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Article *in* Agronomy journal · January 1991

DOI: 10.2134/agronj1991.00021962008300010055x

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Lysimetric Evaluation of Daily Potential Evapotranspiration Models for Grain Sorghum

J. L. Steiner,* T. A. Howell, and A. D. Schneider

ABSTRACT

Evapotranspiration (E_t) information is needed for many applications in agricultural and natural resource management, but commonly used prediction equations have not been adequately tested for the dry, high radiation, windy conditions of the Southern Great Plains. In order to test such equations, two precise weighing lysimeters at Bushland, TX, were used to measure daily E_t from well-watered, irrigated grain sorghum [*Sorghum bicolor* (L.) Moench] in 1987 and 1988. Forms of the Penman, Penman-Monteith, Jensen-Haise, and Priestley-Taylor models were evaluated for prediction of potential evapotranspiration (E_{tp}). The Penman-Monteith model provided the best predictions of E_{tp} and predicted well across the entire range of measured E_t. Forms of the Penman model with empirically fit wind functions overpredicted E_{tp} by 20 to 40%, and attempts to fit a linear wind function to our data were not satisfactory. The Jensen-Haise model, requiring only daily mean temperature and solar radiation data, overpredicted by 30%, but performed consistently across the range of E_t measured. Modification of the Priestley-Taylor model with vapor pressure deficit or temperature advection terms is recommended. Without such modification, the model overpredicts at low E_t rates and underpredicts at high E_t rates.

EVAPOTRANSPIRATION (E_t) information is required for many applications in agricultural and natural resource management from hydrological applications to plant growth and yield models to irrigation scheduling recommendations. The predominant approach for estimating actual E_t is to compute potential evapotranspiration (E_{tp}), based on climatic conditions, and from that estimating E_t depending on crop type, plant cover, soil surface wetness, water availability to the plant, or other factors. One goal of E_t research has been to identify E_{tp} estimation equations that are universally applicable and require only readily available data (Hatfield, 1988; Heermann, 1988; and Saxton and Cordery, 1988).

Estimation of E_{tp} assumes a standard surface, and many different standard surfaces have been used. Penman (1956) defined the standard surface as short, fully transpiring grass. For this paper, the terminology used will follow the definitions used by Jensen et al. (1990). For the general case of E_t from a saturated surface, the term potential evapotranspiration (E_{tp}) will be used. The most common standard surfaces, or reference crops, are short grass and alfalfa; where these surfaces were used, the terms E_{to} and E_{tr}, respectively, will be used. Methods of estimating E_t of a specific crop using a reference E_{to} equation are described in Doorenbos and Pruitt (1977) and Jensen (1974).

For many applications, such as irrigation scheduling or plant growth modeling, a daily time interval has been used. The objective of this paper is to evaluate daily E_{tp} estimation models applicable to irrigation scheduling and plant growth simulation and determine their performance for full-cover, well-watered grain sorghum in a high-wind, high-radiation, semiarid environment.

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Published in Agron. J. 83:240–247 (1991).

Description of Models

The equation developed by Penman (1948), commonly termed the combination equation, predicts E_{tp} as the sum of a radiative and aerodynamic component. The aerodynamic component was based on vapor pressure deficit multiplied by an empirical wind function. Doorenbos and Pruitt (1977) analyzed wind functions using data pooled from lysimeter experiments at many locations worldwide and emphasized the sensitivity of these functions to wind and humidity conditions. The Penman model was developed in Britain using data from a humid, relatively moderate climatic region, but has been tested and used in many different environments. Monteith (1965) proposed a modification of the Penman equation, in which biologically based canopy and physically-based aerodynamic resistance terms were incorporated into the wind function. This approach is often termed the Penman-Monteith model.

The combination equation requires climatic data that are usually not available, particularly vapor pressure deficit and windspeed. In remote areas, which can be extremely important for agriculture, hydrology, or natural resources, climatic data can be quite limiting. The most widely available data are air temperature. Radiation data are not widely collected. However, because it is difficult to accurately estimate daily E_t without radiation, many empirical models to estimate or simulate radiation have been developed. Because temperature data are easily obtained, and radiation data can be estimated on a routine basis, several radiation- and temperature-based models have been proposed.

Jensen and Haise (1963) estimated E_{tr} based on solar radiation and temperature for application to irrigation scheduling in the western USA, which is still the primary application for their equation. Priestley and Taylor (1972) suggested that under near-saturated conditions the aerodynamic component of the Penman combination equation would be less important and that E_{tp} would be proportional to the radiation term in the Penman equation. Their model was intended for large-area prediction, but because of its simplicity it has been adopted for many short-term, local applications. Jury and Tanner (1975) modified the Priestley-Taylor model so that E_{tp} varied with vapor pressure deficit, which improved its applicability to daily E_{tp} estimation in advective environments. Many daily crop growth or water balance models (e.g. Arkin et al., 1976; Kanemasu et al., 1976; and Williams et al., 1984) utilized the Priestley-Taylor equation for water balance estimation, mostly because it required less input data. These models were developed primarily in subhumid regions. The CERES daily-crop-growth models (Jones and Kiniry, 1986) have been incorporated into the IBSNAT Project [International Benchmark Sites Network for Agrotechnology Transfer (DSSAT, 1989)] and, therefore, are likely to be widely used in agroclimatic analyses in many different regions. The E_{tp} equation of the CERES models was developed based on the Priestley-Taylor model, and included an advection modification based on daily maximum air temperature.

Tests of Models

Although very desirable, no single E_{tp} prediction model has yet been accepted as universal. Therefore, local calibration is recommended before using an E_{tp} model in a given area for a given application (Jensen, 1974). Many examples of this type of testing are found in the literature.

Shouse et al. (1980) tested several models in an advective environment (Riverside, CA). They found that the Penman combination model with an empirical wind function recommended by Doorenbos and Pruitt (1977) for advective conditions predicted well, as did the Jury and Tanner (1975) model and an additional method that included wind and relative humidity terms. The Priestley-Taylor method required different calibrations for different years and, therefore, was not suited to their application. Jamieson (1982) compared prediction of E_t from a well-watered barley crop in a humid region (New Zealand) and found good agreement between measured E_t and that predicted by the Priestley-Taylor model based on climatic data collected over 30-min intervals. With 24-h data, the Priestley-Taylor model underpredicted E_t by about 9%, indicating the hazard of prediction based on averages of data when processes are dynamic and relate nonlinearly to climatic conditions. The Penman (1948) equation overpredicted E_t by about 18% and the van Bavel (1966) resistance-based model seriously overpredicted ET. The latter two models include wind influences, and the daily mean windspeeds in Jamieson's (1982) test were relativley high, ranging from about 2 to over 6 m s^{-1}.

Allen (1986) evaluated 10 E_{tp} models using data from three lysimeter locations and found that resistance forms, such as that developed by Monteith (1965), were among the best predictors, while the original Penman (1948) and the Priestley-Taylor models underpredicted ET. Phene et al. (1986) found good agreement between a wide range of prediction methods and measured values of E_t from grass near Fresno, CA. Predicted E_{to} was similar using (i) an hourly calculation of the combination equation with a wind function developed at Davis, CA (Pruitt and Doorenbos, 1977), and daily calculation using (ii) a locally calibrated wind function, (iii) a resistance form of the wind function developed by van Bavel (1966) and (iv) the Jensen-Haise model. The Penman (1948) wind function, which has a low slope but a high intercept, over predicted E_{to} by about 9%, and the Priestley-Taylor model underpredicted E_{to} by about 13%. Meyer et al. (1987) reported an underestimate of E_{tp} of irrigated wheat (*Triticum aestivum* L.) when using the Penman model with a wind function locally derived from lucerne, and pointed out some of the limitations of using an empirically derived wind function. They reported nighttime E_t to be strongly related to windspeed, with winds in the illustrative data being less than 3 m s^{-1}.

METHODS

Lysimeter and Climatic Data

In 1987 and 1988, daily E_t was measured from well-watered, irrigated grain sorghum grown on two weighing lysimeters (Marek et al., 1988) at the USDA-ARS Conservation and Production Research Laboratory at Bushland, TX (35° N, 102° W, 1170 m elev.). The lysimeters were 9 m^2 in surface area with 2.3-m deep monolithic soil cores. Each lysimeter was centered in a 5-ha field irrigated by a lateral-move sprinkler system. Minimum fetch from any direction to any lysimeter was 112 m. The lysimeters were sensitive to mass change as small as 0.05 mm. A weather station was maintained at a 1760-m^2 irrigated, mowed grass plot that was 170 to 400 m from the lysimeters as described by Dusek et al. (1987).

'DeKalb 41Y'[1] grain sorghum was planted on 18 May and 20 June in 1987 and 1988, respectively, on a Pullman clay loam (fine, mixed, thermic Paleustoll). Plants on and around the lysimeters were hand planted and thinned to 16 plants m^{-2}. The field and lysimeter areas were fertilized with 118 kg N ha^{-1}. The crops were sown in 0.76-m east-west rows on listed beds. Furrow dikes were installed after crop establishment, to minimize runoff. The field areas were treated with herbicides for broadleaf control, and the areas on or near lysimeters were hand weeded.

Leaf area index (LAI) was measured on 1.5-m^2 areas at regular intervals in both years from sites near each lysimeter. Evaluation of prediction equations was based on the period when the leaf area index of the crops exceeded 3.0, which included Days 212 to 248 in 1987 and Days 223 to 275 in 1988. All days that had precipitation, irrigation, or drainage from the lysimeters were deleted from the data set to avoid E_t measurement errors. A total of 106 data points (2 lysimeters, 53 d) were used in this evaluation. This is one of the few reports in the literature in which there is a measure of the variability in daily measured E_t.

Climatic variables measured at each lysimeter site and used in the analysis included net radiation (*Rn*, *MJ* m^{-2}) and soil heat flux (*G*, positive toward the soil-atmosphere interface, *MJ* m^{-2}). These measurements were made with Fritschen-type net radiometers (Model 6211, Science Associates, Princeton, NJ) mounted about 1 m above the crop surface and with soil heat flux plates (Model 6505, Science Associates) installed at a 100-mm depth. Heat storage in the layer above the soil heat flux plates was considered negligible on a 24-h basis.

At the weather station, daily solar radiation (*Rs*, *MJ* m^{-2}) was measured with an Eppley PSP pyranometer (Science Associates, Princeton, NJ), daily mean windspeed (*U*, m s^{-1}) at 2 m was measured with a cup anemometer (Model 014A, Met-One, Grants Pass, OR), air temperature and dewpoint temperature (Ta and Tdew, °C) were measured at 1.5 m in a standard cotton-belt instrument shelter (Campbell 207 probe, Campbell Scientific, Inc., Logan, UT, and a YSI 9400A dew cell, Yellow Springs Instruments, Inc., Yellow Springs, OH). Temperatures used in the analysis were daily mean air (Tmean) and daily mean dewpoint (Tdew) temperature (each determined as the mean of data measured at 6-s intervals with averages output at 30-min intervals), and daily maximum (Tmax) and minimum (Tmin) air temperature based on the extremes of the 6-s measurements. Barometric pressure (*P*, kPa) was measured with a pressure transducer (YSI 2014-745/1050mb-3, Yellow Springs Instruments) located in the instrument shelter. Additional details are given by Dusek et al. (1987). Vapor pressure deficit (VPD $= e_s - e_a$) was calculated as the difference between satu-

[1]Mention of a trade name or product in this paper does not constitute a recommendation of endorsement for use by the USDA, nor does it imply registration under FIFRA as amended.

ration vapor pressure at Tmean (e_s) and at Tdew (e_a). For some methods, an alternative calculation of VPD (VPDX) assumed daily mean e_s equal to saturation vapor pressure at the mean of Tmax and Tmin for consistency with assumptions used in derivation of the method.

Prediction Equations

The combination equation (Penman, 1948) for predicting potential evapotranspiration (E_{tp}, mm d^{-1}), as presented by Howell et al. (1986), was used for this analysis

$$E_{tp} = [\Delta/(\Delta + \gamma)][(Rn + G)/L] + [\gamma/(\Delta + \gamma) f(U)\,(\mathrm{VPD})] \quad [1]$$

where Δ (kPa °C^{-1}) is the slope of the saturation vapor pressure-temperature curve and γ (kPa °C^{-1}) is the psychrometric constant, L (MJ kg^{-1}) is the latent heat of vaporization, and $f(U)$ is an empirical wind function (mm kPa^{-1} d^{-1}). The first term of the right-hand side of Eq. [1] will be referred to as the radiation component. Equations used to calculate Δ, γ, L, and saturation vapor pressure are given in Howell et al. (1986).

The wind function is obtained by rearranging Eq. [1] and solving for $f(U)$ with lysimeter data used for E_{tp}. A linear regression is generally fit between daily $f(U)$ values and corresponding daily mean windspeed. The wind function presented in Penman (1948), converted to the appropriate units of mm d^{-1} kPa^{-1}, is given as

$$f(U) = 2.63 + 1.38\ U \quad [2]$$

Doorenbos and Pruitt (1977) presented a different wind function given as

$$f(U) = 2.70 + 2.33\ U \quad [3]$$

Estimates of E_{tp} using Eq. [1] and [2] will be referred to as ETpen48 and those using Eq. [1] with VPDX used in place of VPD and Eq. [3] as ETfao24. The climatic adjustment factor discussed by Doorenbos and Pruitt (1977) was set equal to 1.0 in this analysis.

Monteith (1965) described an aerodynamically-based resistance form of the combination equation given as

$$E_{tp} = [\Delta/(\Delta + \gamma^*)][(Rn + G)/L] + [1/(\Delta + \gamma^*)]\ Ea \quad [4]$$

where Ea in mm d^{-1} is an aerodynamic component. The Ea term was given as

$$Ea = [(\rho\ Cp\ VPD)/(L\ r_{av})]\ (86.400\ \mathrm{s\ d^{-1}}) \quad [5]$$

where ρ is air density in kg m^{-3} (taken here as a constant 1.0 kg m^{-3} from List, 1971), Cp is specific heat of dry air at constant pressure in MJ (kg °C)$^{-1}$ [taken as 1.005 kJ (kg °C)$^{-1}$ from List, 1971], and r_{av} is the aerodynamic resistance to water vapor in s m^{-1}. The γ^* term was calculated as

$$\gamma^* = \gamma(1 + r_c/r_{av}) \quad [6]$$

where r_c is the canopy resistance (s m^{-1}). The r_{av} was estimated following Brutsaert and Stricker (1979) as

$$r_{av} = \ln[Z - d)/Z_{om}]\ \ln[(Z - d)/Z_{ov}]/(k^2\ U_z) \quad [7]$$

where U_z is windspeed in m s^{-1} at height Z (m) above the surface, d is the zero-plane displacement height in m, Z_{om} and Z_{ov} are surface roughness lengths in m for momentum and vapor transfer, respectively, k is von Karman's constant (taken as 0.41) and Z is the height of the wind measurement in m. As recommended by Allen (1986), Z_{ov} was estimated as 0.1 times Z_{om}. Following an approach developed for corn by Jacobs and van Boxel (1988), Z_{om} was calculated assuming

$$d = 0.75\ H \quad [8]$$

$$Z_{om} = 0.25\ (\mathrm{H} - \mathrm{d}) = 0.065\ \mathrm{H} \quad [9]$$

where H is crop height in m. The Z_{om} and Z_{ov} terms are about one-half the value of the estimates used by Allen et al. (1989) for grass and alfalfa surfaces. The windspeed at 2 m over the grain sorghum crop (U_{2s}) was estimated following Allen et al. (1989) from the windspeed at 2 m over grass (U_{2g}) as

$$U_{2s} = U_{2g}\frac{\ln[(Z_e - d_g)/Z_{omg}]\ \ln[(Z_g + H_s - d_s)/Z_{oms}]}{\ln[(Z_e - d_s)/Z_{oms}]\ \ln[(Z_g - d_g)/Z_{omg}]} \quad [10]$$

where the g subscript refers to the grass in the weather station, and the s subscript refers to the grain sorghum, and Z_e is some arbitrary elevation height in m at which the windspeed is unaffected by the surface below but is common to the agricultural region. The height of the grass (H_g) was considered constant at 0.1 m, Z_g was 2 m, and Z_e was taken as 10 m. For H_s equal to 1.0 m, Eq. [10] predicts that the windspeed 2 m over the crop (3 m above the ground) to be 92% of the windspeed 2 m above the ground in the weather station. Because we made this adjustment to windspeed, the Z in Eq. [7] is (2 + H_s).

Canopy resistance (r_c) was estimated two ways. The first method followed Allen et al. (1989) where r_c is given as

$$r_c = R/LAI \quad [11]$$

where LAI is leaf area index (taken as 3.0 for this work) and R is a constant in s m^{-1}. Allen et al. (1989) recommended R as 200 s m^{-1} for a reference crop condition, assuming the daily mean canopy resistance for unstressed alfalfa is 100 s m^{-1} and one half of the leaf area accounts for most of the transpiration. We estimated R as 325 for grain sorghum based on solving for r_c using the mean values of climatic variables in Table 1, which would indicate a higher unstressed stomatal resistance for sorghum than alfalfa. Both values are empirical estimates because there are few data in the literature that allow determination of a daily average stomatal resistance from sunrise to sunset. The daily mean value of *VPD* was estimated by Penman (1948) by determining saturation vapor pressure at daily mean temperature and then subtracting *ea*. Allen et al. (1989) determined the mean saturation vapor pressure as the mean of saturation vapor pressure at Tmax and Tmin. For our analysis we used *VPD* based on daily Tmean. Using the approach of Allen et al. (1989) results in a mean *VPD* about 0.3 kPa greater than the value in Table 1, requires a R of 425 in Eq. [11] for similar predictions, and results in poorer fits (lower r^2 and higher standard error) of the data. Sadler and Evans (1989) emphasized the importance of using the same *VPD* calculation method as was used in derivation of an equation form, but if those assumptions result in a biased *VPD* estimate for a region, it can result in unacceptable bias in the E_{tp} prediction.

An independent method of calculating r_c followed Idso (1983), in which the canopy resistance for non-water stressed crops was estimated from the non-water stressed baseline determined using infrared thermometry as

Table 1. Summary of 24-h climatic variables used to evaluate potential evapotranspiration models for well-watered grain sorghum at Bushland, TX. 1987 and 1988.

Climatic variable	Mean	Maximum	Minimum	n
Tmean (°C)	21.7	27.7	12.4	53
Tmax (°C)	29.5	36.3	19.9	53
Tmin (°C)	14.4	20.6	6.7	53
Solar Radiation (MJ m^{-2} d^{-1})	24.1	30.9	11.6	53
Net Radiation (MJ m^{-2} d^{-1})	13.5	17.4	6.4	106
Soil Heat Flux (MJ m^{-2} d^{-1})	0.1	1.0	−0.7	106
VPD (kPa)	1.26	2.27	0.46	53
VPDX† (kPa)	1.30	2.20	0.50	53
Wind (m s^{-1})	3.6	6.5	1.6	53

† VPDX = e_s[(Tmax + Tmin)/2] − e_s(Tdew)

$$Tc - Ta = a - b*VPD \quad [12]$$

where Tc is canopy temperature (C) and Ta is air temperature (C). O'Toole and Hatfield (1983) reported that a = 2.53 (C) and b = 1.96 (C kPa^{-1}) for grain sorghum. Following Idso (1983), canopy resistance, r_c, was then calculated as

$$r_c = \{[1 - b(\gamma + \Delta)]/(1 - b\,\Delta)\}\;[(a\,\rho\,Cp)/(b\,\gamma\,Rn_f)] \quad [13]$$

where Rn_f is net radiation flux in W m^{-2}. For this analysis, the calculations for the Penman-Monteith equation using the Allen et al. (1989) form of r_c is termed ETpma65 and the one using the r_c value based on Idso's method is termed ETpmi65.

Radiation and Temperature Based Models

The model described by Jensen and Haise (1963), with modifications described in Pair et al. (1975), requires only daily mean air temperature and solar radiation along with long-term temperature records to calculate E_{tr} as follows:

$$E_{tr} = Ct\,(Tmean - Tx)\,Rs/L \quad [14]$$

where Ct and Tx are empirical coefficients that were calculated based on equations given in Howell et al. (1986) using saturated vapor pressure at mean monthly minimum and maximum temperatures of the warmest month of the year, as well as site elevation. For an alfalfa reference at Bushland, Ct = 0.0234 C^{-1} and Tx = −8.76 C. Equation [14] was used to calculate ETjh63 for this analysis.

The Priestley and Taylor (1972) model assumed a strong correlation between the radiation and aerodynamic components of Eq. [1] under near-saturated atmospheric conditions. The Priestley-Taylor potential E_{tp} was calculated as

$$E_{tp} = \alpha\,[\Delta/(\Delta + \gamma)][(Rn + G/L] \quad [15]$$

where α is a constant. Priestley and Taylor proposed 1.26 as a reasonable value for α. Brutsaert (1982) suggested that the appropriate α may be in the range of 1.26 to 1.29. Local calibration of α is commonly recommended to adapt the method to specific crops and regions. Calculations with Eq. [19] with α = 1.26 are presented in this paper as ETpt72.

Jury and Tanner (1975) proposed a modification of the Priestley-Taylor model in which α was a function of VPD (α') rather than a constant. They proposed calculation of α' based on daily mean VPD, and also proposed that VPD could be estimated from $Tmax$ and $Tmin$ if VPD was not measured. Their method required that a locally-calibrated constant α for nonadvective conditions be empirically determined by solving equation [24] for α using mean VPD under nonadvective conditions ($\overline{\text{VPD}}$) for a given location and crop. They used the locally-calibrated α and $\overline{\text{VPD}}$ to calculate α' as

$$\alpha' = 1 + (\alpha - 1)(VPD/\overline{\text{VPD}}) \quad [16]$$

which describes α' for a given location and crop as a linear function of VPD with an intercept of 1 and a slope equal to $[(\alpha - 1)/\overline{\text{VPD}}]$. Equation [15] with the α' function [16] substituted for the constant α was used to calculate ETjt75. For this analysis, $\overline{\text{VPD}}$ was estimated as 1.24 kPa and the "non-advective" α as 1.31, based on a subset of the data (36 points) where 25 C < Tmax < 35 C and U < 5 m s^{-1}.

The E_{tp} equation in the water balance subroutine of the CERES-Maize model (Jones and Kiniry, 1986) was based primarily on the radiation component of E_{tp}, with an advection modification based on daily maximum air temperature, which for LAI > 3.0 was given as

$$\bar{T} = 0.6\,Tmax + 0.4\,Tmin \quad [17]$$

$$EEQ = Rs\,(4.88 \times 10^{-3} - 4.37 \times 10^{-3}\,albedo)\;(\bar{T} + 29) \quad [18]$$

where albedo is assumed to be 0.23 for a full-cover (LAI > 3.0) crop canopy, and EEQ is the equilibrium evaporation rate.

$$E_{tp} = 1.1\,EEQ \quad [5\,C \le Tmax \le 35\,C]\;[19]$$

or

$$E_{tp} = EEQ\,[0.05(Tmax - 35) + 1.1]\quad [Tmax > 35\,C]\;[20]$$

or

$$E_{tp} = EEQ\,\{0.01\,EXP[0.18\,(Tmax + 20)]\}\quad [Tmax < 5\,C] \quad [21]$$

The derivation of the empirical coefficients in Eq. [17] to [21] are not documented in Jones and Kiniry (1986) or elsewhere, to our knowledge. The data set in this analysis was used to test the CERES equations, including high temperature advective modification, but not the low temperature modification. Equations [17] to [20] were used to calculate ETceres for this paper.

RESULTS AND DISCUSSION

The data suited for the evaluation of daily E_{tp} models are summarized in Table 1. A summary of the predictions of daily E_{tp}, relative to measured E_t, is given in Table 2. The Penman-Monteith models predicted E_t very well across a wide range of conditions. Using the Allen et al. (1989) r_c method with R = 325 s m^{-1}, the regression of predicted to measured E_t produced a zero intercept and a slope of 0.99 (r^2 = 0.86). Local calibration of R ensured a fit of mean E_{tp} but would not ensure the excellent fit of extreme values. The calculations using the Idso (1983) r_c method produced the highest r^2 (0.89) of all of the equations tested, but it had significant negative intercept (−0.74 mm day^{-1}) and a slope greater than 1.0 (1.08). Locally fit-

Table 2. Mean, maximum, and minimum daily evapotranspiration of well-watered grain sorghum as measured (E_t) or as estimated (E_{tp}) by published equations. Regression coefficients are given for estimated E_{tp} vs. measured E_t for each method. Bushland, TX. 1987 and 1988.

		Evapotranspiration					Regression Coefficients			
Model	Equations	Mean	Maximum	Minimum	SE of mean	E_{tp}:E_t ratio	Intercept	Slope	r^2	SE of slope
		mm d^{-1}								
ETlysim		5.46	9.8	2.0	0.167	–	–	–	–	–
ETpen48	1,2	6.62	10.2	2.7	0.170	1.21	1.59	0.92	0.81	0.76
ETfao24	1,3	7.91	13.4	3.1	0.222	1.45	1.75	1.13	0.71	1.23
ETpma65	4,11	5.42	8.7	2.1	0.171	0.99	0.00	0.99	0.86	0.66
ETpmi65	4,13	5.23	9.5	1.5	0.197	0.96	−0.80	1.11	0.89	0.66
ETjh63	14	7.12	10.4	2.8	0.189	1.30	1.39	1.05	0.85	0.75
ETpt72	15	5.18	7.1	2.4	0.106	0.95	2.30	0.53	0.68	0.62
ETjt75	15,16	5.58	8.7	2.1	0.159	1.02	0.78	0.88	0.85	0.63
ETceres	17–20	5.46	7.7	2.3	0.121	1.00	1.84	0.66	0.83	0.52

ting the coefficients for the nonwater-stressed baseline (Eq. [12]) might improve the fit of this model.

The ETpen48, ETfao24, and ETjh63 overpredicted mean E_t by 21, 45, and 30%, respectively. These models all overpredicted E_t over the entire range of E_t values, but the Jensen-Haise model had a slope near 1.0 for regression of E_{tr} on E_t, indicating that its responsiveness to the range of evaporative conditions was good. Fitting the Ct and Tx values of Eq. [14] to our data by regression indicated Ct = 0.0188 C^{-1} and Tx = −7.28 C, compared to 0.0234 C^{-1} and −8.76 C, respectively, determined using empirical equations presented by Jensen (1974). Locally fitting Ct and Tx improved the mean predictions as summarized in Table 3 as ETjhbush, but the fitted equation underpredicted high E_t values and resulted in a flatter regression slope.

The Priestley-Taylor model underpredicted mean E_t by about 5% and did not adequately predict extreme values of E_t, as indicated by the high intercept and low slope of the regression line. Mean predicted E_t by ETjt75 and ETceres, which make advective adjustments based on VPD and Tmax, respectively, predicted the mean measured E_t but the ETceres underestimated the larger values and gave a relatively flat slope (0.66) when regressed against measured E_t. The ETjt75 model provided a good prediction of E_t across the range of conditions of the test, as expected from calculations using a locally-calibrated α and $\overline{VPD}$ values.

Combination Equations

The predicted E_{tp} versus measured E_t values are shown for combination equations ETpen48 (Fig. 1) and ETpmi65 (Fig. 2). The Penman-Monteith resistance form provided good agreement without local calibration even though daily mean values of the r_c and r_{av} terms were used to represent dynamic processes which are nonlinearly related to climatic variables. The consistent overprediction (Table 1) by the ETpen48 and ETfao24 models indicates that the crop coefficient discussed by Doorenbos and Pruitt (1977) would be considerably less than 1.0, which is in contrast to values recommended for sorghum of 1.0 to 1.15 depending upon climatic conditions of the location (Doorenbos and Pruitt, 1977). Calculation of *VPD* based on [(Tmax + Tmin)/2], as described by Doorenbos and Pruitt (1977), resulted in about 3% too high a *VPD* (Table 2), compared to calculation based on a 24-hour Tmean and does not explain the high ETfao24 prediction, relative to measured E_t.

The empirically-fit linear wind functions of ETpen48 and ETfao24 did not fit the Bushland data. Attempts to fit a wind function to the local data by regression of the $f(U)$ residual of Eq. [1] against daily mean windspeed were unsuccessful, as shown in Fig. 3. A zero-intercept line with a slope of 2.72 is similar to that determined by Phene et al. (1986), but application of our locally-fit wind function did not improve prediction of E_{tp} relative to that shown in Fig. 1 or by using Phene's slope of 2.31.

Use of threshold wind values did not improve the performance of the wind functions. Other researchers have reported difficulty in applying combination equations in windy regions. Hill et al. (1983) limited windspeed at 1.86 m s^{-1} (100 miles d^{-1}) to make Penman equations work in selected windy locations in the western United States. This approach would result essentially in a constant for our data set, where the average daily mean windspeed was 3.6 m s^{-1} and only 2 d had mean daily windspeeds below 1.86 m s^{-1}.

Table 3. Mean, maximum, and minimum daily evapotranspiration of well-watered grain sorghum as predicted by equations modified to improve the fit to the Bushland data. Regression coefficients are given for estimated E_{tp} vs. measured E_t for each method.

Model	Evapotranspiration					Regression coefficients			
	Mean	Maximum	Minimum	SE of mean	E_{tp}:E_t ratio	Intercept	Slope	r^2	SE of slope
	mm d^{-1}								
ETlysim	5.46	9.8	2.0	0.176	—	—	—	—	—
ETjhbush†	5.44	8.0	2.1	0.148	0.99	0.97	0.82	0.85	0.57
ETptv‡	5.54	8.6	2.1	0.156	1.01	0.80	0.87	0.85	0.62
ETptt§	5.69	8.4	2.4	0.151	1.04	1.24	0.82	0.81	0.68
ETcerbush¶	5.53	8.6	2.1	0.163	1.01	0.52	0.92	0.87	0.61
ETkanem#	5.54	9.6	2.4	0.145	1.01	1.55	0.73	0.71	0.81

† Eq. [14] with Ct = 0.0189 and Tx = −7.28.

‡ Eq. [15] and [22].

§ Modified from Eq. [15],

$$\text{ETptt} = \alpha \frac{\Delta}{(\Delta+\gamma)} \frac{(\text{Rn}+\text{G})}{\text{L}} \qquad [\text{Tmax} \leq 28]$$

or

$$\text{ETptt} = [\alpha + \text{f(T)}] \frac{\Delta}{(\Delta+\gamma)} \frac{(\text{Rn}+\text{G})}{\text{L}} \qquad [\text{Tmax} > 28]$$

$\alpha = 1.26 \quad \text{f(T)} = 0.038\ (\text{Tmax}-28)$

¶ Modified from Eq. [17–20],

$\text{ETcerbush} = \text{EEQ}\ \beta \quad [\text{Tmax} \leq 28]$

or

$\text{ETcerbush} = \text{EEQ}[\beta + f(T)] \quad [\text{Tmax} > 28]$

$\beta = 1.0 \quad \text{f(T)} = 0.035\ (\text{Tmax}-28).$

Eq. [15] with α = 1.28 and an advective component (A) added to transpiration when Tmax > 33 °C. A = 0.1 (Tmax − 33), A ≤ 0.3

Skidmore et al. (1969) showed that the model of van Bavel (1966), with an aerodynamic resistance term to calculate the aerodyamic component of E_{tp}, compared well to Bowen ratio measurements of E_t when windspeed was about 1.5 m s^{-1} but greatly overpredicted the measured E_t when windspeeds ranged from about 2 to 4 m s^{-1}. Jamieson (1982) also showed overprediction of E_{tp} by models with a wind function in a test that involved high windspeeds.

The poor fit of $f(U)$ to windspeed could be related to differences in day and night windspeeds or to interactions between windspeed and *VPD*. Under conditions of high wind, the leaf boundary layer of upper canopy leaves will be quite small, exposing the upper leaf surfaces to ambient *VPD* in the canopy and leading to a possible stomatal response to *VPD* under high *VPD* conditions. For plants that have a relatively large leaf boundary layer (low or moderate wind), the *VPD* near the leaf surface is reduced by a transpiring plant canopy, compared to ambient *VPD* in the canopy.

Radiation and Temperature Based Equations

Predictions by ETjh63 (Fig. 4) and ETjt75 (Fig. 5) showed good agreement with our data based on high r^2 and slopes near 1.0. The Priestley-Taylor model, using the original α of 1.26, underpredicted ET and was unresponsive to variable climatic conditions as indicated by the flat regression slope. Our data indicated the appropriate α to be 1.34 based either on a mean of the daily α value or regression analysis. This did little to improve the predictions of the Priestley-Taylor model even for the data to which the coefficient was fit. The Jury-Tanner advection modification of α', Eq. [16], was calculated using $\alpha = 1.31$ and $\overline{VPD} = 1.24$ kPa based on a subset of the total data set ($n = 36$) with moderate temperature and windspeed (25 *C* < Tmax < 35 *C* and 3 ms^{-1} < *U* < 5 ms^{-1}).

We calculated a new VPD-based modification of the α (α_v) for the Priestley-Taylor model which does not require local calibration of α and $\overline{VPD}$ during a nonadvective period. Figure 6 shows a linear regression of α_v against *VPD*. The α_v values plotted are the daily

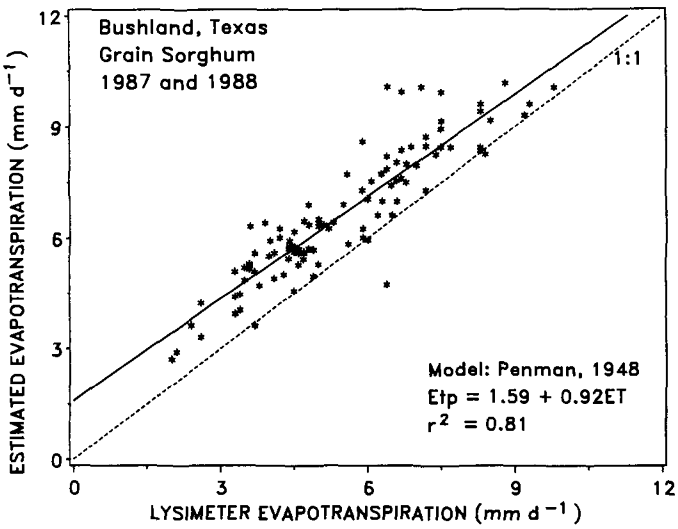

Fig. 1. Measured and predicted (ETpen48) potential evapotranspiration using the Penman (1948) equation.

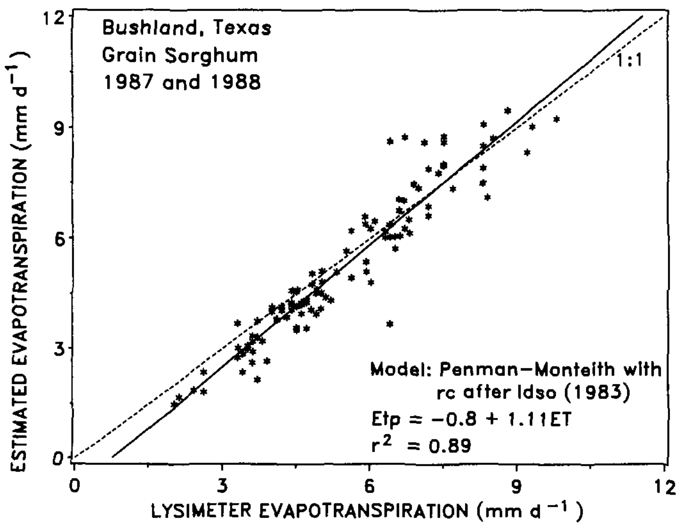

Fig. 2. Measured and predicted (ETpmi65) potential evapotranspiration using the Penman-Monteith model with r_c calculated following Idso (1983).

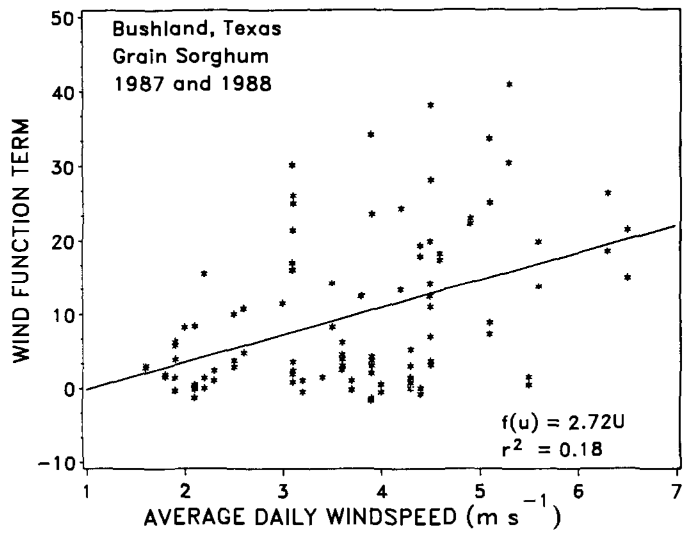

Fig. 3. Regression of the residual wind function for the combination equation on the windspeed for grain sorghum at Bushland, TX.

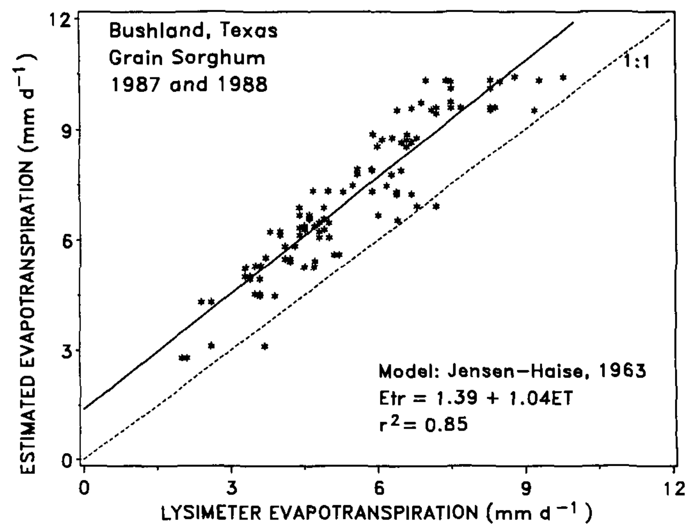

Fig. 4. Measured and predicted (ETjh63) potential evapotranspiration using the Jensen and Haise (1963) equation.

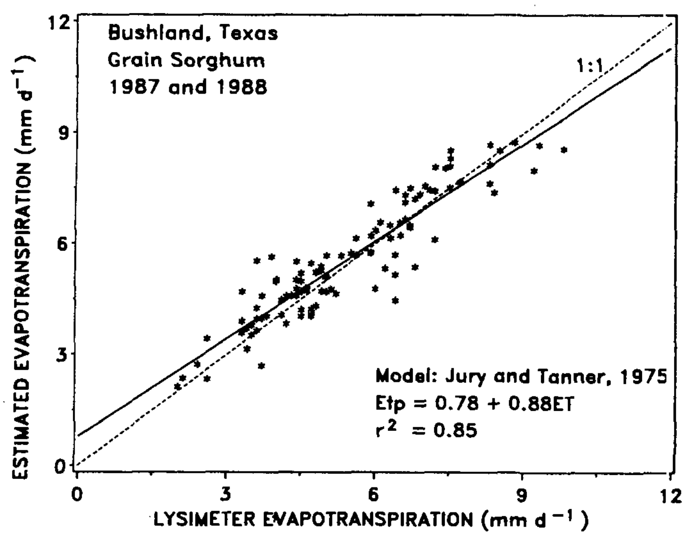

Fig. 5. Measured and predicted (ETjt75) potential evapotranspiration using the Jury and Tanner (1975) modification of the Priestley-Taylor alpha coefficient based on VPD.

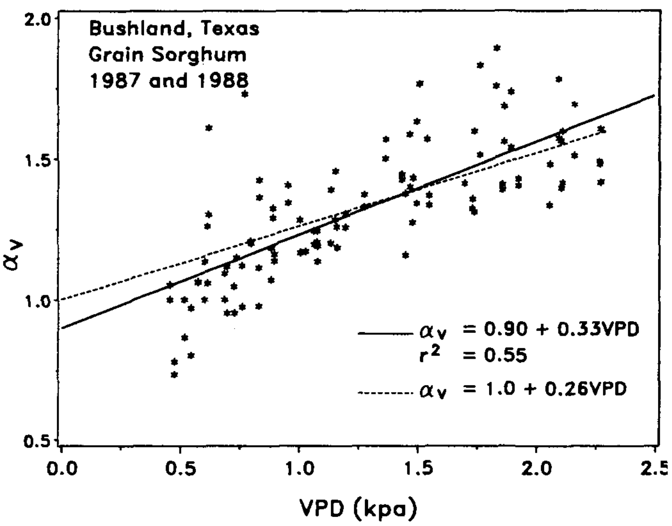

Fig. 6. Regression of ratio (α_v) of the daily E_t to the radiation component of the combination equation on VPD for Bushland, TX.

E_t divided by the radiation component from Eq. [15]. The slope of 1.34 and the insignificant intercept would indicate that the Jury and Tanner α was 1.34 and the nonadvective $\overline{VPD}$ was 1.0 kPa in Eq. [16]. The fact that our data predicted an α so near Priestley and Taylor's 1.26 may indicate that local calibration is not necessary to make a $\overline{VPD}$ correction for α. The VPD-based α (α_v) function developed in Fig. 6, which should be tested across a range of environments is

$$\alpha_v = 1 + (\alpha - 1)VPD \qquad [22]$$

where $\alpha = 1.26$. Equation [15] with [22] substituted for α was used to predict ETptv which is summarized in Table 3.

For cases where *VPD* is not available, an advective component can be based on temperature. The Priestley-Taylor model as modified with a temperature function, $f(T)$, which was found to have a critical Tmax of 28 C. The equation and the results of this modification are given in Table 3 as ETptt. The CERES model has a temperature-based advection component, which is not very responsive to the range of conditions in our test. A fit of our data to the CERES model indicates that the "constant" 1.1 in Eq. [19] and [20] should be 1.0 for our data, and the critical Tmax at which the advective component should be calculated is 28 C rather than 35 C. A summary of this model is given in Table 3 as ETcerbush.

Kanemasu et al. (1976) represented a temperature-based advective component with a crop-specific critical Tmax (33 °C for grain sorghum) developed using crop temperature measurements. Application of their model using their α (α = 1.28) provided reasonably good estimates of E_t across the range of measured values, although there was more variability in the estimates compared to some of the other models tested (Table 3). The good fit of the Kanemasu model to our data indicates that temperature-based advection models provide a reasonable approach for cases when VPD and wind data are not available. The high critical Tmax in the CERES model makes it much less responsive to high evaporative conditions than the Kanemasu et al. (1976) model or the Bushland model.

SUMMARY AND CONCLUSIONS

For well-watered grain sorghum grown at Bushland, radiation, temperature, and *VPD* were the most important climatic variables for calculating E_{tp}. In this windy environment, the combination equations that included an empirical, linear wind function overpredicted E_{tp}. The original form of the Penman combination equation (Penman, 1948) was not improved by modification of the wind term, such as those reported by Doorenbos and Pruitt (1977), by Phene et al. (1986), or by a locally fit function. The Penman-Monteith model worked well without calibration in our environment for full cover conditions.

Radiation- and temperature-based methods produced reasonable predictions of E_{tp} for this region. The Jensen-Haise model, which required only daily solar radiation, mean temperature, and location-specific constants based on elevation and long-term temperature records, tended to overpredict E_{tp}, but had a regression slope near 1.0. This indicated that the predicted E_{tr} was responsive over the entire range of measured E_t values. Predictions based on the Priestley-Taylor (1972) model tended to overpredict at low values, underpredict at high values, and to predict well in the mid-range of the measured E_t values. Advective modifications based on *VPD* (Jury and Tanner, 1975) and temperature (ETkanem and ETceres) improved the prediction of E_{tp} considerably. Our data indicated that a *VPD*-based modification of the Priestley-Taylor α may not require the local calibration proposed by Jury and Tanner (1975), but this should be tested across a wider range of environments. Prediction of E_t from a full-canopy crop, the simplest case, was the only case tested in this paper. Prediction of E_t from a partial canopy crop, regardless of the E_{tp} equation chosen, depends upon empirical relationships relating leaf area, soil surface wetness, and other properties to E_t.

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