slightly from 5 to 10 days, and maintained a near constant value for all methods over longer averaging periods as can be noted from Fig. 2. All methods except the Priestley-Taylor method indicated strong initial statistical correlation between daily measured and estimated reference evapotranspiration at Davis with values above 0.85.

Over the five-day period, the correlation between the Priestley-Taylor estimates and the lysimeter were comparable to the other methods. It is noted that over longer averaging periods, the effects of excess sensible heat causing advection are generally attenuated and the Priestley-Taylor equation can yield accurate results. It appears that a 5–10-day moving average period is a good compromise between an improved standard error of the estimate and coefficient of determination, and time interval in the semiarid climate of Davis.

Analogous to the analysis performed for Davis, a moving average analysis for the standard error and the coefficient of determination was performed for Kimberly. The results are presented graphically in Figs. 3 and 4 for the standard error of estimate and the coefficient of determination, respectively. The Priestley-Taylor method had a higher standard error of estimate and a

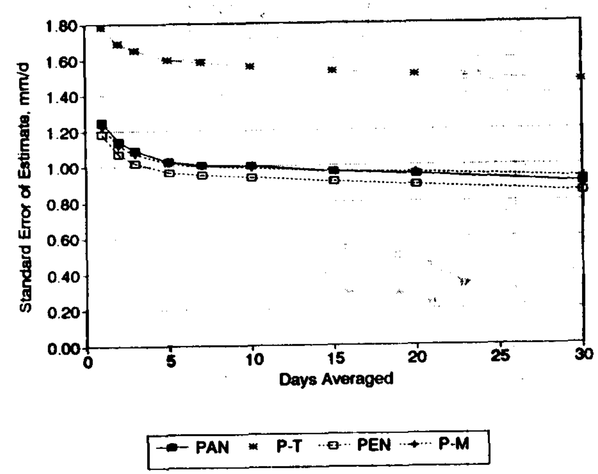

FIG. 3. Standard Error of Estimate (SEE) versus Number of Days Averaged for Kimberly (1969–71), for April–October

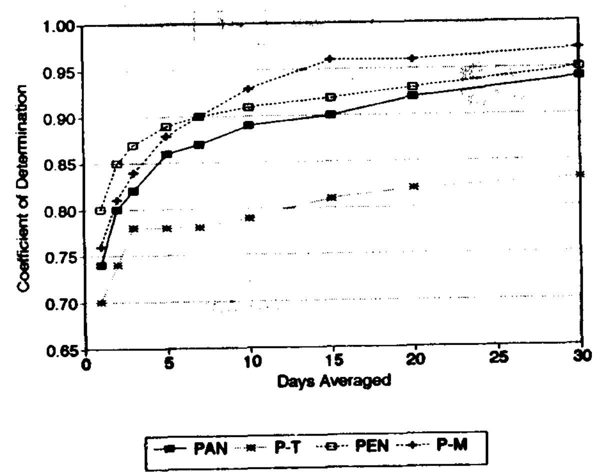

FIG. 4. Coefficient of Determination versus Number of Days Averaged for Kimberly (1969–71), for April–October

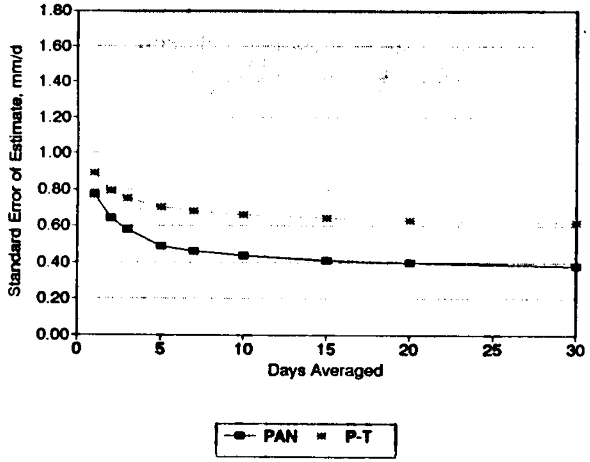

FIG. 5. Standard Error of Estimate (SEE) versus Number of Days Averaged for Versailles (1965–71), for Entire Year

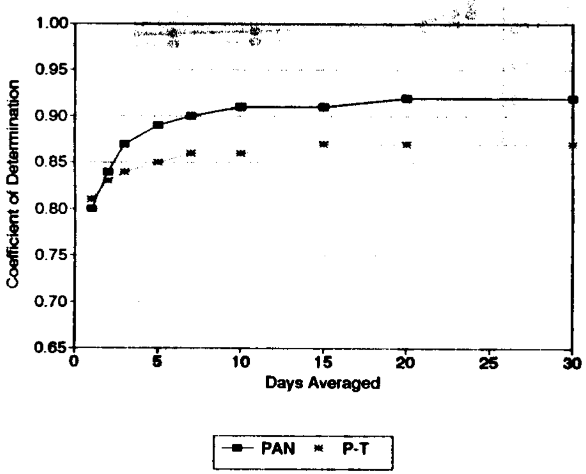

FIG. 6. Coefficient of Determination versus Number of Days Averaged for Versailles (1965–71), for Entire Year

lower coefficient of determination than all other methods. Even after a 30-day interval, the standard error was 40% higher than the other methods. However, similar to Davis, the most rapid decrease in the standard error curve was in the first five days for all four methods. It is not recommended to use the Priestley-Taylor method for arid-windy climates such as Kimberly since the method assumes minimal horizontal advection and does not take into account the sensible heat energy available for evaporation from large-scale advection. The conditions at Kimberly clearly demonstrate that energetic considerations alone are not sufficient to model evaporation and turbulent diffusion transport is important even on a longer period of study (i.e., longer than 10 days). Over an averaging period longer than five days at Kimberly, the Penman-Monteith method displayed better correlation with lysimeter data than the other methods. It should be noted that the pan method did not perform as well as the combination methods at Kimberly. However, after a five-day moving average interval, the coefficient of determination for the pan method was 0.86 indicating the 86% of the lysimeter variation can be explained by the simple pan evaporation method. Unlike Davis, there continued to be a relatively significant decrease in standard error and increase in coefficient of determination in the period from 10 to 15 days at Kimberly. Again, a 5–10-day moving average interval seems to be optimal with regard to reduction in standard error of estimate, increase in the coefficient of determination, and time length for Kimberly.

Similar analysis was performed for the Versailles data set. Due to the limitation of data availability, the two methods considered were the Priestley-Taylor method and the original Penman method. Figs. 5 and 6 display graphically the results of Tables 4 and 5. The Priestley-Taylor method demonstrated better performance for the climate of Versailles as indicated by the standard error and the coefficient of variation. For daily values, the Priestley-Taylor method had a lower standard error of the estimate than the Penman method, although the coefficients of determination are essentially the same. The reduction in standard error as a function of increased moving average time interval was more rapid for the Priestley-Taylor than the Penman method. At the end of the 30-day period, the standard error for the Priestley-Taylor method was 0.38 mm d^{-1}, which is about 40% lower than 0.62 mm d^{-1} for the Penman method. The increase in correlation between the lysimeter data and the Priestley-Taylor method was more marked than that of the Penman method. The 5–10-day averaging interval again seemed to be optimal for Versailles. During the 10–15-day interval, the response of the Versailles data set looks more like that of Davis, i.e., there is a relatively insignificant change in the standard error and coefficient of determination.

Conclusion

Over long averaging periods, the effects of atmospheric stability on the transport of vapor is reduced, and the mean horizontal wind speed can describe the aerodynamic transport in the atmosphere. Simple methods such as pan evaporation correlate well with lysimeter data under certain climatic conditions if a 5–10-day moving average is used. This finding is important since pan data are available at many sites worldwide (Linsely 1982). Strong statistical correlation was observed between water evaporation and reference evapotranspiration. However, it is critical that adequate pan-site conditions be insured including control of considerable upwind fetch area, and the adjustments for pan siting be made (Pruitt 1966; Doorenbos and Pruitt 1977; Cuenca 1989).

The Penman-Monteith equation demonstrated excellent correlation with the lysimeter data at the Davis and Kimberly sites. The drawback of the Penman-Monteith method is the intensive data input. The method requires intensive weather and crop data that are not commonly available, and the gain in the reduction of the standard error does not justify this intensive input when compared to the pan or the original Penman method, especially if periods in excess of five days are considered.

The Priestley-Taylor method gave improved estimates compared to the Penman equation in humid climates indicating its potential use under similar climates where intensive meteorological and crop data are not available for the Penman-Monteith method. The method did show a marked inferiority compared to the other estimating methods for the arid Kimberly region, even when a longer averaging period was used.

For semiarid climates, all the methods perform comparably if a period is equal to or greater than a five-day moving average is employed, with the pan evaporation method and the Penman-Monteith performing better than the Priestley-Taylor and the original Penman methods. The graphs presented in this study can be used as general guidelines to evaluate the averaging interval necessary to obtain a desired standard error of the estimate in a known climate and for a particular estimating method. The graphs indicate the effects of different processes on evapotranspiration under different climatic conditions, and, therefore, serve as a guide as to which methods and equations have improved performance under different climates.

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Appendix I. References

Aboukhaled, A., Alfaro, A., and Smith, M. (1982). "Lysimeters." *FAO Irrigation and Drainage Paper 39*, U.N. Food and Agric. Org., 1–68.

Allen, R. G. (1986). "Penman for all seasons." *J. Irrig. Drain. Div.*, ASCE, 112(4), 348–368.

Brutsaert, W. H. (1982). *Evaporation into the atmosphere. Theory, history, and applications*. D. Reidel Publishing Co., Boston, Mass.

Cuenca, R. H. (1989). *Irrigation system design: An engineering approach*. Prentice Hall, Englewood Cliffs, N.J.

Doorenbos, J., and Pruitt, W. O. (1977). "Guidelines for predicting crop water requirements." *FAO Irrigation and Drainage Paper 24*, U.N. Food and Agr. Org., Rome, Italy.

Jensen, M. E., Burman, R. D., and Allen, R. G., eds. (1990). "Evapotranspiration and irrigation water requirements." *ASCE Manuals and Reports on Engineering Practice, No. 70.*, ASCE, New York, N.Y.

Jensen, M. E., ed. (1974). *Consumptive use of water and irrigation water requirements*. ASCE, New York, N.Y.

Katul, G. G., and Parlange, M. B. (1991). "A Penman-Brutsaert model for wet surface evaporation." *Water Resour. Res.* (28), 121–126.

Katul, G. G. (1990). "Collection and analysis of evaporative flux data for various climates," M.S. thesis, Oregon State Univ., Corvallis, Oreg.

Linsely, R. K. (1982). *Hydrology for engineers*. McGraw-Hill, New York, N.Y.

Mahrt, L., and Ek, M. (1984). "The influence of atmospheric stability on potential evaporation." *J. Climate and Appl. Meteor.*, 23, 222–234.

Mintz, Y. (1984). *The sensitivity of numerically simulated climates to land surface boundary conditions in the Global Climate*. J. T. Houghton, ed., Cambridge Univ. Press, New York, N.Y., 79–103.

Monteith, J. L. (1965). "Evaporation and environment." *The state and movement of water in living organisms*, G. E. Fogg, ed., Academic Press, New York, N.Y., 205–234.

Penman, H. L. (1948). "Natural evaporation from open water, bare soil, and grass." *Proc. Roy. Soc. London*, series A, Vol. 193, 120–146.

Priestley, C. H. B., and Taylor, R. J. (1972). "On the assessment of surface heat flux and evaporation using large scale parameters." *Mon. Weath. Rev.*, 100(2), 81–92.

Pruitt, W. O. (1966). "Empirical method of estimating evapotranspiration using primarily evaporation pans." *Proc. Conf. on Evapotranspiration*, American Society of Agric. Engrs. (ASAE), Chicago, Il., 57–61.

Pruitt, W. O., and Angus, A. (1960). "Large weighing lysimeters for measuring evapotranspiration." *Trans. ASAE*, 3(2), 13–18.

Rind, D., Goldberg, R., Hansen, J., Rosenzweig, C., and Ruedy, R. (1990). "Potential evapotranspiration and the likelihood of future drought." *J. Geophys. Res.*, 95, 9983–10004.

Ritchie, J. T., and Burnett, E. (1968). "A precision weighing lysimeter for row crop water use studies." *Agron. J.*, 60, 545–549.

Slatyer, R. O., and McIlroy, I. C. (1961). *Practical microclimatology*. CSIRO, Melbourne, Australia.

Snyder, R. L., Shaw, R. H., and Paw, K. T. (1987). "Humidity conversion program." *Appl. Agric. Res.*, 2(3), 183–192.

Tanner, C. B., and Pelton, W. L. (1960). "Potential evapotranspiration estimates by approximate energy balance method of Penman." *J. Geophys. Res.*, 65, 3391–3413.

Warrilow, D. A., and Buckeley, E. (1989). "The impact of land surface processes on the moisture budget of a climate model." *Annales Geophysicae*, 7, 439–450.

Wright, J. L. (1988). "Daily and seasonal evapotranspiration yield of irrigated alfalfa in southern Idaho." *Agron. J.*, 80, 662–669.

Wright, J. L., and Jensen, M. E. (1972). "Peak water requirements of crops in southern Idaho." *J. Irrig. Drain. Div.*, ASCE, 96(1), 193–201.

Wright, J. L. (1982). "New evapotranspiration crop coefficients." *J. Irrig. Drain. Div.*, ASCE, 108(2), 57–74.

Appendix II. Notation

The following symbols are used in this paper:

a = empirical regression coefficient;
a_w = empirical wind function coefficient;
b = empirical regression coefficient;
b_w = empirical wind function coefficient;
C_p = specific heat of dry air (J Kg^{-1} K^{-1});
C_s = specific heat capacity of soil (mm d^{-1} $°C^{-1}$);
d = fetch distance of green crop (m);
d_o = zero plane displacement height (mm);
E_a = aerodynamic vapor transport term of combination equation (mm d^{-1});
E_{pan} = pan evaporation (mm d^{-1});
ET_0 = grass reference evapotranspiration (mm d^{-1});
e_a = actual vapor pressure (mb);
e_d = vapor pressure computed using dewpoint temperature (mb);
e_s = saturation vapor pressure (mb);
$f(u)$ = wind function representing vapor transport mechanism;
G = soil heat flux (mm d^{-1});
h_c = canopy height (mm);
K_c = crop coefficient;
K_p = pan coefficient;
k = Von Karman constant;
L = latent heat of vaporization (J Kg^{-1});
M = number of month (1–12);

N_m = number of day in specific month (1–31);
P = atmospheric pressure (mb);
RH = average air relative humidity (%);
R_n = net radiation (mm d^{-1});
R_s = incident short-wave radiation (mm d^{-1});
R_{so} = clear sky short-wave radiation (mm d^{-1});
r^2 = coefficient of determination;
r_{avg} = average aerodynamic resistance (s m^{-1});
r_c = canopy resistance (s m^{-1});
SEE = standard error of estimate (mm d^{-1});
T = average air temperature (°C);
T_{3pd} = average air temperature for previous three days (°C);
T_d = average dewpoint temperature (°C);
Z_{om} = momentum roughness height (mm);
Z_{ov} = vapor roughness height (mm);
α = Priestley-Taylor proportionality constant;
α_s = surface reflectance;
γ = psychrometeric constant (mb $°C^{-1}$);
Δ = slope of saturation vapor pressure-temperature curve (mb $°C^{-1}$)
ε = mass ratio of vapor to dry air;
ρ = density of air (Kg m^{-3}); and
σ = Stephan-Boltzman constant.