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EVALUATION OF REFERENCE EVAPOTRANSPIRATION METHODS IN ARID, SEMIARID, AND HUMID REGIONS[1]

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ABSTRACT: It is often necessary to find a simpler method in different climatic regions to calculate reference crop evapotranspiration (ET_o) since the application of the FAO-56 Penman-Monteith method is often restricted due to the unavailability of a comprehensive weather dataset. Seven ET_o methods, namely the standard FAO-56 Penman-Monteith, the FAO-24 Radiation, FAO-24 Blaney Criddle, 1985 Hargreaves, Priestley-Taylor, 1957 Makkink, and 1961 Turc, were applied to calculate monthly averages of daily ET_o, total annual ET_o, and daily ET_o in an arid region at Aksu, China, in a semiarid region at Tongchuan, China, and in a humid region at Starkville, Mississippi, United States. Comparisons were made between the FAO-56 method and the other six simple alternative methods, using the index of agreement *D*, modeling efficiency (EF), and root mean square error (RMSE). For the monthly averages of daily ET_o, the values of *D*, EF, and RMSE ranged from 0.82 to 0.98, 0.55 to 0.98, and 0.23 to 1.00 mm/day, respectively. For the total annual ET_o, the values of *D*, EF, and RMSE ranged from 0.21 to 0.91, −43.08 to 0.82, and 24.80 to 234.08 mm/year, respectively. For the daily ET_o, the values of *D*, EF, and RMSE ranged from 0.58 to 0.97, 0.57 to 0.97, and 0.30 to 1.06 mm/day, respectively. The results showed that the Priestly-Taylor and 1985 Hargreaves methods worked best in the arid and semiarid regions, while the 1957 Makkink worked best in the humid region.

(KEY TERMS: reference crop evapotranspiration; FAO-56 Penman-Monteith; alternative ET_o methods; diverse climatic conditions.)

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INTRODUCTION

Crop evapotranspiration (ET_c), widely used for determining crop water requirements and designing irrigation systems (Jensen and Haise, 1963; Tabari *et al.*, 2011), is defined as the combined processes of water loss from the soil surface by evaporation and from the crop by transpiration (Allen *et al.*, 1998). There are a number of methods for measuring crop evapotranspiration, such as energy balance methods (Tanner, 1960), soil water balance methods (Malek and Bingham, 1993), and pan evaporation methods (Grismer *et al.*, 2002). However, crop

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evapotranspiration is not easy to measure since it depends on weather parameters, crop type, soil type, and agricultural management. Expensive devices such as lysimeters can be used, but experienced researchers are required (Allen *et al.*, 1998). To avoid these restrictions, Jensen (1968) introduced a method of calculating crop evapotranspiration (ET_c) by multiplying reference crop evapotranspiration (ET_o) by a crop-specific crop coefficient (K_c). ET_o is defined as "the rate of evapotranspiration from a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s/m, and an albedo of 0.23, 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). Accurate estimation of ET_o is necessary for improving the use efficiency of water resources as well as increasing production for growers (Droogers and Allen, 2002).

In the past 50 years, numerous methods have been developed for calculating ET_o according to the climatic conditions and weather data. Penman (1948) developed a theoretical equation to compute evaporation from open water, bare soil, and grass by combining the energy balance with a mass transfer method, but Allen *et al.* (1998) considered that it could also be applied for calculating ET_o if resistance factors were introduced to this equation. The Penman method was modified by Monteith (1965) through incorporating the aerodynamic resistance and surface resistance factors, leading to the generation of the well-known Penman-Monteith method, which can be directly used to calculate ET_o. In order to improve the performance of ET_o methods, the Food and Agriculture Organization of the United Nations (FAO) recommended four methods to calculate ET_o, including the Blaney-Criddle method, radiation method, modified Penman method, and pan evaporation method (Doorenbos and Pruitt, 1977). However, these methods would often give variable ET_o results among different locations and had huge deviations (Allen *et al.*, 1998; Pereira *et al.*, 2015). As a result, the improved FAO-56 Penman-Monteith method was recommended as the standard method for calculating ET_o, which included solar radiation, air temperature, humidity, and wind speed as input parameters (Allen *et al.*, 1998). The Evapotranspiration in Irrigation and Hydrology Committee of the American Society of Civil Engineers (ASCE) also introduced a Penman-Monteith equation for calculating both hourly and daily ET_o, the form of which is identical to FAO-56 Penman-Monteith method at daily time step (Allen *et al.*, 2005).

In addition to the methods mentioned above, there are other empirical equations that only need radiation and temperature data to calculate ET_o. Makkink (1957) developed a radiation-based equation to estimate ET_o which neglected the aerodynamic factors and substituted incoming shortwave solar radiation for the net radiation balance. The Turc (1961) method estimated ET_o with only temperature and solar radiation data. Priestley and Taylor (1972) developed an equation derived from the original Penman (1948) equation, and has been of interest to crop modelers due to lesser data requirements (Liu and Erda, 2005). Hargreaves and Samani (1985) developed an empirical equation for arid areas which needs only temperature to calculate ET_o. These and other methods widely used for ET_o calculation can be classified into three groups: combination methods, radiation methods, and temperature methods (Irmak *et al.*, 2008).

ET_o depends on and is sensitive to weather data and climate type (Zhang *et al.*, 2010; Dinpashoh *et al.*, 2011). In order to evaluate the performance of equations under different climatological conditions, comparisons among these methods have been carried out to identify the most suitable method for calculating ET_o in a certain area. Jensen *et al.* (1990) assessed performance of 20 different methods compared to lysimeter data from 11 locations with variable climatological conditions, and results indicated that ET_o calculated by different methods varies greatly. European research institutes (Allen *et al.*, 1998) also studied the validity of different ET_o equations in comparison with lysimeter data and came to similar conclusions. Many researchers have indicated that the FAO-56 Penman-Monteith method could be used for the calculation of ET_o in a wide range of locations and climates (Kashyap and Panda, 2001; Allen *et al.*, 2005, 2006). While the FAO-56 Penman-Monteith method has become the most accurate method for estimating ET_o, the application of this method is restricted in many locations since it requires a number of weather parameters, including solar radiation, air temperature, air humidity, and wind speed. It is often not easy to obtain these weather data due to limitations of installing expensive and complicated weather stations. To resolve this problem, methods with less required meteorological data are recommended to estimate ET_o in many regions. Comparisons were made by Yoder *et al.* (2005) between daily ET_o estimated from eight different equations and measured by lysimeter in the Cumberland Plateau of the humid Southeast United States (U.S.). Their results showed that the FAO-56 Penman-Monteith method is the best method for this humid climate, followed by the Penman (1948) and Turc (1961) methods. The Turc (1961) equation was an attractive alternative because it only requires temperature and solar radiation data. Studies have indicated that the Turc equation is suitable for ET_o calculation in humid and subhumid regions

(Trajkovic and Kolakovic, 2009; Fisher and Pringle, 2013). Simple methods compared to the FAO-56 Penman-Monteith have also been tested in arid and semiarid locations. Hargreaves and Allen (2003) reported that the 1985 Hargreaves method can be used in arid and semiarid locations with only measurements of maximum and minimum air temperature. Raziei and Pereira (2013) used three different methods to calculate ET_o using data from 40 weather stations in Iran, and found that the 1985 Hargreaves method is an appropriate alternative for estimation of ET_o for all arid regions of Iran.

While these simpler alternative methods have been widely used in different climatic regions, Valipour (2014) cautioned about using these methods in a specific site without considering the local climatic conditions, since the performance of these methods could differ greatly even if the climates of a selected area were similar to those in previous studies. It is necessary to check the performance of the simpler methods which were tested somewhere else by making comparison with the FAO-56 Penman-Monteith method. In addition, some regions lack simpler methods to replace the FAO-56 Penman-Monteith method to estimate ET_o. In order to extend the spatial coverage for evaluating alternative methods of ET_o estimation, it is essential to calculate ET_o by different methods at additional synoptic stations and make comparisons from various climates in the world. To our knowledge, such studies are limited in Aksu, China (an arid region), Tongchuan, China (a semiarid region), and Starkville, Mississippi, U.S. (a humid region). Also, there is an insufficient network of weather stations in these three sites, leading to limitations in the use of the FAO-56 Penman-Monteith method for calculating ET_o. The objectives of this research were to: (1) calculate ET_o using seven different ET_o methods and make comparisons between six simpler alternative ET_o methods and the FAO-56 Penman-Monteith method; and (2) to identify which simpler ET_o methods could be a substitution for the FAO-56 Penman-Monteith method in these three locations for calculating ET_o that could be further used in water balance models for making irrigation scheduling decisions.

MATERIALS AND METHODS

Study Areas and Weather Data

Three different climatic locations from China and the U.S. (Aksu, Tongchuan, and Starkville) were selected for this study based on climate types and weather data availability (Figure 1). Aksu, within an arid region, is located in the northwest of the Taklimakan Desert in Xinjiang province, China, while Tongchuan, within a semiarid region, is located in the south of the Loess Plateau in Shanxi province, China. Starkville, within a humid region, is located in the northeast of Mississippi, U.S. The elevation of Aksu, Tongchuan, and Starkville are 1,028, 978, and 102 m above mean sea level, and mean annual precipitation totals are 61, 630, and 1,390 mm, respectively. The average annual temperature ranges from −27.6 to 40.7°C in Aksu, 8.9 to 12.3°C in Tongchuan, and 10.4 to 23.4°C in Starkville. Average annual wind speed of Aksu, Tongchuan, and Starkville are 1.6, 2.0, and 2.6 m/s, while average annual solar radiation of Aksu, Tongchuan, and Starkville are 17.8, 14.4, and 17.5 MJ/m^2. Weather data comprised of daily maximum and minimum air temperatures, solar radiation, relative humidity, and wind speed were downloaded from the China Meteorological Data Sharing Service System (CMDS) (http://www.escience.gov.cn) and Natural Resources Conservation Service of the U.S. Department of Agriculture (NRCS) (http://wcc.sc.egov.usda.gov/nwcc/site?sitenum=2064). Summary information on location and weather data is given in Table 1. The time spans of weather datasets for the ET_o calculation were 60 years for Aksu, 27 years for Tongchuan, and 65 years for Starkville (Table 1). Nandagiri and Kovoor (2006) used four years of weather data in India, and Yoder *et al.* (2005) used five years of weather data in the U.S. to conduct similar research, suggesting that the datasets used in our research should be long enough to represent weather conditions at the three locations and make comparisons of the seven ET_o methods. The quality of the weather data at each site was assessed, using the REF-ET QA/QC (Quality Analysis and Quality Control) algorithms of Li and Allen (2012). There are some missing weather data in our study including the wind speed from 1953 to 1954, all the solar radiation and relative humidity in Aksu, and all the solar radiation and relative humidity in Tongchuan. Also, there are 1,096 samples of wind speed missing among the total samples in Starkville (Table 1). These missing data can be estimated by the RefET (Reference Evapotranspiration Calculator) software (Allen, 2013).

ET_o Estimation Methods

The weather datasets were first input to the RefET (Reference Evapotranspiration Calculator) software (Allen, 2013) to obtain the daily ET_o for the FAO-56 Penman-Monteith, and six alternative methods in each year. Then, the daily ET_o estimates were input to a spreadsheet and were averaged in each month to

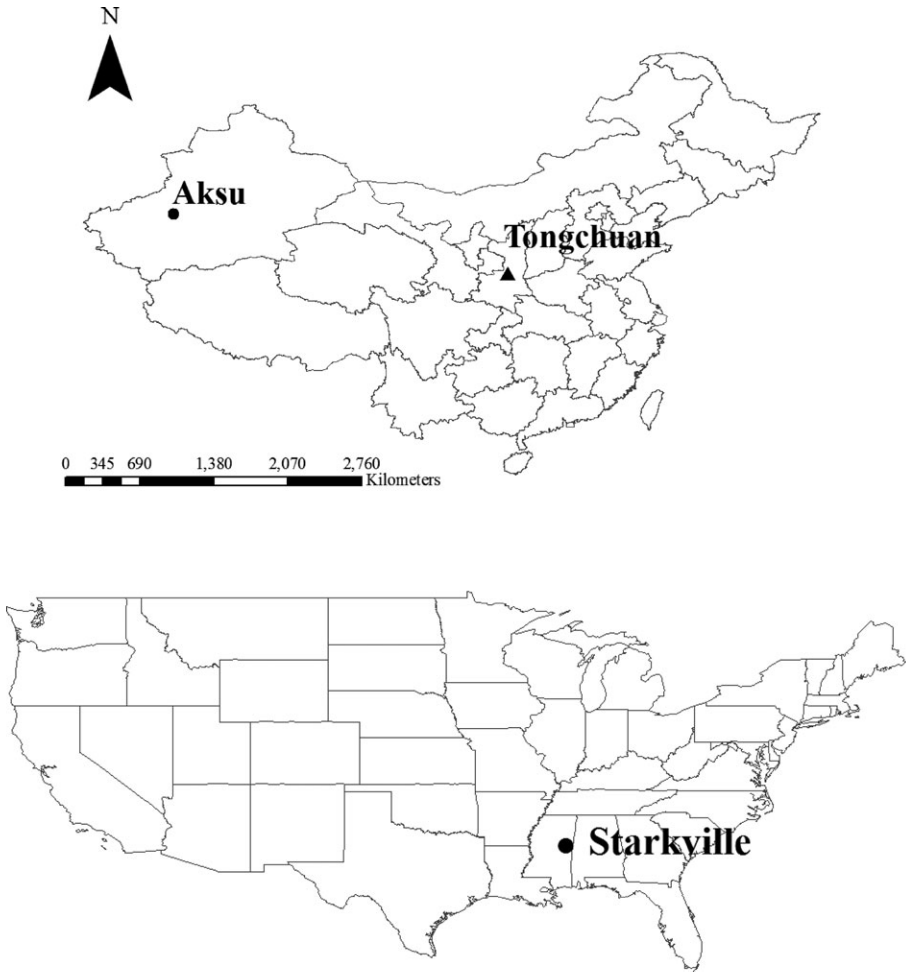

FIGURE 1. Location of Study Sites in China (Aksu, Tongchuan) and the United States (Starkville)

TABLE 1. Location and Time Periods of Weather Data at Aksu, Tongchuan, and Starkville.

	Aksu	Tongchuan	Starkville
Latitude	40°10′N	35°05′N	33°27′N
Longitude	80°51′E	109°04′E	88°46′W
Start	Jan 1954	Jan 1973	Jan 1950
End	Dec 2013	Dec 1999	Dec 2014
Number of samples	21,914	9,858	23,739

obtain monthly averages of daily ET_o. We focus on monthly averages of daily ET_o because there can be considerable variability in ET_o estimates from one day to the next, and averaging over longer time periods can reduce some of that variability (Allen *et al.*, 1998). Total annual ET_o were also obtained from daily ET_o values since annual ET_o is important for simulations of global water budgets (Federer *et al.*, 1996). The methods used for this study are based on the required number of input weather data. The FAO-56 Penman-Monteith needs solar radiation, air temperature, humidity, and wind speed, while Priestley-Taylor and 1957 Makkink need only solar radiation and/or air temperature. The FAO-24 Radiation needs solar radiation, air temperature, and wind speed; 1985 Hargreaves needs air temperature. FAO-24 Blaney Criddle requires relative humidity, sunshine hours, wind speed and 1961 Turc method requires solar radiation, air temperature, and relative humidity. All the values of coefficients used in the ET_o equations at three study sites were summarized in Table 2.

FAO-56 Penman-Monteith Method. The FAO-56 Penman-Monteith method (Allen *et al.*, 1998), referred to as FAO-56 hereafter, can be expressed as follows:

$$\mathrm{ETo} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\, u_2)}, \qquad (1)$$

where ET_o is the reference evapotranspiration (mm/day), R_n is the net radiation (MJ/m^2), G is the soil

TABLE 2. Description of the Coefficients Used in the ET_o Equations at Three Study Sites.

Coefficients	Description
a	Mean daily percentage of total annual daytime hours
b	Adjustment factor depends on minimum relative humidity, sunshine hours, and daytime wind speed
c	Adjustment factor depends on mean humidity and daytime wind conditions
α	Empirically derived constant and was defined as 1.26
a_T	Humidity correction coefficient
γ	Psychrometric constant (kPa/°C)
λ	Latent heat of vaporization (MJ/kg)

heat flux (MJ/m^2), T is average air temperature (°C), u_2 is the wind speed at 2-m height (m/s), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope of vapor pressure curve (kPa/°C), and γ is the psychrometric constant (kPa/°C).

FAO-24 Radiation Method. The FAO-24 Radiation method (Doorenbos and Pruitt, 1977), referred to as FAO-24 Rd hereafter, can be expressed as follows:

$$\mathrm{ETo} = c\frac{\Delta}{\Delta+\gamma}R_s, \tag{2}$$

where c is the adjustment factor which depends on mean humidity and daytime wind conditions, and R_s is the solar radiation (MJ/m^2).

FAO-24 Blaney Criddle Method. The FAO-24 Blaney-Criddle method (Doorenbos and Pruitt, 1977), referred to as FAO-24 BC hereafter, can be expressed as:

$$\mathrm{ETo} = b[a(0.46T+8)], \tag{3}$$

where a is the mean daily percentage of total annual daytime hours, and b is the adjustment factor which depends on minimum relative humidity, sunshine hours, and daytime wind speed.

1985 Hargreaves Method. The 1985 Hargreaves method (Hargreaves and Samani, 1985), referred to as 1985 Har hereafter, can be expressed as follows:

$$\mathrm{ETo} = 0.0023R_a(T+17.8)(T_{\max}-T_{\min})^{0.5}, \tag{4}$$

where R_a is the extraterrestrial radiation (MJ/m^2/day), and $T_{\max}$ and $T_{\min}$ are mean maximum and mean minimum temperatures (°C), respectively.

Priestley-Taylor Method. The Priestley-Taylor (1972) method, referred to as Prs-Tylr hereafter, can be expressed as:

$$\mathrm{ETo} = \alpha\frac{\Delta}{\Delta+\gamma}\frac{R_n-G}{\lambda}, \tag{5}$$

where α is the empirically derived constant and was defined as 1.26 by Priestley and Taylor (1972), and λ is the latent heat of vaporization (MJ/kg).

1957 Makkink Method. The 1957 Makkink (1957) method, referred to as 1957 Makk hereafter, can be expressed as:

$$\mathrm{ETo} = 0.61\frac{\Delta}{\Delta+\gamma}\frac{R_s}{2.45}-0.12 \tag{6}$$

1961 Turc Method. The 1961 Turc (1961) method, referred to as 1961 Turc hereafter, can be expressed as:

$$\mathrm{ETo} = a_T 0.013\frac{T}{T+15}\frac{23.8856R_s+50}{\lambda} \tag{7}$$

The term a_T is the humidity correction coefficient and is determined by

$$a_T = 1.0, \mathrm{RH}_{\mathrm{mean}} \geq 50\% \tag{8}$$

$$a_T = 1.0 + \frac{50-\mathrm{RH}_{\mathrm{mean}}}{70}, \mathrm{RH}_{\mathrm{mean}} < 50\%, \tag{9}$$

where $\mathrm{RH}_{\mathrm{mean}}$ is mean daily relative humidity (%).

Evaluation Criteria

Legates and McCabe (1999) recommended that the indexes of agreement D (Willmott, 1981), modeling efficiency EF (Loague and Green, 1991), and root mean square error (RMSE) be used to evaluate the performance of the alternate ET_o methods relative to the FAO-56 method. These criteria are defined as

$$D = 1.0 - \left[\frac{\sum_{i=1}^{n}(P_i-O_i)^2}{\sum_{i=1}^{n}\left(\left|P_i-\overline{O}\right|+\left|O_i-\overline{O}\right|\right)^2}\right] \tag{10}$$

$$\mathrm{EF} = \frac{\left[\sum_{i=1}^{n}(O_i-\overline{O})^2-(P_i-O_i)^2\right]}{\sum_{i=1}^{n}(O_i-\overline{O})^2} \tag{11}$$

$$\text{RMSE} = \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n} \right]^{0.5}, \quad (12)$$

where D, EF, and RMSE are the index of agreement, modeling efficiency, and root mean square error between the ET_o calculated by the FAO-56 method and six alternative ET_o methods, respectively, O_i is the ET_o calculated by the FAO-56 method, P_i is the ET_o calculated by the six alternative ET_o methods, n is the number of calculated values, and $\overline{O}$ is average ET_o calculated by the FAO-56 method. The units of RMSE, O_i, P_i, and $\overline{O}$ are mm/day for monthly averages of daily ET_o and daily ET_o, and mm/year for total annual ET_o, while D and EF are dimensionless. D varies from 0 to 1.0 and higher values indicate better agreement between the FAO-56 method and other ET_o methods. EF can be negative and have a maximum value of 1.0 and higher EF values indicate better agreement between the FAO-56 method and other ET_o methods, while lower RMSE values indicate better agreement with the FAO-56 method.

RESULTS

Arid Region

Monthly averages of daily ET_o estimated by each method in an arid region (Aksu) are shown in Figure 2. The slope of regression lines ranged from 0.84 to 1.18. In general, the FAO-24 Rd, FAO-24 BC, and 1985 Har methods overpredicted ET_o compared to the FAO-56 method as indicated by slopes of the regression lines >1.0, while 1957 Makk and 1961 Turc underpredicted ET_o. Compared to the other six alternative methods, the slope value between Prs-Tylr ET_o and FAO-56 ET_o of 1.02 indicated that Prs-Tylr ET_o estimates had the lowest difference relative to FAO-56 ET_o estimates. The coefficients of determination, r^2, for each method were 0.99 except for the 1961 Turc method, indicating that these alternative methods had strong relationships with the FAO-56 method. Based on the values of slope and r^2, Prs-Tylr was the best alternative method for estimating monthly averages of daily ET_o in the arid region ($r^2 = 0.99$, slope = 1.02), but Legates and McCabe (1999) reported that r^2 is oversensitive to outliers and is insensitive to additive and proportional differences between estimated and measured values, which implies it is not always reliable to evaluate the "goodness-of-fit" if it only depends on r^2 and slope. Considering this limitation, the index of agreement D, modeling efficiency EF, and root mean square error RMSE were used in addition to evaluate the performance of these simple ET_o methods. The values of D, EF, and RMSE, shown in Table 3, ranged from 0.88 to 0.98, 0.87 to 0.98, and 0.28 to 0.89 mm/day, respectively. The Prs-Tylr method gave the highest D and EF values, and the lowest RMSE, indicating that this method was the best method for calculating monthly averages of daily ET_o in this arid region, followed by 1985 Har method with D value of 0.97, EF value of 0.96, and RMSE value of 0.36 mm/day. Temporal variation of comparison statistics (D, EF, RMSE) on monthly averages of daily ET_o for different methods are presented in Figure 3. The value of D, EF, RMSE for the different methods did not experience obvious change across years except for the 1961 Turc method with the maximum D, EF, RMSE of 0.99, 0.97, 1.10 mm/day and the minimum value of 0.90, 0.67, 0.33 mm/day.

Comparisons of total annual ET_o calculated by the six simple methods *vs.* the FAO-56 method in arid region (Aksu) are presented in Figure 8a. The FAO-24 Rd method yielded the highest total annual ET_o, ranging from 1,054 to 1,376 mm/year during the periods of 1954 to 2013, while the 1957 Makk method estimated the lowest values, ranging from 770 to 959 mm/year. Both FAO-24 BC and 1985 Har methods gave higher total annual ET_o than the FAO-56 method. The long-term average annual ET_o values for Aksu for each method are presented in Table 4, and show that FAO-24 Rd, FAO-24 BC, 1985 Har, and 1961 Turc overpredicted ET_o by 19%, 11%, 8%, and 1%, while Prs-Tylr and 1957 Makk underestimated by 1% and 14%, respectively. The values of D, EF, RMSE, and r^2 compared with the FAO-56 method in the arid region (Aksu) are displayed in Table 5. All the values of r^2 between ET_o calculated by the FAO-56 and estimated by the six alternative methods were 0.99, indicating that the ET_o estimates calculated by six simple methods had strong correlation with the FAO-56 method. Prs-Tylr had the highest D and EF, and the lowest RMSE values ($D = 0.84$, EF = 0.65, RMSE = 38.12 mm/year), while FAO-24 Rd had the lowest D and EF, and the highest RMSE values ($D = 0.32$, EF = −8.38, RMSE = 197.42 mm/year), indicating that Prs-Tylr is the best simple method for calculating total annual ET_o in the arid region followed by 1961 Turc method with D value of 0.81, EF value of 0.53, and RMSE value of 44.03 mm/year.

Comparison of statistical analysis of estimated daily ET_o between the six simple ET_o methods and the FAO-56 method for Aksu are presented in Table 6. The coefficients of determination r^2 for each method were 0.99 except for the 1961 Turc method.

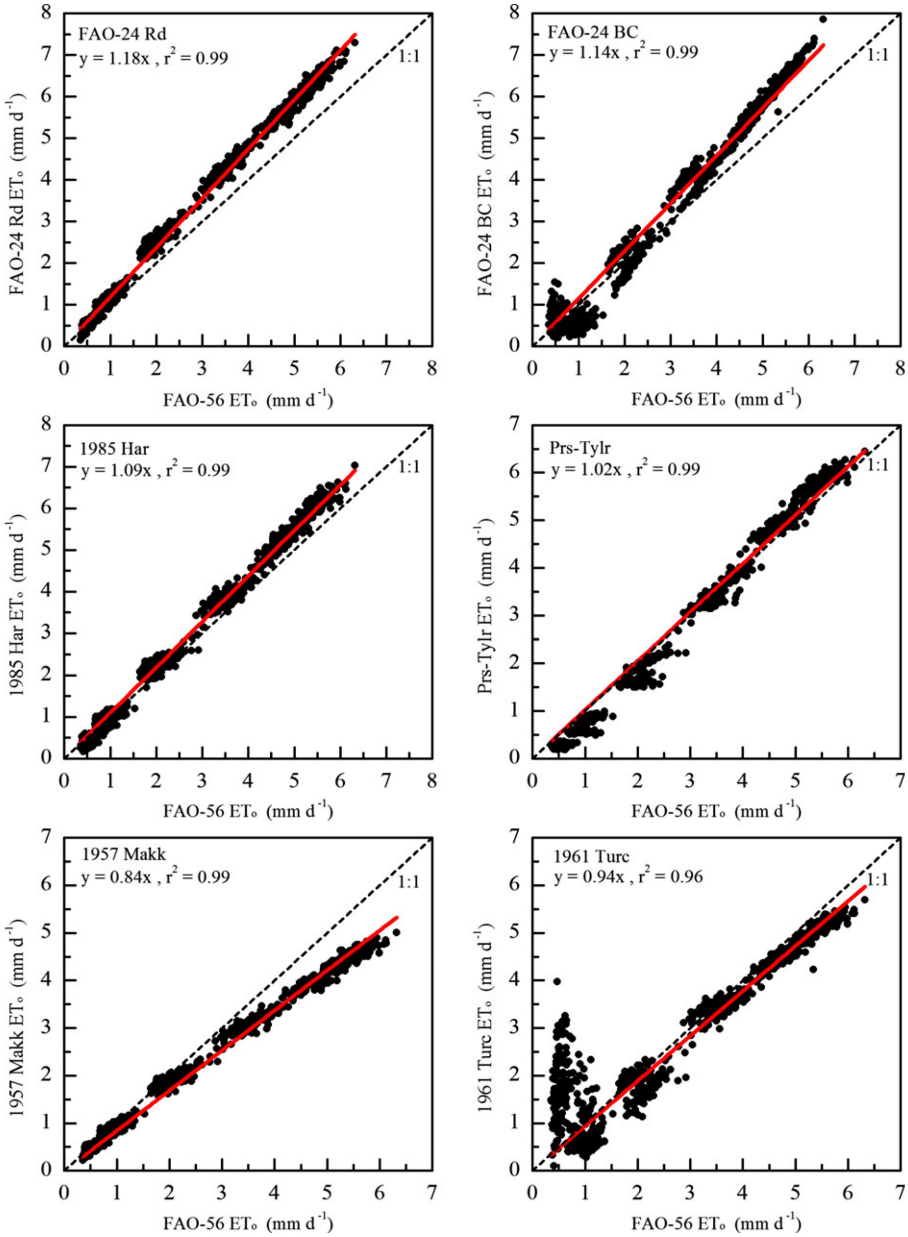

FIGURE 2. Monthly Averages of Daily ET_o Calculated by Six Alternative Methods *vs*. FAO-56 Method in an Arid Region (Aksu).

The Prs-Tylr method gave the highest D and EF values, and the lowest RMSE, indicating that this method was the best method for calculating daily ET_o in this arid region followed by 1985 Har method with D value of 0.96, EF value of 0.94, and RMSE value of 0.48 mm/day.

Semiarid Region

Monthly averages of daily ET_o estimated by each method in a semiarid region (Tongchuan) are shown in Figure 4. The slope of regression lines, ranging from 0.82 to 1.13, indicated that the FAO-24 Rd and 1985 Har methods overestimated ET_o as compared with FAO-56 ET_o, while 1957 Makk and 1961 Turc method underestimated ET_o relative to the FAO-56 method. Although the slope value of FAO-24 BC is 0.99, FAO-24 BC underestimated ET_o at lower ET_o values and overestimated ET_o at higher ET_o values. Except for the FAO-24 BC ET_o estimates, Prs-Tylr ET_o estimates had the lowest difference compared to FAO-56 with a slope value of 1.03. The r^2 value of each method was 0.99 except for the FAO-24 BC and 1961 Turc methods, indicating that all the selected simple alternative methods had strong relationships with the FAO-56 method. Based on the value of r^2 and slope, Prs-Tylr was the best simple method for

TABLE 3. Statistical Comparison of Estimated Monthly Averages of Daily ET_o Calculated by Six Alternative ET_o Methods and FAO-56 Method for Aksu, Tongchuan, and Starkville.

	Aksu			Tongchuan			Starkville		
Methods[1]	***D***[2]	**EF**[3]	**RMSE**[4]	***D***	**EF**	**RMSE**	***D***	**EF**	**RMSE**
FAO-24 Rd	0.88	0.93	0.88	0.94	0.90	0.44	0.82	0.55	1.00
FAO-24 BC	0.89	0.94	0.89	0.95	0.91	0.41	0.88	0.75	0.74
1985 Har	0.97	0.96	0.36	0.98	0.97	0.23	0.90	0.81	0.64
Prs-Tylr	0.98	0.98	0.28	0.97	0.96	0.29	0.90	0.81	0.64
1957 Makk	0.94	0.91	0.56	0.92	0.85	0.55	0.95	0.91	0.43
1961 Turc	0.92	0.87	0.66	0.94	0.91	0.43	0.93	0.89	0.49

[1]Six simple alternative ET_o Estimation Methods: FAO-24 Radiation (FAO-24 Rd), FAO-24 Blaney Criddle (FAO-24 BC), 1985 Hargreaves (1985 Har), Priestley-Taylor (Prs-Tylr), 1957 Makkink (1957 Makk), 1961 Turc (1961 Turc).
[2]*D* is the index of agreement between each alternative ET_o method and FAO-56 method.
[3]EF is the modeling efficiency between each alternative ET_o method and FAO-56 method.
[4]RMSE (mm/day) is the root mean square error between each alternative ET_o method and FAO-56 method.

estimating monthly averages of daily ET_o in the semiarid region (r^2 = 0.99, slope = 1.03). The values of *D*, EF, and RMSE for Tongchuan shown in Table 3 ranged from 0.92 to 0.98, 0.85 to 0.97, and 0.23 to 0.55 mm/day, respectively. The 1985 Har method gave the highest *D* and EF, and the lowest RMSE, indicating that the 1985 Har method is the best method for calculating monthly averages of daily ET_o in the semiarid region followed by the Prs-Tylr method with *D* value of 0.97, EF value of 0.96, and RMSE value of 0.29 mm/day. Temporal variation of comparison statistics (*D*, EF, RMSE) on monthly averages of daily ET_o for different methods are presented in Figure 5. The value of *D*, EF, RMSE for the different methods did not experience obvious change across years except for the 1957 Makk method with the maximum *D*, EF, RMSE of 0.96, 0.89, 0.72 mm/day and the minimum value of 0.93, 0.79, 0.40 mm/day.

Figure 8b shows the annual ET_o during the periods of 1973-1999 in a semiarid region (Tongchuan). The FAO-24 Rd method had the highest total annual ET_o, ranging from 1,009 to 1,264 mm/year, while the 1957 Makk method gave the lowest values, ranging from 767 to 909 mm/year. The 1985 Har method estimated higher total annual ET_o than FAO-56 method, while both FAO-24 BC and 1961 Turc methods estimated lower values. The long-term average annual ET_o values for Tongchuan for each method are presented in Table 4, and show that FAO-24 Rd, 1985 Har, and Prs-Tylr overpredicted ET_o by 12%, 3%, and 1%, while FAO-24 BC, 1957 Makk, and 1961 Turc underestimated by 6%, 17%, and 10%, respectively. The values of *D*, EF, RMSE, and r^2 in comparison with FAO-56 method in the semiarid region (Tongchuan) are presented in Table 5. The values of r^2 suggest similar performance as discussed for the arid region. The Prs-Tylr method had the highest *D* and EF values, and the lowest RMSE values (*D* = 0.91, EF = 0.82, RMSE = 24.80 mm/year), while 1957 Makk gave the lowest *D* and EF, and the highest RMSE values (*D* = 0.40, EF = −7.99, RMSE = 172.98 mm/year). suggesting that Prs-Tylr is the best simple method for calculating total annual ET_o in the semiarid region followed by 1985 Har method with *D* value of 0.83, EF value of 0.59, and RMSE value of 37.15 mm/year.

Comparison of statistical analyses of estimated daily ET_o between the six simple ET_o methods and the FAO-56 method for Tongchuan are presented in Table 6. The coefficients of determination r^2 ranged from 0.95 to 0.99. The 1985 Har method gave the highest *D* and EF values, and the lowest RMSE, indicating that this method was the best method for calculating daily ET_o in this semiarid region followed by the Prs-Tylr method with *D* value of 0.95, EF value of 0.93, and an RMSE value of 0.42 mm/day.

Humid Region

Monthly averages of daily ET_o estimated by each method in a humid region (Starkville) are shown in Figure 6. The slope of regression lines, ranging from 0.95 to 1.26, indicated that all the simple methods except the 1957 Makk method, had higher ET_o than FAO-56. The r^2 values for each method were very high (0.98 or 0.99), indicating that all the selected methods had strong relationships with the FAO-56 method. Based on the value of r^2 and slope, 1957 Makk was the best simple method for estimating monthly averages of daily ET_o in this humid region (r^2 = 0.98, slope = 0.95). The values of *D*, EF, and RMSE for Starkville ranged from 0.82 to 0.95, 0.55 to 0.91, and 0.43 to 1.00 mm/day, respectively (Table 3). The 1957 Makk method had the highest *D* and EF,

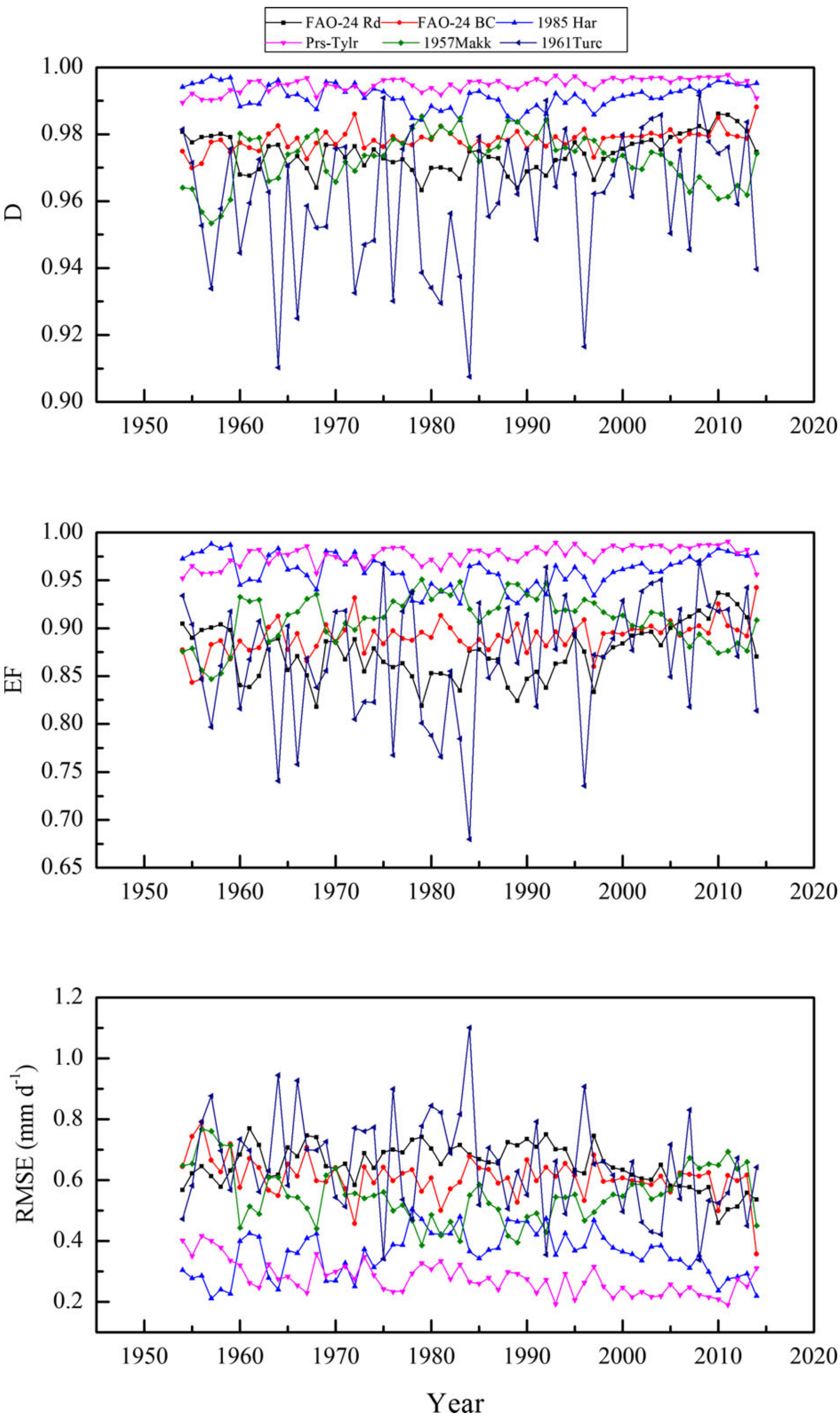

FIGURE 3. Temporal Variation of Comparison Statistics (*D*, EF, root mean square error [RMSE]) on Monthly Averages of Daily ET_o for Different Methods in an Arid Region (Aksu).

and the lowest RMSE values, suggesting that the 1957 Makk is the best method for calculating monthly averages of daily ET_o in the humid region. Temporal variation of comparison statistics (*D*, EF, RMSE) on monthly averages of daily ET_o for different methods are presented in Figure 7. The value of *D*, EF, RMSE for the different methods did not experience obvious change across years except for the FAO-

TABLE 4. Comparison of Statistical Analysis of Estimated Total Annual ET_o between Six Simple ET_o Methods and the FAO-56 Method for Aksu, Tongchuan, and Starkville.

	Aksu				Tongchuan				Starkville			
Methods[1]	D[2]	EF[3]	RMSE[4]	r^2*	D	EF	RMSE	r^2	D	EF	RMSE	r^2
FAO-24 Rd	0.32	−8.38	197.42	0.99	0.49	−3.76	125.88	0.99	0.21	−43.08	355.92	0.99
FAO-24 BC	0.47	−2.43	119.38	0.99	0.67	−0.41	68.44	0.99	0.29	−18.07	234.08	0.99
1985 Har	0.53	−1.08	92.87	0.99	0.83	0.59	37.15	0.99	0.33	−12.88	199.74	0.99
Prs-Tylr	0.84	0.65	38.12	0.99	0.91	0.82	24.80	0.99	0.42	−6.03	142.13	0.99
1957 Makk	0.42	−4.66	153.43	0.99	0.40	−7.99	172.98	0.99	0.75	0.22	47.34	0.99
1961 Turc	0.81	0.53	44.03	0.99	0.51	−3.01	115.49	0.99	0.41	−6.46	146.39	0.99

[1]Six simple alternative ET_o Estimation Methods: FAO-24 Radiation (FAO-24 Rd), FAO-24 Blaney Criddle (FAO-24 BC), 1985 Hargreaves (1985 Har), Priestley-Taylor (Prs-Tylr), 1957 Makkink (1957 Makk), 1961 Turc (1961 Turc).
[2]D is the index of agreement between each alternative ET_o method and FAO-56 method.
[3]EF is the modeling efficiency between each alternative ET_o method and FAO-56 method.
[4]RMSE (mm year^{-1}) is the root mean square error between each alternative ET_o method and FAO-56 method.
*r^2 is the coefficients of determination between each alternative ET_o method and FAO-56 method.

TABLE 5. Long-Term Average Annual ET_o and Precipitation of the *De Facto* Standard and Six Simple Alternative ET_o Estimation Methods for Aksu, Tongchuan, and Starkville.

	Long-Term Average Annual ET_o and Precipitation (mm/year)		
Methods[1]	Aksu[2]	Tongchuan[3]	Starkville[4]
FAO-56	1,060	1,007	1,034
FAO-24 Rd	1,259	1,132	1,389
FAO-24 BC	1,180	942	1,267
1985 Har	1,149	1,042	1,228
Prs-Tylr	1,042	1,015	1,171
1957 Makk	910	835	1,057
1961 Turc	1,066	896	1,175
Precipitation	61	630	1,390

[1]FAO-56 Penman-Monteith (FAO-56), FAO-24 Radiation method (FAO-24 Rd), FAO-24 Blaney Criddle method (FAO-24 BC), 1985 Hargreaves method (1985 Har), Priestley-Taylor method (Prs-Tylr), 1957 Makkink method (1957 Makk), 1961 Turc method (1961 Turc).
[2]Long-term average annual ET_o during the period of 1954-2013 for Aksu.
[3]Long-term average annual ET_o during the period of 1973-1999 for Tongchuan.
[4]Long-term average annual ET_o during the period of 1950-2014 for Starkville.

24 Rd method with the maximum D, EF, RMSE of 0.94, 0.72, 1.22 mm/day and the minimum value of 0.86, 0.35, 0.78 mm/day. Comparisons of total annual ET_o estimated by the six simple methods *vs*. FAO-56 in a humid region (Starkville) are reported in Figure 8c. Except for the 1957 Makk method, other methods had higher total annual ET_o than the FAO-56 method during the period of 1950 to 2014. The long-term average annual ET_o values for Starkville for each method are presented in Table 4, and show that FAO-24 Rd, FAO-24 BC, 1985 Har, Prs-Tylr, 1957 Makk, and 1961 Turc overpredicted ET_o by 34, 22, 18, 13, 2, and 13%, respectively. The values of D, EF, RMSE, and r^2 shown in Table 5 indicate that the 1957 Makk was the best simple method for calculating total annual ET_o in the humid region (D = 0.75, EF = 0.22, RMSE = 47.34 mm/year). Comparison of statistical analysis of estimated daily ET_o between six the simple ET_o methods and the FAO-56 method for Starkville are presented in Table 6. The coefficients of determination r^2 ranged from 0.97 to 0.99. The 1957 Makk method gave the highest D and EF values, and the lowest RMSE, indicating that this method was the best method for calculating daily ET_o in this humid region.

DISCUSSION

Seven ET_o methods, the *de facto* standard FAO-56, and six alternative methods, FAO-24 Rd, FAO-24 BC, 1985 Har, Prs-Tylr, 1957 Makk, and 1961 Turc were used to calculate monthly averages of daily ET_o, total annual ET_o, and daily ET_o at Aksu in an arid region, Tongchuan in a semiarid region, and Starkville in a humid region. Comparisons between the FAO-56 method and the six simple methods were made to identify which method could be a substitution for the FAO-56 method if full weather datasets were not available at these three locations.

Calculating monthly averages of daily ET_o can reduce the variability in ET_o estimates from one day to the next. Although our results show similar magnitude of RMSE for monthly averages of daily ET_o (0.23-1 mm/day) and daily ET_o (0.30-1.06 mm/day) across all the simple ET_o methods and these three sites, the RMSE for monthly averages of daily ET_o

TABLE 6. Comparison of Statistical Analysis of Estimated Daily ET_o between Six Simple ET_o Methods and the FAO-56 Method for Aksu, Tongchuan, and Starkville.

	Aksu				Tongchuan				Starkville			
Methods[1]	D[2]	**EF**[3]	**RMSE**[4]	r^{2*}	D	**EF**	**RMSE**	r^2	D	**EF**	**RMSE**	r^2
FAO-24 Rd	0.92	0.86	0.72	0.99	0.94	0.90	0.51	0.99	0.58	0.57	1.06	0.97
FAO-24 BC	0.93	0.87	0.70	0.99	0.94	0.90	0.52	0.97	0.69	0.73	0.84	0.98
1985 Har	0.96	0.94	0.48	0.99	0.97	0.97	0.30	0.99	0.75	0.82	0.69	0.99
Prs-Tylr	0.97	0.96	0.41	0.99	0.95	0.93	0.42	0.98	0.77	0.83	0.67	0.98
1957 Makk	0.93	0.89	0.64	0.99	0.92	0.86	0.61	0.99	0.86	0.91	0.49	0.97
1961 Turc	0.86	0.74	1.00	0.96	0.89	0.81	0.71	0.95	0.79	0.86	0.60	0.97

[1]Six simple alternative ET_o Estimation Methods: FAO-24 Radiation (FAO-24 Rd), FAO-24 Blaney Criddle (FAO-24 BC), 1985 Hargreaves (1985 Har), Priestley-Taylor (Prs-Tylr), 1957 Makkink (1957 Makk), 1961 Turc (1961 Turc).
[2]D is the index of agreement between each alternative ET_o method and FAO-56 method.
[3]EF is the modeling efficiency between each alternative ET_o method and FAO-56 method.
[4]RMSE (mm/day) is the root mean square error between each alternative ET_o method and FAO-56 method.
*r^2 is the coefficients of determination between each alternative ET_o method and FAO-56 method.

for each method is much lower than the daily ET_o have. For example, RMSE for monthly averages of daily ET_o for FAO-24 Rd is 0.88 in Aksu, while the RMSE for daily ET_o is 0.72 (Tables 3 and 6). Figure 2 also showed that 1961 Turc overestimates ET_o at lower FAO-56 ET_o values in arid region (Aksu) which may be caused by the wind speed. Trajkovic and Stojnic (2007) reported that the performance of the 1961 Turc method depends on the wind speed and this method overpredicted FAO-56 PM ET_o estimates at windless locations. Table 7 shows the average wind speed for each month in Aksu and the number of points which the FAO-56 PM ET_o value ranged from 0 to 1 mm/day and 1961 Turc ET_o >1 mm/day. It revealed that 1961 Turc overestimated ET_o in January, February, and December when the average monthly wind speed is lowest than any other months.

Our results suggested that the 1985 Har method and Prs-Tylr method were superior to other simple methods for calculating the daily ET_o, monthly averages of daily ET_o, and total annual ET_o in an arid region (Aksu) and semiarid region (Tongchuan). Since Hargreaves and Samani (1985) established the 1985 Har method, many comparison studies have confirmed that this method can be used to calculate ET_o if the full weather datasets were not available in arid and semiarid regions. George *et al.* (2002) tested eight ET_o estimation methods in Davis, California (an arid region) and found that, although the 1985 Har method underpredicted ET_o by 1% compared to the FAO-56 method, it ranked in the first place among all the simple methods to calculate the daily ET_o with SEE (standard error) value of 0.97 mm/day and r^2 value of 0.85. Martínez-Cob and Tejero-Juste (2004) also made comparison studies between the 1985 Har method and measured lysimeter ET_o at a semiarid site in Spain during the period of May 1997 to October 2000, and the results suggested that the 1985 Har method could be used to estimate monthly ET_o under the semiarid condition, with an RMSE value of 0.49 mm/day and r^2 value of 0.95. Lu *et al.* (2005) contrasted six ET_o methods with measured ET_o and calculated the long-term annual ET_o over 36 forested watersheds in the southeastern U.S. They found that the 1985 Har method had the lowest r^2 values of 0.57 compared with other methods, and concluded that the 1985 Har method may not be approporiate in the humid southeastern U.S. since it was originally developed in arid areas. Hargreaves and Allen (2003) reported that the site aridity can affect the performance of 1985 Har method. As compared to other simple method, 1985 Har has less aridity-bias impact, especially in the arid and semiarid region. Although our results indicated that the Prs-Tylr method can be applied in an arid region, others have reported varying results, using this empirical method in different climate regions. Nandagiri and Kovoor (2006) evaluated the performance of several ET_o methods in humid regions of India and showed that the Prs-Tylr method was reasonably good in the wetter climates, but poor in the drier climates, while Tabari (2009) reported that Prs-Tylr was poor in estimating ET_o for all climates in Iran compared to other simple methods. The reason for this can be explained by the condition of advection in a certain place. Daneshkar and Tajrishy (2008) reported that Prs-Tylr method would give good performance in lower advection conditions which is a main restriction used in arid region. Although Aksu is an arid region in the northwest of China, Zhang (2011) revealed that advection in Aksu is at lower levels which account for the availability of Prs-Tylr method in Aksu. Priestley-Taylor (1972) suggested that the α value of 1.26 can be used to calculate ET_o,

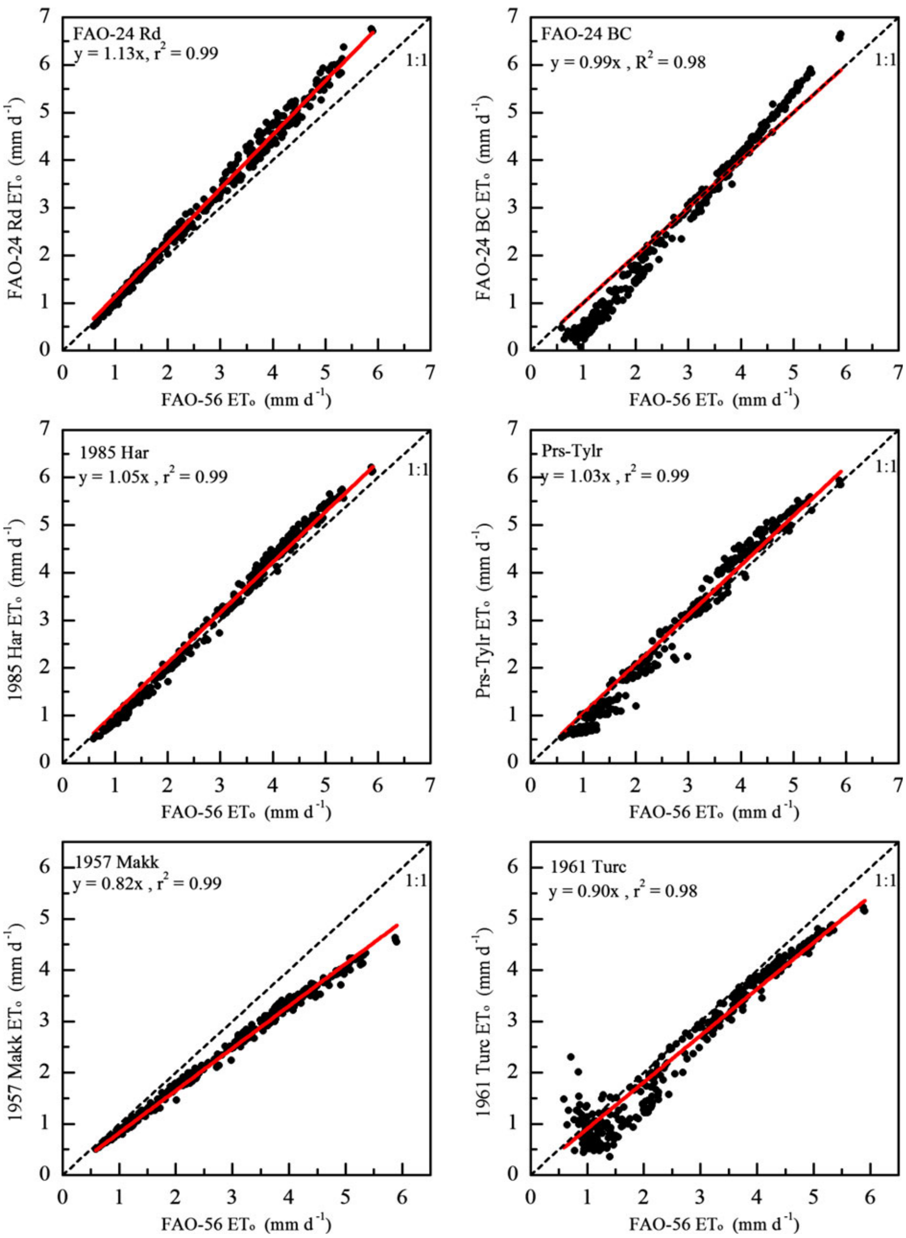

FIGURE 4. Monthly Averages of Daily ET_o Calculated by Six Alternative Methods *vs*. FAO-56 Method in a Semiarid Region (Tongchuan).

while Daneshkar and Tajrishy (2008) reported that the range of α value can be from 0.77 to 2.32. Furthermore, Singh and Taillefer (1986) reported that the performance of the Prs-Tylr method was influenced by the empirically derived constant α which could differ greatly according to surfaces and surface wetness, and Lhomme (1997) also reported that the α value should be higher in arid regions and lower in humid regions. For example, Barton (1979) found an α value of 1.04 to be acceptable in wet regions, however, Jensen *et al.* (1990) recommended higher values of α, ranging up to 1.74 as appropriate in arid regions. The α value is 1.26 for both our articles and Nandagiri and Kovoor's paper (2006), this α value of 1.26 ranked in the middle of that range which was reported by Daneshkar and Tajrishy (2008). As a result, the Prs-Tylr method would produce different results in arid and humid regions it should be advisable to compare estimates from the Prs-Tylr method and FAO-56 method at a specific site before direct use, even though Prs-Tylr has been shown to work well in previous studies. Our results also suggest that the 1957 Makk method is the best method for calculating monthly averages of daily ET_o, total annual ET_o, and daily ET_o in a humid region. In order to identify a suitable alternative to the FAO-56 method for

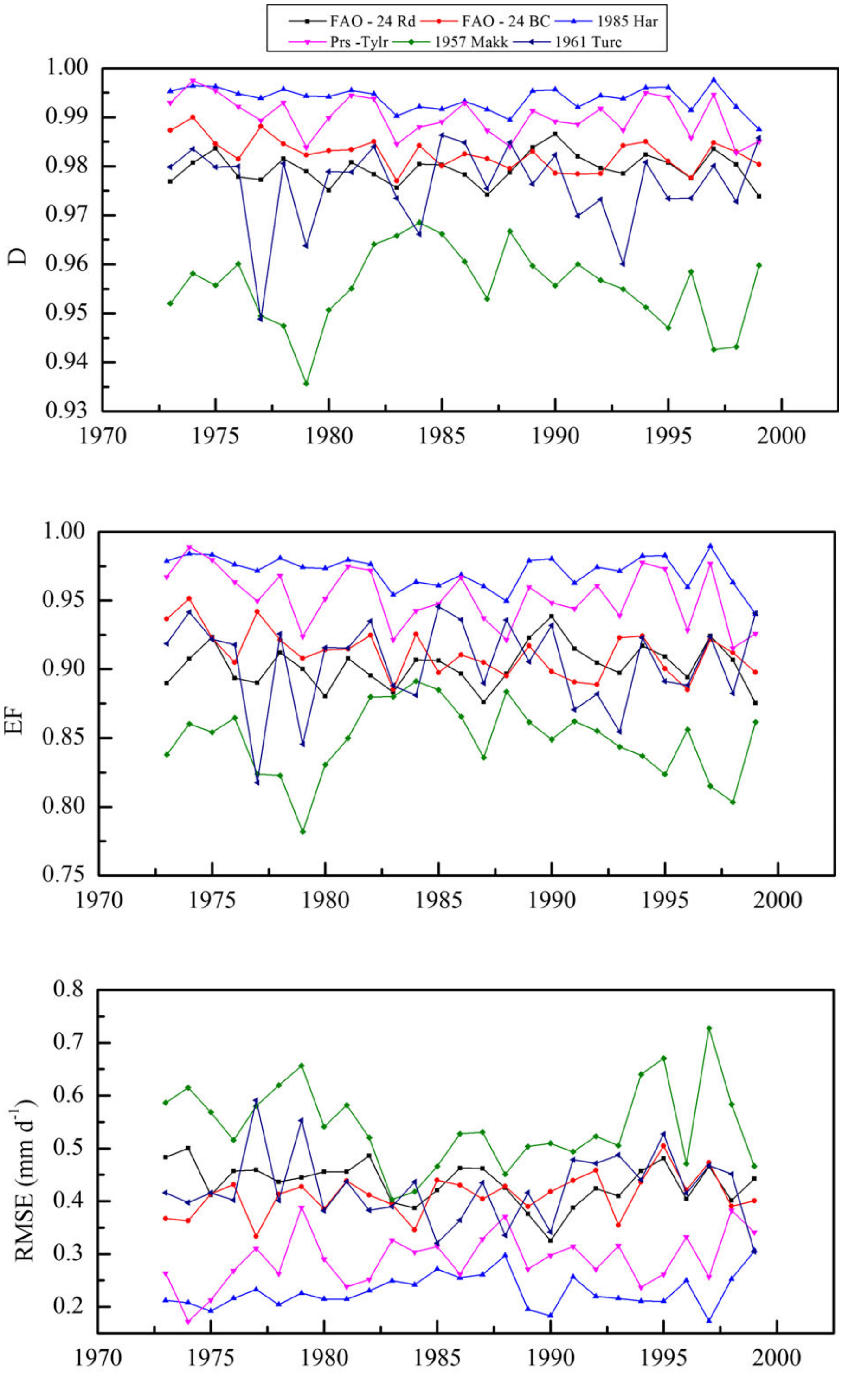

FIGURE 5. Temporal Variation of Comparison Statistics (D, EF, root mean square error [RMSE]) on Monthly Averages of Daily ET_o for Different Methods at a Semiarid Region (Tongchuan).

calculating reference evapotranspiration in northeast India, which falls under the humid subtropical ecosystem, Pandey *et al.* (2016) compared 17 different ET_o methods, and found that the 1957 Makk was one of the 5 best methods in calculating mean daily ET_o with a D value of 0.85, and r^2 of 0.84.

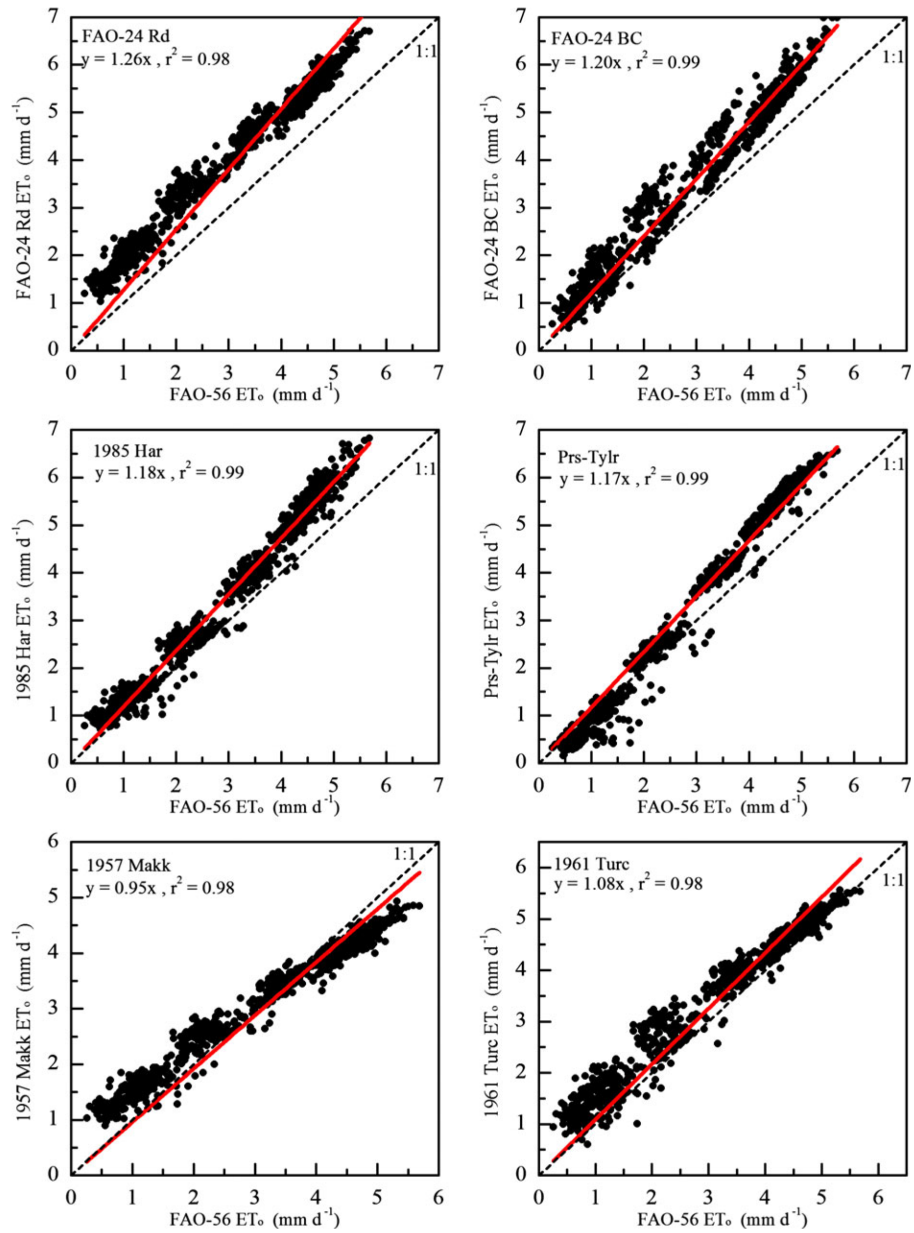

FIGURE 6. Monthly Averages of Daily ET_o Calculated by Six Alternative Methods *vs*. FAO-56 Method in a Humid Region (Starkville).

Some simple ET_o methods agreed well with FAO-56 method, while others did not, even in the same region. In the arid (Aksu) and semiarid region (Tongchuan), 1985 Har and Prs-Tylr agreed well with FAO-56–better than other methods, while in the humid region, 1957 Makk and 1961 Turc methods produced better results (Figures 2, 4, and 6 and Table 3). The 1961 Turc method needs relative humidity data to calculate ET_o according to Jensen *et al*. (1990), while the 1985 Har and Prs-Tylr need temperature data, but the relative humidity data was not available in arid region (Aksu) and semiarid region (Tongchuan), and the relative humidity was available in humid region (Starkville). Furthermore, these climatic parameters were estimated by the RefET (Reference Evapotranspiration Calculator) software (Allen, 2013), which might have induced some error. As a result, the 1985 Har and Prs-Tylr agreed well with FAO-56 than 1961 Turc method did in arid and semiarid regions but it was not true in the humid region. FAO-24 Radiation did not agree well with FAO-56 method under arid and humid conditions compared to semiarid region due to the fact that the part of the missing wind speed data were estimated in arid and humid regions but observed in semiarid region. The FAO-24 Blaney-

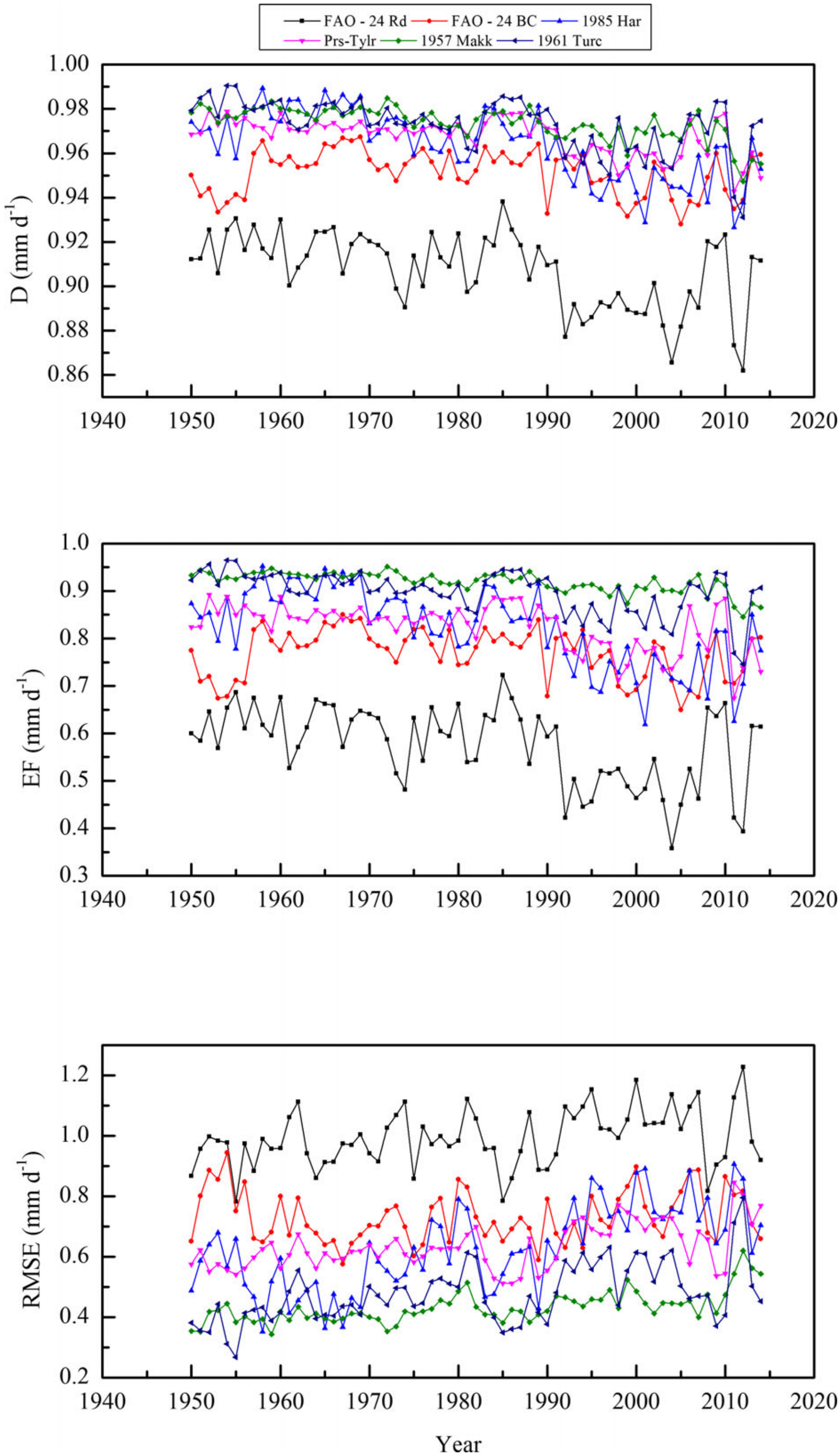

FIGURE 7. Monthly Averages of Daily ET_o Temporal Variation of D, EF, Root Mean Square Error (RMSE) for Different ET_o Methods at a Humid Region (Starkville).

Criddle method also did not agree well with FAO-56 method, this is due to the fact that FAO-24 Blaney-Criddle would provide good ET_o estimates if 24-h measurements of wind are available. However, our wind speed data is daily time step (Allen and Pruitt, 1986).

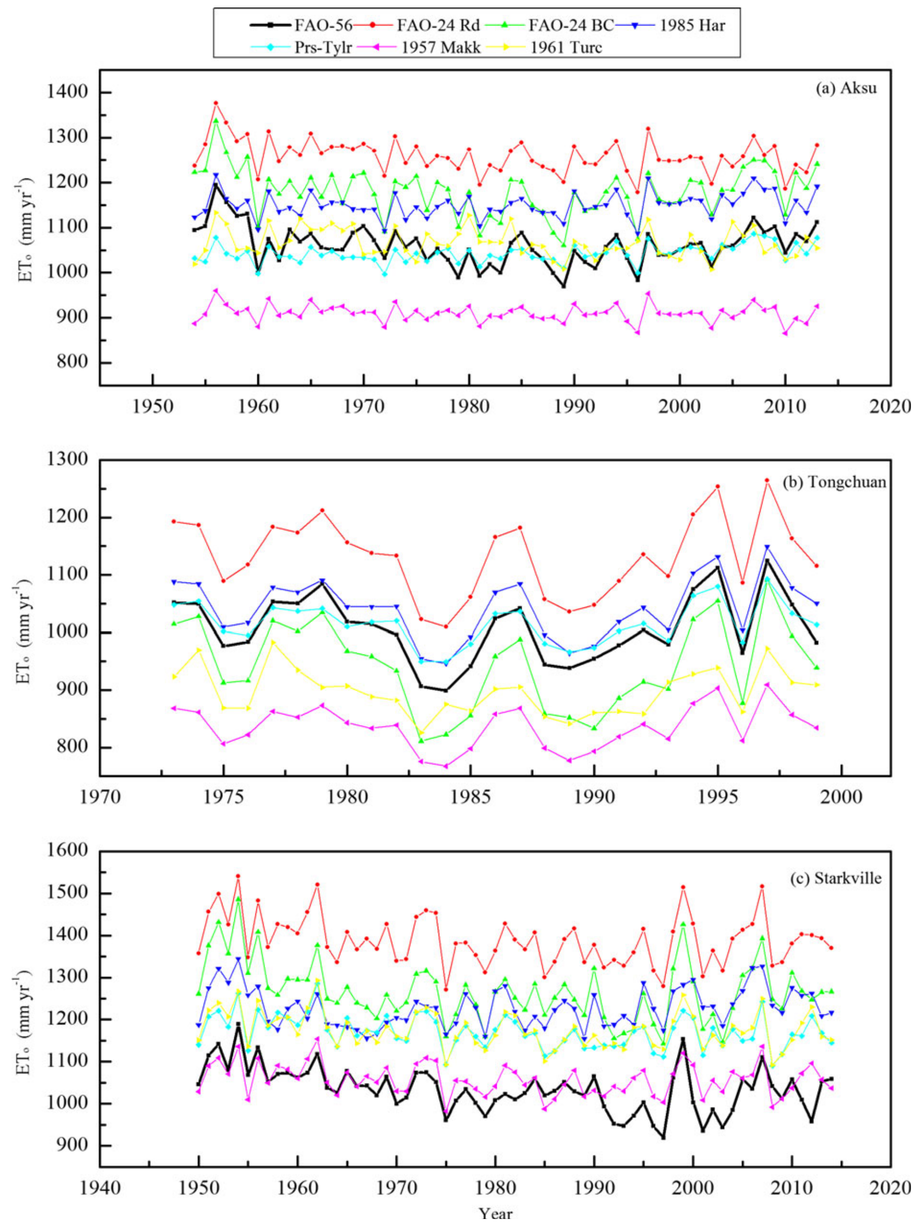

FIGURE 8. Comparison of Total Annual ET_o by Six Alternative Simple Methods *vs*. FAO-56 Method at an Arid Region (Aksu), a Semiarid Region (Tongchuan), and a Humid Region (Starkville).

CONCLUSIONS

In order to select simpler ET_o calculation methods for different climatic regions, the FAO-56 Penman-Monteith and six alternative ET_o methods were compared based on monthly averages of daily ET_o, total annual ET_o, and daily ET_o in Aksu (arid region), Tongchuan (semiarid region), and Starkville (humid region). The Priestley-Taylor and 1985 Hargreaves methods can be used as substitutes for the FAO-56 method for calculating monthly averages of daily ET_o, total annual ET_o, and daily ET_o in both arid and semiarid regions, while in the humid region, the 1957 Makkink method can be used. The results suggest that different methods perform better in certain climates to calculate ET_o, and that these simple alternative methods can be used when the full weather datasets required by the FAO-56 Penman-Monteith method are not available. Results also show that caution should be used when applying these methods at a specific site since the performance of the methods may differ greatly. It is necessary to check the performance of the simpler

TABLE 7. Average Wind Speed for Each Month in Aksu and the Number of Points Which the FAO-56 PM ET_o Value Ranged from 0 to 1 mm/day and 1961 Turc ETo >1 mm/day.

Month	Number of Points	Average Wind Speed (m/s)
1	58	1.1
2	18	1.2
3	0	1.7
4	0	2.1
5	0	2.1
6	0	2.2
7	0	1.9
8	0	1.7
9	0	1.5
10	0	1.3
11	0	1.2
12	44	1.1

methods which were tested somewhere else by making comparison with FAO-56 method even if the climate of a selected area is similar to that tested in previous studies.

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