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Reference evapotranspiration models using different time scales in the Jaboticabal region of São Paulo, Brazil

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ABSTRACT. The aim of this paper is to compare 18 reference evapotranspiration models to the standard Penman-Monteith model in the Jaboticabal, São Paulo, region for the following time scales: daily, 5-day, 15-day and seasonal. A total of 5 years of daily meteorological data was used for the following analyses: accuracy (mean absolute percentage error, Mape), precision (R^2) and tendency (bias) (systematic error, SE). The results were also compared at the 95% probability level with Tukey's test. The Priestley-Taylor (1972) method was the most accurate for all time scales, the Tanner-Pelton (1960) method was the most accurate in the winter, and the Thornthwaite (1948) method was the most accurate of the methods that only used temperature data in the equations.

Keywords: model, penman-monteith, Priestley and Taylor, Tanner and Pelton, Thornthwaite.

Modelos de evapotranspiração de referência em diferentes escalas de tempo para a região de Jaboticabal, Estado de São Paulo, Brasil

RESUMO. Este trabalho objetivou comparar 18 métodos para a estimativa da Evapotranspiração de referência (ETo) com o método padrão Penman-Monteith, nas escalas diária, quinquidial, quinzenal e por estações do ano, para a região de Jaboticabal, Estado de São Paulo. Jaboticabal é a região mais importante para produção de amendoim e cana-de-açúcar no estado de São Paulo. Uma série de 5 anos de dados foi utilizada e as análises foram feitas em termos de acurácia pelo erro percentual absoluto médio (Mape), de tendência pelo erro sistemático (ES) e precisão pelo R^2. Os resultados foram analisados também no nível de 95% de probabilidade com o teste de Tukey para comparação de médias. Como resultado observou-se que o método de Priestley e Taylor (1972) foi o mais acurado em todas as escalas de tempo, o método de Tanner e Pelton (1960) foi o mais acurado no inverno e o método de Thornthwaite (1948) foi o mais acurado dentre aqueles que só utilizam dados de temperatura em suas equações.

Palavras-chave: modelo, Penman-Monteith, Priestley e Taylor, Tanner e Pelton, Thornthwaite.

Introduction

Accurate knowledge of crop water requirements is important for correct water management, particularly regarding the current discussion of the optimal utilization of water resources. In Brazil, most users of irrigated agriculture still apply inappropriate strategies to the water management of irrigated crops, such as weather monitoring to estimate reference evapotranspiration (ETo) (MENDONÇA; DANTAS, 2010; SOUZA et al., 2010). Because climatic elements influence variation in ETo, establishing reliable and practical methods to estimate ETo in distinct regions is of great importance. The Jaboticabal region, in the Middle North of the State of São Paulo, is of considerable agricultural significance because it is the State's largest peanut and sugarcane producer.

There are several methods for determining ETo: for example, methods that only require temperature data, such as the Thornthwaite (1948), Camargo (1971) and Hargreaves and Samani (1985) methods; methods that use temperature and relative humidity, such as the Benevidez and Lopez (1970), Jobson (1980), Linacre (1977) and Romanenko (1961) methods; methods that also use insolation and photoperiod, such as the Blaney-Criddle (1950), Kharrufa (1985) and Hamon (1961) methods; methods that use global radiation, radiation balance and/or soil heat flux, such as the methods described by Penman and Monteith (apud ALLEN et al., 1998), Jensen and Haise (1963), Tanner and Pelton (1960), Turc (1961), Penman (1948), Makkink (1957), Priestley and Taylor (1972), and Radiation; and the methods based on water evaporation, such as the Class A pan method (DOORENBOS; PRUITT, 1977). Selection of a method depends on the required accuracy and on the available meteorological data (MENDONÇA et al., 2003).

Numerous studies have tested the accuracy of different ETo models. For example, in Mossoró, RN (northeastern Brazil), the analyses by Cavalcanti Júnior et al. (2011) of ETo on a daily scale indicated better performance using the Penman, Radiation and Blaney-Criddle methods. In contrast, in the northern region of the country, in Boa Vista (Roraima State), the best results were obtained on a monthly scale with the Blaney and Criddle and Class A pan methods. In the central western region, in Aquidauana (Mato Grosso do Sul State), Oliveira et al. (2011) observed acceptable accuracy results from the Hargreaves-Samani and Camargo methods. In the South (Santa Maria, Rio Grande do Sul State), Medeiros (1998) concluded that on a daily scale, the Penman, Camargo and Tanner and Pelton methods were better. Finally, in the Southeast, in Serra da Mantiqueira (Minas Gerais State), Pereira et al. (2009) concluded that the Jensen and Haise, Penman, Radiation and Blaney-Criddle methods had the best accuracy. Syperreck et al. (2008) showed that the performance of the Thornthwaite, Camargo and Hargreaves-Samani methods were similar to the Penman-Monteith equation for daily scale for Palotina, Paraná region. The differences among the ETo models are caused by the regional climate, as was noted by Camargo and Camargo (2000) in their analyses of several models for ETo calculation for different regions of the State of São Paulo.

Using a monthly scale for Jacupiranga, São Paulo State, Borges and Mendiondo (2007) observed that the methods of Hargreaves and of Camargo are more reliable than other methods. In contrast, Camargo and Sentelhas (1997) evaluated twenty methods for estimating ETo, also on a monthly scale, in the following regions in São Paulo: Campinas, Pindamonhangaba and Ribeirão Preto. The researchers concluded that the methods of Camargo, Thornthwaite, Thornthwaite with heat index 'T' and Priestley-Taylor resulted in the best estimates when compared to the estimate from lysimetric measurements.

In the Jaboticabal, SP region, Oliveira and Volpe (2003) compared daily data to determine ETo using the Penman and Monteith, Penman and Class A pan methods. The researchers observed differences between the Penman and Penman-Monteith methods, independent of season (winter or summer). These differences indicate that both methods underestimated the values compared to those obtained using the Class A pan method.

Testing ETo models, particularly with different time scales, is important for minimizing the water usage in irrigation systems. The availability of meteorological data is one of the main factors considered by agricultural companies when choosing a model. Accurate models that require less spending on meteorological sensors are always required. Therefore, the aim of this paper is to compare 18 methods of estimating ETo to the standard Penman-Monteith method on daily, 5-day, 15-day and seasonal scales in the Jaboticabal, SP region.

Material and methods

For this project, daily meteorological data from January 2005 to December 2010 were used from the Agroclimatological Station of the Department of Exact Sciences from University of the State of São Paulo (Unesp), Faculty of Agronomical and Veterinary Sciences (Fcav), Campus of Jaboticabal (Latitude 21° 14' 05" S; Longitude 48° 17' 09" W; Altitude 615,01 m). The regional climate is classified as $B_1rA'a'$ using Thornthwaite's method (1948).

The data were obtained from a conventional meteorological station (EMC), which provides insolation, class A pan evaporation and wet-bulb temperature data. An automatic meteorological station (EMA) also provided the following data: global solar radiation; mean, maximum and minimum air temperature; relative humidity; soil heat flux; net radiation and wind velocity at a height of 2 m.

The following equipment was used in the EMC station: insolation: heliograph (R. Fuess, Campbell and Stockes); wet-bulb temperature: wet-bulb thermometer (R. Fuess – glass mercury thermometer); and evaporation: evaporation pan (Class A pan). The EMA station had the following equipment: Datalogger system: Micrologger CR23X (Campbell Scientific, Inc.); air temperature and relative air humidity: CS500 Temperature sensor and Relative Humidity Probe (Campbell Scientific, Inc.); wind velocity: Anemometer 014A Met One Wind Speed Sensor placed 2 m high; global solar radiation: LI-200SZ LI-COR pyranometer; net radiation: NR-LITE (Campbell Scientific, Inc.); soil heat flux: fluxmeter, HFT3 Soil Heat Flux Plate (Campbell Scientific, Inc.).

Eighteen models were tested to determine the ETo and were compared to the Penman – Monteith method:

a) Penman and Monteith (ALLEN et al., 1998) (PM):

$$ETo = \frac{0{,}408 \times s \times (Rn - G) + \frac{\gamma \times 900 \times U_2 \times (es - ea)}{T + 273}}{s + \gamma \times (1 + 0{,}34 \times U_2)}$$

$$s = \frac{4098 \times es}{(T + 273)^2} \qquad ea = \frac{UR \times es}{100} \qquad es = 0{,}6108 \times e^{\frac{17{,}27 \times T}{237{,}3 + T}}$$

b) Camargo (1971) (apud PEREIRA et al., 2002) (CAM):

$$ETo = 0{,}01 \times \frac{Qo}{2{,}45} \times T \times ND$$

$$hn = \arccos\,(-\tan\phi \times \tan\delta)$$

$$Qo = 37{,}6 \times DR \times \left[\left(\frac{\pi}{180}\right) \times hn \times sen\,\phi \times sen\,\delta + \cos\phi \times \cos\delta \times sen\,hn\right]$$

$$DR = 1 + 0{,}33 \times \cos\left(360 \times \frac{NDA}{365}\right)$$

$$\delta = 23{,}45 \times sen\left[\left(\frac{360}{365}\right) \times NDA \times 80\right]$$

c) Class A pan (DOORENBOS; PRUITT, 1977) (TCA):

$$Kp = 0{,}482 + 0{,}024 \times \ln(B) - 0{,}000376 \times U_2 \times 86{,}4 + 0{,}0045 \times UR$$

$$ETo = Kp \times ECA$$

d) Priestley and Taylor (1972) (apud MEDEIROS, 1998) (PT):

$$ETo = 1{,}26 \times W \times \left[\frac{(Rn - G)}{2{,}45}\right]$$

$$\begin{cases} W = 0{,}407 + 0{,}0145 * Tu, \text{ para } 0°C < T \le 16°C \\ W = 0{,}483 + 0{,}01 * Tu, \text{ para } 16°C < T \le 32°C \end{cases}$$

e) Benevides and Lopez (1970) (apud MEDEIROS, 1998) (BL):

$$ETo = 1{,}21 \times 10^{\frac{7{,}5 \times T}{237{,}5 + T}} \times (1 - 0{,}01 \times UR) + 0{,}21 \times T - 2{,}3$$

f) Jensen and Haise (1963) (apud MEDEIROS, 1998) (JH):

$$ETo = \frac{Qg}{2{,}45} \times (0{,}078 + 0{,}052 \times T)$$

g) Tanner and Pelton (1960) (apud MEDEIROS, 1998) (TP):

$$ETo = 1{,}12 \times \left[\left(\frac{Rn \times 100}{4{,}18}\right) \Big/ 59\right] - 0{,}11$$

h) Turc (1961) (apud MEDEIROS, 1998) (TUR):

$$ETo = 0{,}013 \times \left(\frac{T\max}{T\max + 15}\right) \times \left(\frac{Qg \times 100}{4{,}18} + 50\right)$$

i) Hargreaves and Samani (1985) (apud MEDEIROS, 1998) (HS):

$$ETo = 0{,}0023 \times \frac{Qo}{2{,}45} \times (T\max - T\min)^{0{,}5} \times (T + 17{,}8)$$

j) Jobson (apud BOWIE et al., 1985) (JOB):

$$ETo = 3{,}01 + 1{,}13 \times U_2 \times (es - ea)$$

k) Hamon (1961) (apud XU; SINGH, 2001) (HAM):

$$ETo = 0{,}55 \times \left(\frac{N}{12}\right)^2 \times \left(\frac{4{,}95 \times e^{0{,}062 \times T}}{100}\right) \times 25{,}4$$

$$N = \frac{2 \times hn}{15}$$

l) Makkink (1957) (apud MEDEIROS, 2008) (MAK):

$$ETo = 0{,}61 \times W \times \left(\frac{Qg}{2{,}45}\right) - 0{,}12$$

m) Linacre (1977) (apud PEREIRA et al, 1997) (LIN):

$$ETo = \frac{\frac{500 \times Tm}{(100 - \phi)} + 15 \times (T - To)}{80 - T} \qquad To = \frac{237{,}3 \times \log\left(\frac{ea}{0{,}611}\right)}{7{,}5 - \log\left(\frac{ea}{0{,}611}\right)}$$

$$Tm = T + 0{,}006 \times h$$

n) Romanenko (1961) (apud XU; SINGH, 2001) (ROM):

$$ETo = 0{,}0018 \times (25 + T)^2 \times (100 - UR)$$

o) Kharrufa (1985) (apud XU; SINGH, 2001) (KHA):

$$ETo = 0{,}34 \times p \times (T^{1{,}3})$$

p) Penman (1948) (apud PEREIRA et al., 1997) (PEN):

$$ETo = \frac{[W \times Rn + (1-W) \times \lambda Ea]}{2,45}$$

$$\lambda Ea = 6,43 \times (1 + 0,526 \times U_2) \times (es - ea)$$

q) Radiation (DOORENBOS; PRUITT, 1977) (RAD):

$$ETo = co + cl \times W \times \left(\frac{Qg}{2,45}\right)$$

$$co = -0,3 \quad al = -1,275*10^{-3} \quad a3 = -2,033*10^{-4}$$

$$ao = 1,0656 \quad a2 = 4,4953*10^{-2} \quad a4 = -3,1508*10^{-5} \quad a5 = -1,1026*10^{-3}$$

$$cl = a0 + a1 \times UR + a2 \times U_2 + a3 \times UR \times u_2 + a4 \times UR^2 + a5 \times U_2^2$$

r) Blaney and Criddle (1950) (apud PEREIRA et al., 1997) (BC):

$$ET_0 = a + b \times p \times (0,46 \times T + 8,13)$$

$$a = 0,043 \times UR\min \times \left(\frac{n}{N}\right) \times 1,41$$

$$b = ao + a1 \times UR\min + a2 \times \frac{n}{N} + a3 \times U_2 + a4 \times UR\min \times \frac{n}{N} + a5 \times UR\min \times U_2$$

$$ao = 0,81917 \quad a2 = 1,0705 \quad a4 = -5,9684*10^{-3}$$

$$al = -4,0922*10^{-3} \quad a3 = 6,5649*10^{-2} \quad a5 = -5,967*10^{-4}$$

s) Thornthwaite (1948) (apud PEREIRA et al., 2002) (THO):

$$ETo = ETp \times Cor \qquad Cor = \left(\frac{ND}{30}\right) \times \left(\frac{N}{12}\right) \qquad I = (0,2 \times Tn)^{1,514}$$

$$\begin{cases} ETp = -415,85 + 23,24 \times T - 0,43 \times T^2 & \text{para } T \geq 26,5°C \\ ETp = 16 \times \left(10 \times \frac{T}{I}\right)^a & \text{para } 0°C \leq T < 26,5°C \end{cases}$$

$$a = 6,75 \times 10^{-7} \times I^3 \times (-7,71 \times 10^{-5}) \times I^2 + 1,7912 \times 10^{-2} \times I + 0,49239$$

where:

Rn is the radiation balance (MJ m^{-2} day^{-1}), G is the soil heat flux (MJ m^{-2} day^{-1}), UR is the relative air humidity (%), U_2 is the wind velocity (m s^{-1}) at a height of 2 m, γ is the psychrometric constant equal to 0.063 kPa °C^{-1}, T is the mean air temperature (°C), es is the humidity saturation pressure (kPa), ea is the humidity partial pressure (kPa), s is the humidity pressure curve decline at the air temperature (kPa °C^{-1}), Qo is the extraterrestrial solar irradiance (MJ m^{-2} day^{-1}), ND is the number of days, hn is the hour at which sunrise occurs, ϕ is the latitude (°), δ is the solar declination (°), NDA is the Julian day, DR is the relative Earth-Sun distance, B is the class A pan fetch distance (10 m), ECA is the daily evaporation of the Class A pan (mm d^{-1}), W is the weight factor dependent on the temperature and the psychrometric coefficient (°C), Tu is the wet-bulb temperature (°C), Qg is the global solar irradiation (MJ m^{-2} d^{-1}), Tmax is the daily maximum temperature (°C), Tmin is the daily minimum temperature (°C), N is the photoperiod (hours), n is the insolation (hour), To is the dew-point temperature (°C), h is the altitude (m), Tm is the mean temperature at sea level (°C), λEa is the air evaporating power (MJ m^{-2} day^{-1}), Tn is the mean monthly temperature (°C), I is the monthly heat index (°C), a is an exponential function of the index I, p is the index provided by Doorenbos and Pruitt (1977), and co, ao, a1, a2, a3, a4, and a5 are adjustment coefficients.

The following statistical analyses were performed to evaluate the accuracy of the methods: mean absolute percentage error (Mape), precision as measured by the coefficient of determination (R^2), and tendency as measured by the systematic error (SE). The Mape and SE were calculated with the following equations:

$$MAPE = \frac{\sum_{i=1}^{N}\left(\left|\frac{Yest_i - Yobs_i}{Yobs_i}\right| \times 100\right)}{N} \qquad SE = \sqrt{\frac{\sum_{i=1}^{N}(Yobs_i - \overline{Y}est)^2}{N}}$$

where:

Yobs is the observed data using different models, Yest is the ETo estimated using the Penman-Monteith method, and $\overline{Y}est$ is the average estimation of Yobs. Utilizing a 10-day moving average to detect mean differences, Tukey's test was also applied at 95% probability to evaluate the Mape and SE results.

Results and discussion

The estimated yearly data from all ETo models was compared with the data from the standard Penman-Monteith method for analysis on a daily scale. The most accurate model was PT, followed by PEN and MAK because these models showed lower values of Mape (15.4, 15.8 and 17.8% for the PT, PEN, and MAK methods, respectively), lower tendencies (1.30 mm day^{-1}, 1.41 mm day^{-1}, 1.41 mm day^{-1} for the PT, PEN, and MAK methods, respectively) and lower precision (R^2) (0.75, 0.98, 0.79, for the PT, PEN, and MAK methods, respectively) (Table 1). This performance was confirmed using Tukey's test, which indicated significant differences among the models.

Table 1. Statistic performance of ETo methods in daily scale in relation to the Penman-Monteith method, considering the Accuracy (mean absolute percentage error, Mape), Precision (R^2), Tendency (systematic error, SE). Tukey´s test with significant minimum difference (DMS) at level of 5% probability for annual (AN), summer (SU), autumn (AU), winter (WI) and spring (SP) analysis. ETo´s models: Priestley-Taylor (PT), Penman (PEN), Makkink (MAK), Tanner-Pelton (TP), Radiation (RAD), Turc (TUR), Thornthwaite (THO), Class A pan (TCA), Hamon (HAM), Benevidez-Lopez (BL), Camargo (CAM), Hargreaves-Samani (HS), Jensen-Haise (JH), Romanenko (ROM), Linacre (LIN), Blaney-Criddle (BC), Jobson (JOB) and Kharrufa (KHA).

	Mape (%)					R^2					SE (mm d^{-1})				
	AN	SU	AU	WI	SP	AN	SU	AU	WI	SP	AN	SU	AU	WI	SP
PT	15.3a	13.1 a	11.6 a	23.8a	12.7a	0.75a	0.96a	0.9a	0.62a	0.78a	1.3a	1.4a	1.0a	1.4a	1.4 a
PEN	15.8 a	12.5 a	14.9b	20.6b	14.8b	0.98a	0.99a	0.99a	0.99a	0.99a	1.4a	1.4a	1.1a	1.3a	1.5 a
MAK	17.8b	16.9b	14.7b	19.5d	20.1d	0.79a	0.86a	0.74a	0.69a	0.81a	1.4a	1.5a	1.1a	1.3 a	1.6 a
TP	23.2c	32.0if	22.6c	16.2a	22.3e	0.81a	0.95a	0.92a	0.64a	0.82a	1.4a	1.8ab	1.2a	1.1 a	1.5 a
RAD	23.8c	17.5b	30.8efg	26.7cf	19.8d	0.84a	0.88a	0.73a	0.79a	0.89a	1.4a	1.4 a	1.3ab	1.3 a	1.5 a
TUR	26.1d	19.7c	38.4i	28.1c	17.9c	0.8a	0.88a	0.72a	0.71a	0.84a	1.4a	1.4 a	1.4ab	1.3 a	1.4 a
THO	27.5e	27.1e	27.4d	28.4c	27.0f	0.5b	0.56b	0.38b	0.55b	0.44b	1.4a	1.4 a	1.1 a	1.3 a	1.5 a
TCA	29.8f	30.0fh	32.3eh	25.3cde	31.9ghi	0.66a	0.64a	0.51b	0.7a	0.13c	1.5a	1.5 a	1.2 a	1.2 a	1.6 a
HAM	32.gh	32.8i	29.6ef	34.5g	31.5gh	0.4b	0.36b	0.37b	0.54b	0.34b	1.5a	1.4 a	1.2 a	1.5ab	1.5 a
BL	32.7hi	24.9d	40.1i	38.2h	27.5f	0.61a	0.7a	0.46b	0.71a	0.63a	1.5a	1.4 a	1.3ab	1.5ab	1.5 a
CAM	33.9j	37.1k	30.5ef	34.8g	33.2gj	0.33b	0.38b	0.31b	0.51b	0.35a	1.4a	1.3 a	1.2 a	1.4 a	1.4 a
HS	35.6k	42.1l	33.8e	24.5cd	42.6l	0.66a	0.7a	0.56b	0.68a	0.74a	1.5a	1.7 a	1.2 a	1.2 a	1.8 a
JH	40.7l	41.4l	48.8j	35.8g	37.0k	0.85a	0.88a	0.77a	0.79a	0.87b	1.8ab	2.0bc	1.6 c	1.5 ab	2.0ab
ROM	44.1m	27.2e	47.2j	66.3k	34.4j	0.33b	0.56b	0.22b	0.57a	0.47b	1.4a	1.5 a	1.2 a	2.1c	1.4 a
LIN	47.9n	30.9fgh	62.3k	63.6j	33.6j	0.51b	0.7b	0.41b	0.71a	0.62a	1.7a	1.4 a	1.7c	2.1c	1.6 a
BC	54.1o	50.6m	70.7m	56.4i	38.3k	0.48b	0.52b	0.25b	0.48b	0.55b	1.9ab	1.8bc	1.8c	2.0ab	2.0 ab
JOB	54.9o	35.5j	66.3l	70.8l	46.2m	0.41b	0.51b	0.18b	0.76a	0.56b	1.8ab	1.4 a	1.6c	2.2c	1.9 ab
KHA	76.8p	93.9n	86.8n	54.5i	72.8n	0.45b	0.57b	0.39b	0.55b	0.39b	2.2b	2.7bc	1.9cd	1.7ab	2.4 b
DMS	1.34	1.55	1.77	1.98	1.64	0.42	0.39	0.39	0.43	0.38	0.45	0.45	0.28	0.38	0.48

In the summer, the PEN and PT methods were more accurate, with both having lower values of Mape (12.6 and 13.1%) and R^2 (0.99 and 0.96). In the autumn, the most accurate model was PT, followed by MAK and PEN, and the latter exhibited the same significance value according to Tukey's test. The PT method showed lower Mape and ES (11.59% and 1.03 mm day^{-1}), and the PEN method showed the highest R^2 (0.99).

In general, the accuracy of the analyzed models was not adequate for winter. Regardless, the evaluated methods with the best accuracy were TP, MAK and PEN. Despite the low R^2 (0.62), the TP model showed lower values of Mape and ES for this season: 16.20% and 1.08 mm day^{-1}, respectively. PEN, however, had the highest R^2 among all models (0.98). The MAK and PEN models exhibited low accuracy with Mape values of 19.52 and 20.59%, respectively, compared to that of the Penman-Monteith method.

For spring, the most accurate model was PT, followed by PEN and TUR, and PT showed the highest Mape value (12.67%) and one of the lowest ES values (1.34 mm day^{-1}). For the PEN and TUR models, the Mape (14.84 and 17.88%) was slightly higher than that of the PT model, and the ES values (1.55 and 1.43 mm day^{-1}) were reasonable. The PEN model had the highest R^2 (0.99). These results are different from those found by Pereira et al. (2009), who analyzed data from 2007 to 2008 and observed that the JH, RAD, PEN and BC methods are adequate for estimating reference evapotranspiration on a daily scale, regardless of the season, in the Serra da Manriquiera region, Minas Gerais State. This dissimilar result is most likely because of the differences in climate and altitude between the regions.

The THO, HS and BL models were among the most accurate of those that only used temperature and relative humidity in their equations. For this study, the most accurate model for the whole year was THO (Mape = 27.5%), and the most accurate models were BL, THO, HS and THO, for summer, autumn, winter and spring, respectively. All of the models exhibited low values of ES and R^2 (between 0.5 and 0.6).

The other models that were analyzed on a daily time scale did not show good accuracy. The Mape values were 17.5 and 93.9% using the RAD and KHA methods, respectively, for summer

The same estimated ETo methods were evaluated for periods of 5 days (Table 2). The model with the best accuracy was PT, followed by PEN and MAK. However, according to Tukey's analysis, the latter two models performed similarly. The Mapes were 14.1, 15.9, and 16.1% for the PT, PEN and MAK models, respectively. The PT model showed the lowest SE (1.0 mm day^{-1}), and the PEN model had the highest R^2 (0.98). Tagliaferre et al. (2010) similarly evaluated ETo estimation methods in Eunápolis (BA) on a 5-day scale and obtained excellent results from the PEN, RAD and BC methods and very good results with the PT and TUR methods.

Table 2. Statistic performance of ETo methods in 5-day scale in relation to the Penman-Monteith method, considering the Accuracy (mean absolute percentage error, Mape), Precision (R^2), Tendency (Systematic Error, SE). Tukey´s test with significant minimum difference (DMS) at level of 5% probability for annual (AN), summer (SU), autumn (AU), winter (WI) and spring (SP) analysis. ETo´s models: Priestley-Taylor (PT), Penman (PEN), Makkink (MAK), Tanner-Pelton (TP), Radiation (RAD), Turc (TUR), Thornthwaite (THO), Class A pan (TCA), Hamon (HAM), Benevidez-Lopez (BL), Camargo (CAM), Hargreaves-Samani (HS), Jensen-Haise (JH), Romanenko (ROM), Linacre (LIN), Blaney-Criddle (BC), Jobson (JOB) and Kharrufa (KHA).

	Mape (%)					R^2					SE (mm d^{-1})				
	AN	SU	AU	WI	SP	AN	SU	AU	WI	SP	AN	SU	AU	WI	SP
PT	14.1a	12.5ab	10.2a	23.5 a	10.0 a	0.7a	0.96a	0.92a	0.59b	0.66a	1.0 a	1.1 a	0.9 a	1.2b	0.9 a
PEN	15.9b	12.4ab	15.0b	20.8f	15.2cd	0.98a	0.99a	0.99a	0.99a	0.99a	1.2 a	1.1 a	1 a	1.1 ab	1.1 a
MAK	16.1b	14.9cde	11.6 a	18.9cd	19.2hi	0.8a	0.82a	0.76a	0.76a	0.78a	1.2 a	1.1 a	0.9 a	1.1 ab	1.2 a
THO	18.3ef	15.5efg	17.4e	23.4 a	16.7k	0.57a	0.59a	0.47a	0.63a	0.44b	1.1 a	1.0 a	0.9 a	1.1 ab	1.1 a
TP	20.5c	31.9def	19.3c	11.5g	19.5def	0.78a	0.95a	0.94a	0.63a	0.76a	1.2 a	1.6b	1 a	0.8 a	1.2 a
RAD	21.3de	15.1l	28.7d	23.6 a	17.1i	0.83a	0.84a	0.71a	0.82a	0.89a	1.2 a	1.1 a	1.1 a	1.1ab	1.1 a
TCA	21.6ef	17.5def	25.4h	19.0g	24.4b	0.8a	0.83a	0.64a	0.87a	0.7a	1.2 a	1.2 a	1.0 a	1.0 a	1.3ab
TUR	22.0ef	15.5de	35.1f	23.4 a	13.1efg	0.8b	0.85b	0.73b	0.75a	0.82a	1.2 a	1.1a	1.2 a	1.1ab	1.0ab
CAM	22.0g	20.6bcd	20.9g	28.7i	17.6ghi	0.42b	0.33b	0.39b	0.62b	0.33b	1.1 a	1.0 a	1 a	1.3bc	0.9 a
HAM	22.4ef	19.9ghi	20.7d	29.6h	19.2fgh	0.47b	0.3b	0.46b	0.63a	0.29b	1.2 a	1.1 a	1.0 a	1.3bc	1.1ab
BL	24.3ef	14.4ghi	32.5d	31.7h	17.9hi	0.64a	0.76a	0.5b	0.78a	0.65a	1.2 a	1.0 a	1.1 a	1.3bc	1.1ab
HS	26.6h	32.1l	25.6e	16.1b	33.3m	0.71a	0.81a	0.57b	0.77a	0.8a	1.3 a	1.4ab	1 a	0.9 a	1.5b
JH	38.2i	38.7m	45.9i	32.9i	34.8m	0.85a	0.85a	0.77a	0.83a	0.85a	1.7b	1.8c	1.5b	1.4cd	1.7dc
LIN	38.9j	19.3k	54.6i	55.9n	24.0i	0.48b	0.77a	0.39b	0.77a	0.64a	1.5ab	1.1 a	1.6b	2.0d	1.3ab
ROM	41.2i	23.4fgh	44.9j	65.3l	30.4j	0.27b	0.56b	0.16c	0.6b	0.44b	1.1 a	1.2 a	1.1 a	2.0d	0.9 a
JOB	44.0l	21.5n	56.9l	61.6k	34.7m	0.37b	0.5b	0.09g	0.78a	0.62a	1.6b	1.1 a	1.5b	2.1d	1.6b
BC	50.7k	46.3ij	67.8k	52.8m	34.3m	0.35b	0.35b	0.11d	0.39b	0.43b	1.8bc	1.6b	1.7b	1.9d	1.7bc
KHA	62.6m	76.7 o	73.5m	42.4j	57.4n	0.54b	0.56b	0.54b	0.65a	0.38b	2.1c	2.5c	1.9bc	1.5cd	2.2c
DMS	1,58	2,05	1,76	1,84	1,62	0.4	0.34	0.39	0.36	0.38	0.29	0.28	0.27	0.25	0.29

For summer (Table 2), the models with better accuracy were PEN, PT and BL, with Mape values of 12.4, 12.5, and 14.4%, respectively. However, the PEN and BL models performed similarly according to Tukey's test. The lowest tendency values were for the THO, BL and CAM models (1.0 mm day^{-1}). For autumn, the PT and MAK models exhibited the best accuracy, with lower values of Mape (10.2 and 11.6%, respectively). For both evaluations, the most precise method was PEN with an R^2 of 0.99.

For winter, the TP model was much more accurate than the others, with an 11.5% Mape in addition to a lower value of ES (0.83 mm day^{-1}). In this case, HS was the second most accurate model, with a Mape of 16.1%. The HS model was also somewhat biased because the ES was 0.93 mm day^{-1}. Finally, in the spring, the model with the best accuracy was PT, followed by TUR, PEN and THO with Mapes of 10.0, 13.1, 15.2 and 16.7%, respectively, while the less tendentious models were PT, CAM and ROM, which all had an ES of 0.9 mm day^{-1}.

THO was the most accurate of the models that only used temperature and relative humidity data for the annual and spring periods; BL was best for summer, HS was best for winter, and CAM was best for autumn. All the Mape values were higher than 14,4%.

The other models that were analyzed on a 5-day time scale did not show good accuracy. The Mape values were 14,4 and 76,7% for the BL and KHA methods, respectively, for summer.

When analyzing the same models using a biweekly scale (Table 3), the most accurate models were PT, THO and MAK, with Mapes of 13.82, 15.33, and 15.62%, respectively. Despite the good accuracy, the models showed low precision compared to the PM model; the R^2 values were 0.68, 0.64, and 0.79 for PT, THO and MAK, respectively. The methods with greater accuracy on a biweekly scale during the summer were THO and BL, followed by PT and PEN. The former two had Mapes of 10.56 and 11.25%, respectively, and both had the same low tendency (ES) of 0.74 mm day^{-1} and the same representativity, according to Tukey's test. For autumn, the MAK and PT methods showed the lowest Mapes (9.7 and 9.8%, respectively) and the lowest ES values (0.8 and 0.7 mm day^{-1}, respectively); both methods showed similar results from Tukey's test. For winter, the TP, HS and TCA, TP models exhibited better accuracy with a Mape of 9.68%, and the HS and TCA models showed low tendencies with ES values of 0.82 mm day^{-1} and 0.91 mm day^{-1}, respectively. Finally, for spring, the PT, CAM and TUR models were the most accurate. Among those models, the PT method showed the lowest values of Mape and ES: 8.70% and 0.62 mm day^{-1}, respectively.

These results are close to those found by Vescove and Turco (2005), who analyzed the biweekly mean evapotranspiration in Araraquara, São Paulo State, a region next to Jaboticabal. According to the authors, the MAK method underestimates evapotranspiration to a greater degree during the winter-spring period than during the summer-autumn period.

Table 3. Statistic performance of ETo methods in 15-day scale in relation to the Penman-Monteith method, considering the Accuracy (mean absolute percentage error, Mape), Precision (R^2), Tendency (Systematic Error, SE). Tukey´s test with significant minimum difference (DMS) at level of 5% probability for annual (AN), summer (SU), autumn (AU), winter (WI) and spring (SP) analysis. ETo´s models: Priestley-Taylor (PT), Penman (PEN), Makkink (MAK), Tanner-Pelton (TP), Radiation (RAD), Turc (TUR), Thornthwaite (THO), Class A pan (TCA), Hamon (HAM), Benevidez-Lopez (BL), Camargo (CAM), Hargreaves-Samani (HS), Jensen-Haise (JH), Romanenko (ROM), Linacre (LIN), Blaney-Criddle (BC), Jobson (JOB) and Kharrufa (KHA).

	Mape (%)					R^2					SE (mm d^{-1})				
	AN	SU	AU	WI	SP	AN	SU	AU	WI	SP	AN	SU	AU	WI	SP
PT	13.8abc	12.4bcde	9.8a	24.2g	8.7a	0.68a	0.94a	0.94a	0.54c	0.52b	0.9 a	0.8 a	0.7 a	1.1ab	0.6 a
THO	15.3bcd	10.6abc	14.3b	22.2f	13.9de	0.64a	0.57b	0.57b	0.71b	0.33b	1.0 a	0.7 a	0.8 a	1.0ab	0.8 a
MAK	15.6def	14.8ghi	9.7a	20.0d	18.3j	0.79a	0.65ab	0.78a	0.8b	0.70a	1.0 a	0.9 a	0.8 a	1.0ab	1.0ab
PEN	16.0ef	12.6cde	15.5b	20.7de	15.2efh	0.98a	0.99a	0.99a	0.99a	0.98a	1.0 a	0.8 a	0.8 a	1.0ab	0.9 a
CAM	17.5f	13.5defg	19.0c	26.4h	10.8b	0.52b	0.17d	0.45b	0.63c	0.25b	0.9 a	0.7 a	0.9 a	1.1ab	0.6 a
HAM	19.6gh	14.6fgh	18.9c	29.0i	15.9hi	0.54b	0.15d	0.54b	0.65b	0.17b	1.1 a	0.8 a	0.9 a	1.2b	0.9 a
TP	19.9gh	32.4l	17.5c	9.7[a]	20.0k	0.77a	0.94a	0.96a	0.62c	0.65a	1.0 a	1.4ab	0.9 a	0.7 a	1.0ab
TCA	20.4hi	16.6i	24.3i	18.1c	22.7l	0.84a	0.78ab	0.71a	0.91a	0.67a	1.1 a	0.9 a	0.9 a	0.9 a	1.1ab
RAD	20.8hi	15.0ghi	29.0e	22.2f	16.7i	0.81a	0.71ab	0.75a	0.83b	0.85a	1.1 a	0.8 a	1.0 a	1.0ab	0.9 a
TUR	20.9hi	14.6fgh	35.6g	20.4de	12.0c	0.79a	0.71ab	0.46b	0.79b	0.76a	1.0 a	0.8 a	1.2ab	0.9 a	0.7 a
BL	22.1h	11.2bcd	32.5f	29.6i	14.2def	0.64a	0.75ab	0.56b	0.83b	0.54b	1.1 a	0.7 a	1.1ab	1.2b	0.8 a
HS	24.3j	28.9k	24.0d	14.6b	29.9n	0.75a	0.75ab	0.56b	0.82b	0.78a	1.1 a	1.2ab	0.9 a	0.8 a	1.3ab
LIN	36.5k	15.8hi	55.7j	53.1m	19.9k	0.4b	0.76ab	0.4b	0.76b	0.51b	1.4b	0.8a	1.6b	1.9c	1.0 ab
JH	37.7l	38.2m	45.9h	31.5j	35.0o	0.84a	0.72ab	0.8a	0.86b	0.79a	1.5b	1.6b	1.4b	1.3b	1.6b
JOB	40.5m	15.7hi	57j	59.6n	28.8n	0.33b	0.48c	0.08c	0.77b	0.54b	1.5b	0.8 a	1.5b	2.1d	1.3ab
ROM	40.7m	22.7j	47.7i	64.1o	27.3m	0.19b	0.56b	0.11c	0.55c	0.38b	1.0 a	1.0 a	1.0 a	1.9c	0.6 a
BC	49.7n	47.6n	66.5k	49.2l	34.2o	0.24b	0.15d	0.01d	0.33c	0.25b	1.7bc	1.5ab	1.6b	1.8c	1.5b
KHA	58.5o	72.4o	69.2l	39.6k	52.2p	0.61a	0.51c	0.58b	0.72b	0.28b	2.0 c	2.4c	1.8bc	1.4b	2.1c
DMS	1,93	1,93	1,77	1,70	1.15	0.37	0.36	0.37	0.34	0.40	0.25	0.33	0.30	0.23	0.32

The RAD method overestimates evapotranspiration to a greater degree in the summer-autumn period than in the spring-winter period. The TCA method overestimates reference evapotranspiration by 26% in summer-autumn period and by 24% in the winter-spring period relative to the values from the standard method of FAO (PM).

THO surpasses the models that use only temperature and relative humidity for summer and autumn. The best models were HS for winter and CAM for spring. The THO model was developed for a monthly scale and has better accuracy when the time scale changes from daily to biweekly, with Mapes of 27.49 and 15.33%, respectively. Confirming the report of Camargo and Camargo (2000), the Thornthwaite model is adequate for the wet climate regions of São Paulo State, independent of latitude and altitude.

In general, the models had a low tendency, not exceeding 2.7 mm day^{-1} for all scales. The PEN model showed higher values of precision for all analyses.

The PT method, despite the high accuracy for all time scales, underestimated ETo in the winter (Figure 1) by up to 1.5 mm day^{-1}, 2 mm day^{-1}, and 2 mm day^{-1} for the daily, 5-day and biweekly scales, respectively, when the ETo estimated by PM was approximately 5 mm day^{-1}. Additionally, in the summer, the PT model overestimates up to 1 mm on daily, 5-day and biweekly scales.

Therefore, the PT method is accurate for the summer, when the weather is hot and wet (Figure 1). However, the PT method is less precise for winter, when the climate is drier. During this season, the Tanner and Pelton method can be applied because of the greater accuracy shown for all analyses in the winter.

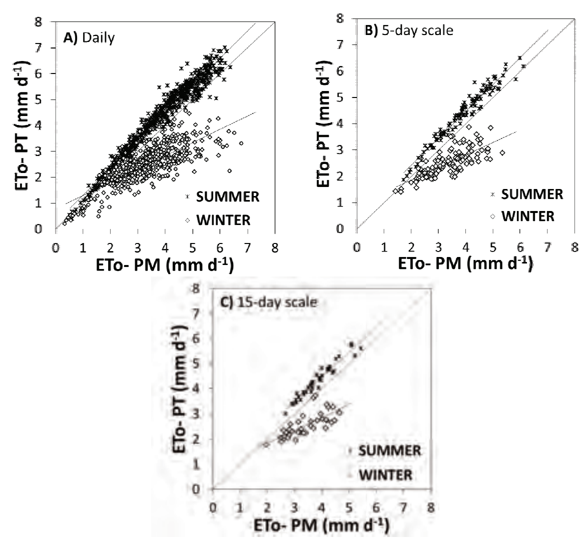

Figure 1. Relation between ETo measured by the Priestley and Taylor method (PT) and ETo observed by the Penman and Monteith method (PM) in daily (A), 5-day (B) and 15-day (C) scales during summer and winter.

The other models that were analyzed on a 15-day time scale were not accurate. The Mape values were 15,0 and 72,4% using the RAD and KHA methods, respectively, for summer.

Conclusion

The Priestley-Taylor method can be considered the most accurate method for determining the ETo in the Jaboticabal region, SP, for all time scales. However, the methods of Penman and Makkink must not be dismissed.

Especially in the winter, the method of Tanner and Pelton is more accurate and less biased of all the methods.

Finally, the Thornthwaite method is the most accurate of those that only require temperature and relative humidity in equations for annual analysis.

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