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Evaluation Of Methods For Estimating Daily Reference Crop Evapotranspiration At A Site In The Humid Southeast United States

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R. E. Yoder, L. O. Odhiambo, W. C. Wright

Abstract. *Estimated daily reference crop evapotranspiration (ET_o) is normally used to determine the water requirement of crops using the crop factor method. Many ET_o estimation methods have been developed for different types of climatic data, and the accuracy of these methods varies with climatic conditions. In this study, pair−wise comparisons were made between daily ET_o estimated from eight different ET_o equations and ET_o measured by lysimeter to provide information helpful in selecting an appropriate ET_o equation for the Cumberland Plateau located in the humid Southeast United States. Based on the standard error of the estimate (S_{yx}), the relationship between the estimated and measured ET_o was the best using the FAO−56 Penman−Monteith equation (coefficient of determination (r^2) = 0.91, S_{yx} = 0.31 mm d^{-1}, and a coefficient of efficiency (E) = 0.87), followed by the Penman (1948) equation (r^2 = 0.91, S_{yx} = 0.34 mm d^{-1}, and E = 0.88), and Turc's equation (r^2 = 0.90, S_{yx} = 0.36 mm d^{-1}, and E = 0.88). The FAO−24 Penman and Priestly−Taylor methods overestimated ET_o, while the Makkink equation underestimated ET_o. The results for the Hargreaves−Samani equation showed low correlation with lysimeter ET_o data (r^2 = 0.51, S_{yx} = 0.68 mm d^{-1}, and E = 0.20), while those for the Kimberly Penman were reasonable (r^2 = 0.87, S_{yx} = 0.40 mm d^{-1}, and E = 0.87). These results support the adoption of the FAO−56 Penman−Monteith equation for the climatological conditions occurring in the humid Southeast. However, Turc's equation may be an attractive alternative to the more complex Penman−Monteith method. The Turc method requires fewer input parameters, i.e., mean air temperature and solar irradiance data only.*

Keywords. *Evapotranspiration, Penman−Monteith, Turc.*

Accurate evapotranspiration estimates are needed to determine the water requirement of crops for irrigation scheduling. Field measurement of evapotranspiration is rarely available and actual crop evapotranspiration (ET_c) is usually calculated from estimated reference crop evapotranspiration (ET_o) using the crop factor method, which consists of multiplying ET_o with crop specific coefficients (k_c) to obtain ET_c (i.e., $ET_c = ET_o \times k_c$). Reference crop evapotranspiration (ET_o) is defined as the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1}, and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground, and not short of water (Allen et al., 1998). Inaccurate estimation of ET_o, and hence ET_c, can lead to inefficient use of water, increased potential for surface and ground water pollution, and reduced profits for the grower.

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Over the years, many methods have been developed, revised, and recommended for estimation of ET_o for different types of weather data and climatic conditions. Jensen and Allen (2000) gave a good overview of the evolution of practical ET_o estimation methods including theoretical and empirical equations. The theoretical methods in common use include the original Penman method (Penman, 1948) and its variations such as the FAO−24 Penman (Doorenbos and Pruitt, 1977) and the Kimberly Penman (Wright, 1982, 1996). The Penman methods combine an energy balance with expressions that describe heat fluxes to derive a method to estimate vapor flux from a vegetated surface. Monteith (1965) introduced modifications to the original Penman equation by incorporating a stomatal resistance term resulting in the well−known Penman−Monteith equation. For a number of years, the FAO−24 Penman method was used as a standard equation for estimating ET_o when all weather data (temperature, humidity, wind, and solar radiation) were available. However, recent studies have revealed the FAO−24 Penman method to lack proven global validity and interest has shifted to the Penman−Monteith equation (Jensen et al., 1990; Allen et al., 1994; Allen et al., 1998; Walter et al., 2001).

The Penman−Monteith equation has been extensively evaluated and compared with measured lysimeter ET under different climatic conditions. Jensen et al. (1990) analyzed the performance of 20 different methods against lysimeter measured ET_o for 11 stations located in different climatic zones around the world. The Penman−Monteith method ranked as the best method for all climatic conditions. Allen et al. (1994) also showed that ET_o computed using the

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Penman−Monteith equation yielded estimates close to measured ET_o values. Following these studies, the FAO−56 Penman−Monteith method (Allen et al., 1998) was adopted as the standard method for definition and computation of ET_o from a grass reference surface (cool season grass). Several other works have confirmed the validity of the Penman−Monteith equation (De Souza and Yoder, 1994; Chiew et al., 1995; Howell et al., 1997, 2000; Oliveria and Yoder, 2000; Itenfisu 2003). Motivated by the desire to bring commonality to the various ET_o equations and crop coefficients now in use, the ASCE Technical Committee on Evapotranspiration in Irrigation and Hydrology recommended a standardized reference evapotranspiration equation for a grass surface (ET_o) along with computational procedures (Walter et al., 2000). The FAO−56 Penman−Monteith and the standardized ASCE Penman−Monteith equation for ET_o are exactly the same for daily time steps. However, for hourly time steps, the standardized ASCE Penman−Monteith method uses a smaller value for surface resistance (r_s) during the daytime, and a larger value for r_s during nighttime than does the FAO−56 Penman−Monteith equation (Allen, 2000).

Despite the advantages of the more physically based Penman methods, empirical ET_o equations have remained in popular use because of simplicity and the smaller number of input parameters (weather data and other constants) needed for computation. The 1985 Hargreaves−Samani equation is among the empirical methods in common use. Hargreaves (2003) presented a good review of some background and abbreviated history of the development of the 1985 Hargreaves−Samani method and contrasts this method with other commonly used approaches. The method is popular in cases where the availability of data is limited, as it requires only measurements of maximum and minimum temperature, with extraterrestrial radiation calculated as a function of latitude and day of the year. The1985 Hargreaves−Samani method is often used to provide ET_o estimations for weekly or longer periods and has been shown to provide ET_o estimates that compare favorably to those of the FAO−56 Penman−Monteith equation at some arid and semi arid locations (Hargreaves, 2003).

The 1972 Priestly−Taylor, the 1957 Makkink, and the 1961 Turc equations are other commonly used empirical methods (Allen, 2000), and require only air temperature and solar irradiance as input data. However, there are no reports of studies that have been conducted to evaluate the performance of these methods against measured lysimeter ET_o under the humid conditions in the southeast of the United States. Amatya et al. (1995) evaluated the reliability of the Hargreaves and Samani, Makkink, Priestly−Taylor, Turc, and Thornwaite ET_o estimation methods by comparing the estimates with results from the Penman−Monteith method for conditions in eastern North Carolina, and found that Turc's method gave the best daily ET_o estimates. Irmak et al. (2003) evaluated 21 ET_o estimation methods based on their daily performance under the humid climatic conditions in Florida, and found the 1948 Penman method to be the closest to the FAO−56 Penman−Monteith method, and among the temperature−based equations, Turc's equation was ranked the best. In earlier studies by Jensen et al. (1990), the ranking of these empirical methods varied depending on local calibration and conditions.

In this study, pair−wise comparisons were made between daily ET_o estimated from eight different ET_o equations and ET_o measured by lysimeter to provide information helpful in selecting appropriate ET_o equation for climates similar to the Cumberland Plateau located in the humid southeast of the United States.

MATERIALS AND METHODS

STUDY AREA AND DATA MEASUREMENTS

The Cumberland Plateau is the southern portion of the Appalachian plateau, and extends in a southwesterly direction from the eastern portion of Kentucky and parts of Virginia, running through middle Tennessee to the northern part of Alabama (fig. 1). The elevation ranges from 200 to 1200 m above mean sea level (MSL). The weather of the Cumberland Plateau is influenced by cold dry continental air masses from Canada, and warm moist air from the Gulf of Mexico. The average annual precipitation is 1175 mm with 525 mm falling during the growing season (May to October). The average annual temperature is 13°C and the area has an average freeze−free period of 175 days (Soil Survey Staff, 1981).

The weather and lysimeter data used in this study were measured at the Plateau Experiment Station (University of Tennessee Agricultural Experiment Station) located on the Cumberland Plateau near Crossville, Tennessee. The site is at an elevation of 573.6 m above MSL and lies at a latitude of 35° 55' N and a longitude of 85° 07' W. An automatic weather station and one large weighing lysimeter are installed within a large, nearly level field of uniform grass cover, extending more than 100 m in all directions from the station. The grass cover was maintained at a height of less than 0.5 m, and supplied with sufficient water through precipitation and irrigation. The weather variables including air temperature (T), wind speed (u_2), relative humidity (RH), and solar irradiance (R_S) were measured by the weather station, and the ET_o was measured by the lysimeter. The lysimeter was well watered and covered with a healthy growth of grass clipped to a height of 0.12 m. The lysimeter was calibrated before the start of each data gathering period (late April to early November) and when the grass cover was fully established. The records of lysimeter condition and maintenance were used to select days with good measured ET_o. Both weather and measured ET_o data were recorded every 15 min and subsequently integrated to daily values for use in the study. The quality and integrity of the weather data were assessed using the guidelines given by Allen (1996) and Walter et al. (2001), and were found to be of good quality. The

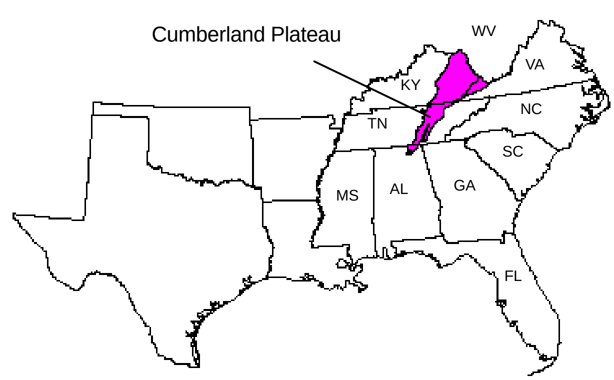

Figure 1. Location of the Cumberland Plateau covering parts of Alabama, Kentucky, Virginia, and Tennessee.

Table 1. Monthly averages of the main climatic variables for the Plateau Experiment Station, Crossville, Tenn. (1996–2001).

Month	Radiation (MJ m^{-2} d^{-1})	Air Temp. (°C)	Dew−Point Temp. (°C)[a]	Relative Humidity (%)	Wind Speed (m s^{-1})
May	21.6	18.2	13.8	76.8	1.2
June	21.8	21.1	17.3	80.4	1.1
July	20.8	22.9	19.6	83.5	1.0
August	19.8	22.1	18.7	82.4	0.9
September	17.6	19.4	15.3	78.2	1.0
October	14.4	13.9	9.1	76.4	1.1

[a] Dew−point temperature is calculated.

Table 2. Characteristics of the lysimeter used in the study.

Characteristic	Description
Type of lysimeter	Weighing
Type of scale system	Counterbalance lever load cell
Soil profile	Undisturbed
Wall material	Steel
Surface area	4.0 (m^2)
Soil depth	1.8 (m)
Drainage type	Free drainage
Sensitivity	0.05 (mm ET_o)
Type of grass	Kentucky blue grass/fescue mix

monthly averages of the main weather variables for the period of the study (1996−2001) are given in table 1, and a description of the characteristics of the lysimeter is given in table 2.

Evaluation of ET_O Estimation Methods

Eight ET_o estimation methods comprising combination, radiation−based, and temperature−based equations were selected for comparison using weather data collected at the Plateau Experiment Station. The estimated ET_o values for each method were calculated using a reference crop evapotranspiration calculator (REF−ET) developed by Allen (2000). The REF−ET program supports ET_o computation guidelines and procedures for all the selected methods as given in Jensen et al. (1990), Wright (1982, 1996), Allen et al. (1998), and the ASCE report on standardization of reference evapotranspiration calculations (Walter et al., 2001). The specific methods used to predict net radiation, soil heat flux, aerodynamic and bulk resistances, and other coefficients needed in each equation are described in the REF−ET manual (Allen, 2000). The ET_o estimation methods selected for comparison and the representative equations as defined in REF−ET are given in table 3. The terms in these equations are defined as:

ET_o = the reference crop evapotranspiration (mm d^{-1})
R_n = the net radiation (MJ m^{-2} d^{-1})
R_a = extraterrestrial radiation (MJ m^{-2} d^{-1})
R_s = solar radiation (MJ m^{-2} d^{-1})
G = the soil heat flux (MJ m^{-2} d^{-1})
e_s = daily mean saturation vapor pressure (kPa)
e_a = actual vapor pressure (kPa)
Δ = the slope of the vapor pressure curve (kPa °C^{-1})
γ = the psychrometric constant (kPa °C^{-1})
λ = the latent heat of vaporization (MJ kg^{-1})
K_w = a units constant
a_w, b_w = wind functions
u_2 = mean daily wind speed at 2−m height (m s^{-1})
T_{max} = daily maximum air temperature (°C)
T_{min} = daily minimum air temperature (°C)
T_{mean} = mean daily air temperature, computed as (T_{max} + T_{min})/2, °C
a_T = 1.0 for RH_{mean} = 50%
a_T = 1.0 + (50 – RH_{mean})/70 when RH_{mean} < 50%

How well the estimated ET_o matched the lysimeter measured ET_o was determined by pair−wise comparisons of the estimated and measured values. The parameters used to evaluate the equations included average daily ET_o computed from the entire data set (n = 296), the coefficient of determination (r^2), the slope of the trend line (S), the standard error of the estimate (S_{yx}), and the coefficient of efficiency (E) proposed by Nash and Sutcliffe (1970). Both r^2 and S_{yx} were calculated using the standard equations in Microsoft® Excel 2000 (Microsoft, 1999). The coefficient of efficiency (E) can be expressed as follows:

Table 3. Methods selected for comparison and the representative equations.

Method	Representative Equation[a]	
1948 Penman	$ET_o = \dfrac{\dfrac{\Delta}{\Delta+\gamma}(R_n - G) + K_w \dfrac{\gamma}{\Delta+\gamma}(a_w + b_w u_2)(e_s - e_a)}{\lambda}$	eq. 1
FAO−24 Penman	Same form as eq. 1, but with some variations in the calculation of R_n, a_w, and b_w. Also includes a correction factor.	
1996 Kimberly Penman	Same form as eq. 1, but with some variations in the calculation of the coefficients a_w and b_w.	
FAO−56 Penman−Monteith	$ET_o = \dfrac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T_{mean}+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$	eq. 2
1985 Hargreaves−Samani	$ET_o = 0.0023(T_{\max} - T_{\min})^{0.5}(T_{mean} + 17.8)R_a$	eq. 3
1957 Makkink	$ET_o = 0.61 \dfrac{\Delta}{\Delta+\gamma} \dfrac{R_s}{2.45} - 0.12$	eq. 4
1961 Turc	$ET_o = a_T\, 0.013 \dfrac{T_{mean}}{T_{mean}+15} \dfrac{23.8856 R_s + 50}{\lambda}$	eq. 5
1972 Priestly−Taylor	$ET_o = 1.26 \dfrac{\Delta}{\Delta+\gamma} \dfrac{R_n - G}{\lambda}$	eq. 6

[a] All terms in the equations are defined in the text.

$$E = 1.0 - \frac{\sum_{i=1}^{N}\left(MET_{oi} - EET_{oi}\right)^2}{\sum_{i=1}^{N}\left(MET_{oi} - \overline{MET_o}\right)^2}$$

where MET_o is the measured ET_o value, EET_o is the estimated ET_o value, and $\overline{MET_o}$ is the mean of the measured values. The statistic E examines whether the difference between the estimated and measured data is as large as the variability in the measured data. The possible values of E range from $-\infty$ to 1, with higher values indicating better agreement between the estimated and measured data. For interpretation, if E = 0, the observed mean is as good an estimator as the equation. If E > 0, the larger the positive number, the better the equation fit. The coefficient of efficiency represents an improvement over r^2 in that it is sensitive to differences in the measured and estimated means and variances, and will always be lower than that value (Legates and McCabe, 1999).

Results and Discussion

The results of the statistical analysis of equation estimated versus lysimeter measured evapotranspiration values are given in table 4. Figure 2 shows the plots of estimated ET_o versus measured ET_o for all methods that were analyzed. The coefficient of determination (r^2) has been widely used to evaluate the "goodness−of−fit" of evapotranspiration equations. However, the r^2 is oversensitive to extreme values (outliers) and is insensitive to additive and proportional differences between estimated and measured values (Legates and McCabe, 1999). Because of these limitations, r^2 values when used alone can indicate that an equation is the best estimator of ET_o when it is not. For example, comparison of the equations based on the r^2 values alone gives a false impression that the FAO−24 Penman equation (r^2 = 0.91) is among the best equations for estimating ET_o in this climate. Assessment of the daily average ET_o values, and slope and intercept of the trend line, shows that the FAO−24 Penman, Hargreaves−Samani, and Priestly−Taylor equations overestimate ET_o, while the Makkink method underestimates ET_o. The standard error of the estimate (S_{yx}) represents a rough estimate of the average amount by which each ET_o estimation method will either overestimate or underestimate the true ET_o given by lysimeter measurements. The results show that the lowest S_{yx} of the estimated daily ET_o was obtained with the FAO−56 Penman−Monteith equation followed by the original Penman and Makkink equations (0.31, 0.34, and 0.34 mm d^{-1}). The Hargreaves−Samani method had the highest S_{yx}, followed by the Priestly−Taylor method, and the FAO−24 Penman method (0.68, 0.46, and 0.41 mm d^{-1}). If the coefficient of efficiency, E, is used for the comparison, the original Penman and Turc equations give similar results and are slightly better than the FAO−56 Penman−Monteith and Kimberly Penman equations.

Hargreaves (2003) reported that at humid irrigated sites, the 1985 Hargreaves−Samani method produces values for periods of five or more days that compare favorably with those of the FAO−56 Penman−Monteith equation. Based on Hargreaves (2003) findings, we further evaluated the Hargreaves−Samani equation for the conditions at our study site by direct comparison with ET_o values estimated by the FAO−56 Penman−Monteith for daily and weekly time periods. The climatic data used were for the period May to October for the years 1998, 2000, and 2001. The results presented in figure 3 show that the Hargreaves−Samani equation overestimated ET_o compared to the FAO−56 Penman−Monteith equation for both 1−day and weekly time periods; the r^2 value was better for the weekly time periods.

Consideration of all the results from the analysis indicated that the relationship between the estimated and measured ET_o was best using the FAO−56 Penman−Monteith equation (r^2 = 0.91, S_{yx} = 0.31 mm d^{-1}, and E = 0.87), followed by the original Penman equation (r^2 = 0.91, S_{yx} = 0.34 mm d^{-1}, and E = 0.88) and Turc's equation (r^2 = 0.90, S_{yx} = 0.36 mm d^{-1}, and E = 0.88). The results for the Hargreaves−Samani equation showed low correlation with measured lysimeter ET_o data (r^2 = 0.51, S_{yx} = 0.68 mm d^{-1}, and E = 0.2), while those of the Kimberly Penman were reasonable (r^2 = 0.87, S_{yx} = 0.40 mm d^{-1}, and E = 0.87). These results are in agreement with other studies conducted at sites in the humid southeast of the United States (Amatya et al., 1995; Irmak et al., 2003) and support the adoption of the FAO−56 Penman−Monteith equation for climatological conditions similar to those on the Cumberland Plateau. However, the little−known Turc equation may be an attractive alternative to the more complex Penman−Monteith method since only mean air temperature and solar irradiance data are required.

Summary and Conclusion

Pair−wise comparisons were made between daily ET_o estimated with eight different ET_o equations, and ET_o

Table 4. Statistical analysis of estimated evapotranspiration using different methods vs. measured lysimeter evapotranspiration.

Method	No. of Data	Average ET_o (mm d^{-1})	r^2	E[a]	Slope	Intercept	S_{yx}[b] (mm d^{-1})
Lysimeter	296	3.6	–	–	–	–	–
1948 Penman	296	3.8	0.91	0.88	0.84	0.81	0.34
FAO−24 Penman	296	4.1	0.91	0.76	1.04	0.33	0.41
1996 Kimberly Penman	296	3.6	0.87	0.87	0.81	0.72	0.40
FAO−56 Penman−Monteith	296	3.4	0.91	0.87	0.76	0.71	0.31
1985 Hargreaves−Samani	296	4.3	0.51	0.20	0.54	2.38	0.68
1957 Makkink	296	3.1	0.90	0.74	0.77	0.36	0.34
1961 Turc	296	3.7	0.90	0.88	0.81	0.75	0.36
1972 Priestly−Taylor	296	4.0	0.86	0.78	0.90	0.74	0.46

[a] E is coefficient of efficiency.
[b] S_{yx} is the standard error of the estimate.

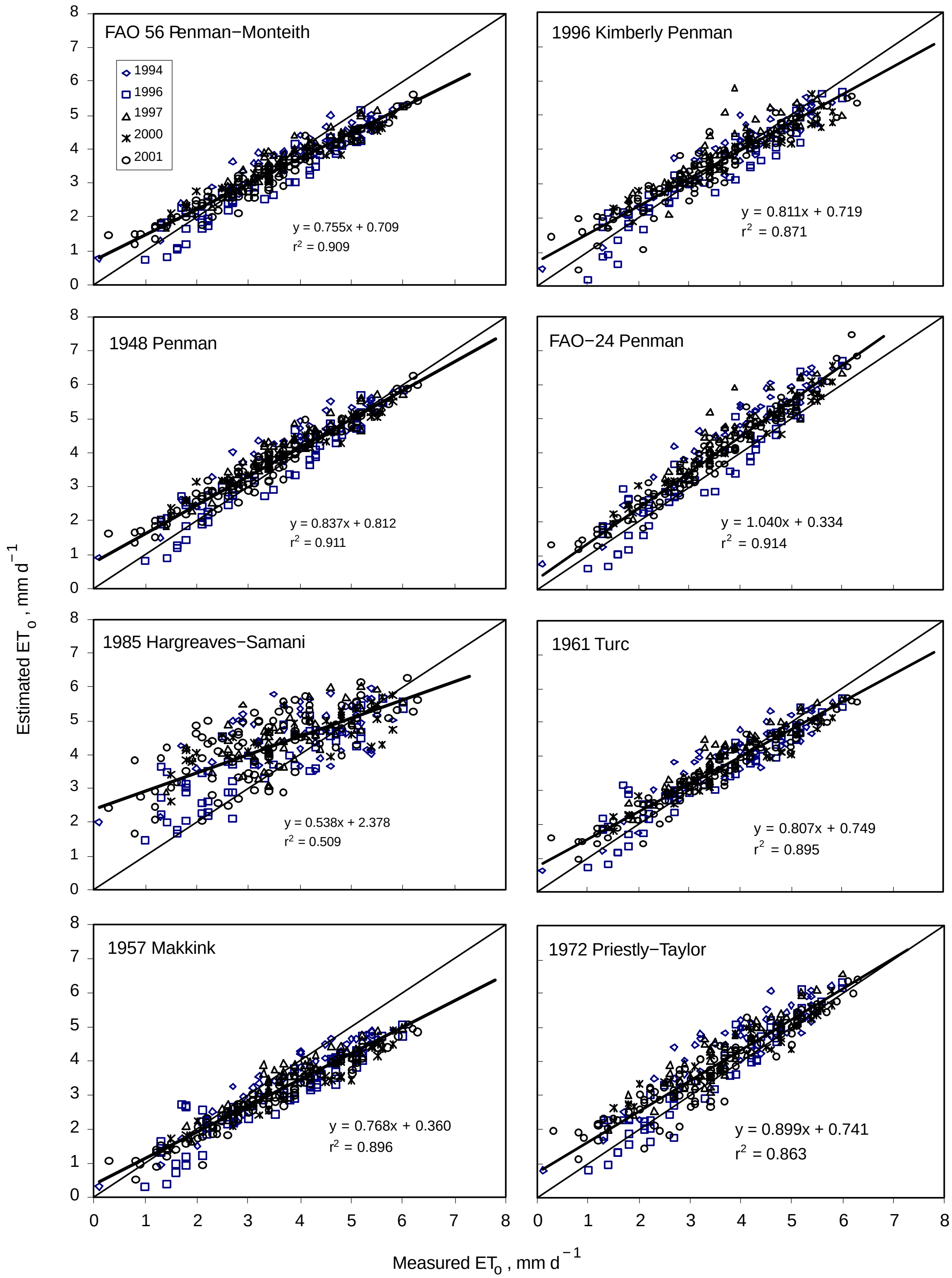

Figure 2. Comparison of daily evapotranspiration computed by eight ET_o estimation methods vs. measured lysimeter evapotranspiration.

measured by a weighing lysimeter for conditions on the Cumberland Plateau in the humid southeast of the United States. The results indicate that the FAO−56 Penman−Monteith equation is the best method for this humid climate, followed by the original Penman equation and Turc's equation. The FAO−24 Penman, Hargreaves−Samani, and Priestly−Taylor equations overestimated ET_o, while the Makkink method underestimated the ET_o. The results for the Hargreaves−Samani equation showed low correlation with measured lysimeter ET_o as expected, because it was developed for arid and semi−arid climates, and for ET_o computations for longer time periods. Hence, the Hargreaves−Samani equation is not suitable for estimating daily evapotranspiration in humid climates similar to that in this study. The Turc equation may be an attractive alternative to the more complicated Penman−Monteith method because

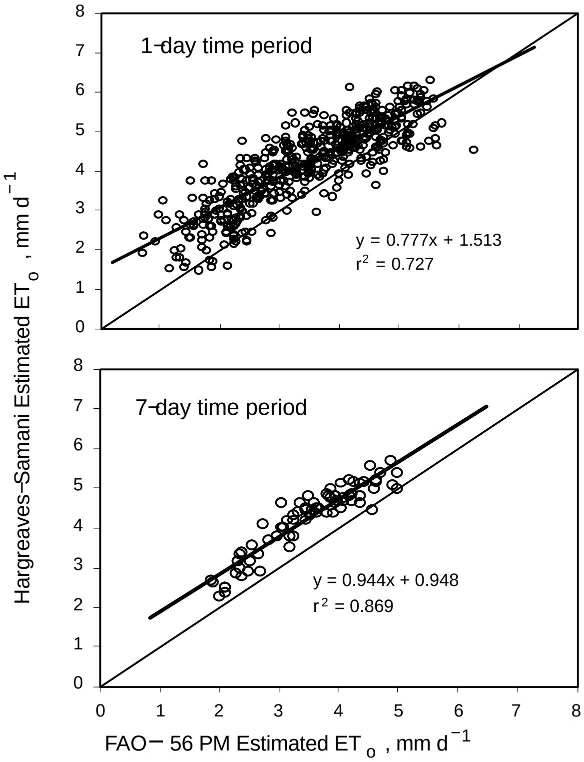

Figure 3. Comparison of estimated evapotranspiration values computed by the 1985 Hargreaves−Samani and FAO−56 Penman−Monteith methods.

it requires fewer input parameters, i.e., mean air temperature and solar irradiance data only.

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