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Article

Alternative Methods of Reference Evapotranspiration for Brazilian Climate Types

Bruno César Gurski[1], Daniela Jerszurki[2], Jorge Luiz Moretti de Souza[1]

[1]Programa de Pós Graduação em Ciência do Solo, Universidade Federal do Paraná, Curitiba, PR, Brazil.
[2]Wyler Department for Dryland Agriculture, Jacob Blaustein Institute for Desert Research, Ben-Gurion University of Negev, Beersheba, Israel.

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Abstract

The choice of consistent alternative methods is essential for the improvement of reference evapotranspiration (*ETo*) estimation for different climatic regions. Due to a critical gap in knowledge concerning the most adequate alternative *ETo* methods for the climatic conditions in Paraná, Brazil, this study aimed to test and to evaluate the main estimation alternative methods (Thornthwaite - ETo_{TH}; Camargo - ETo_C; Hargreaves and Samani - ETo_{HS}; Linacre - ETo_L; and, Budyko - ETo_B) for the subtropical (Cfb) and semi-arid (Bsh) climate types in Brazil. We compared our results with standard ETo_{PM} (Penman-Monteith) estimated between 1970 and 2015, using the minimum and maximum air temperature (*T*), sunshine hours (*n*), relative humidity (*RH*) and wind speed (U_2). Least square regression analysis of *ETo* estimated by alternative methods vs ETo_{PM} were used to calibrate the methods for each analyzed climate type. The performance of calibrated and noncalibrated methods was evaluated by index of agreement *"d"* and performance *"c"*, root mean square error (*RMSE*) and mean error (*ME*). Our results showed the importance of calibration process of alternative methods for the improvement of *ETo* estimations in Brazil. The Hargreaves and Samani and Linacre calibrated methods showed better performance in the subtropical and semi-arid climates, respectively. Also, the Linacre and Budyko calibrated methods were particularly robust in subtropical and semi-arid climates, outlining the importance of continuous measurements of *T* used in the ETo_L and ETo_B modeling effort. The results presented here showed the importance to calibrate the alternative methods on *ETo* estimations and outlined the need for improvement and proposition of new *ETo* methods based on a limited number of climatic variables commonly available in subtropical and semi-arid climates in Brazil.
Keywords: modeling, Penman Monteith ASCE, semi-arid, subtropical zones.

Métodos Alternativos de Evapotranspiração de Referência para Tipos Climáticos Brasileiros

Resumo

A escolha de métodos alternativos consistentes é essencial para a melhoria das estimativas da evapotranspiração de referência (*ETo*) em diferentes zonas climáticas. Devido ao desconhecimento dos métodos alternativos mais adequados para as condições climáticas paranaenses, teve-se por objetivo no presente trabalho testar e avaliar os principais métodos alternativos de estimativa da *ETo* (Thornthwaite - ETo_{TH}; Camargo - ETo_C; Hargreaves e Samani - ETo_{HS}; Linacre - ETo_L; and, Budyko - ETo_B) para os tipos climáticos subtropical (Cfb) e semi-árido (Bsh) no Brasil. As estimativas alternativas foram comparadas com a *ETo* estimada como o método de Penman-Monteith ASCE (ETo_{PM}) entre 1970 e 2015, a partir da temperatura máxima e mínima do ar (*T*), horas de brilho solar (*n*), umidade relativa média (*UR*) e velocidade do vento a dois metros de altura (U_2). Análises de regressão linear simples entre a *ETo* estimada com os métodos alternativos vs ETo_{PM} para cada tipo climático analisado, foram utilizadas para a calibração dos métodos. O desempenho dos métodos calibrados e não calibrados foi obtido a partir do índice *"d"* de concordância, *"c"* de desempenho, raiz quadrada do erro médio (*RMSE*) e erro médio (*EM*). Os resultados demonstraram a importância da calibração dos métodos alternativos para a melhoria das estimativas nas condições climáticas brasileiras. Os melhores

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Corresponding author: Bruno César Gurski, brunocep@gmail.com.

desempenhos foram observados para os métodos calibrados Hargreaves and Samani e Linacre para os tipos climáticos subtropical e semi-árido, respectivamente. Além disso, os métodos calibrados Linacre e Budyko mostraram-se particularmente robustos nos tipos climáticos subtropical e semi-árido, respectivamente, destacando a importância de medidas contínuas da variável *T*, utilizada na modelagem de ETo_L e ETo_B. Os resultados obtidos indicaram a necessidade da melhoria das estimativas alternativas da *ETo*, a partir da utilização de pequeno conjunto de variáveis disponíveis para os tipos climáticos subtropical e semi-árido no Brasil.

Palavras-chave: modelagem, Penman Monteith ASCE, semi-árido, zonas subtropicais.

1. Introduction

The reference evapotranspiration (*ETo*) has fundamental role in the study and determination of water relations in the activities of rural engineering. Besides that, it is one of the most important hydrological variables for crop evapotranspiration, estimation and interpretation of agricultural water balances and irrigation management (Blaney and Criddle, 1950; Xu and Singh, 2005). The *ETo* can be measured directly from lysimeters or evapotranspirometers (Doorenbos and Pruitt, 1977) or estimated from theoretical methods based on climate variables such as temperature (Thorthwaite, 1948; Doorenbos and Pruitt, 1977) and solar radiation (Hargreaves and Samani, 1985). Due to the dissemination of weather stations and the high cost of direct measurement, the estimated *ETo* has been used with satisfactory performance around the world (Pandey *et al.*, 2016). Traditionally, the combined method of Penman-Monteith parameterized by the Food and Agriculture Organization of the United Nations - FAO (Allen *et al.*, 1998) and the American Society of Civil Engineers - ASCE (ASCE-EWRI, 2005) is recognized as a standard method to estimate *ETo* (Chauhan and Shrivastava, 2009). However, all the weather data needed to solve the method are often incomplete or not available in many of the Brazilian regions, which limits their use (Souza *et al.*, 2014; Alencar *et al.*, 2015). Even considering the different climate database of meteorological data around world, as World Climate Database (Hijmans *et al.*, 2005), the complete set of data needed to estimate *ETo* by Penman-Monteith method is not available, because key variables such as wind speed, solar radiation, daily insolation and relative humidity are still missing or not consistent.

Therefore, alternative methods developed to estimate the reference evapotranspiration, with a small number of climate variables of easy measurement, are promising for the alternative estimation of *ETo* (Chauhan and Shrivastava, 2009). Over the last 50 years, many alternative models have been developed (Penman 1948; Thornthwaite 1948; Campbell 1971; Budyko 1974; Linacre 1977; Hargreaves and Samani, 1985), but the literature only reports a comparative performance to the Penman-Monteith standard method (Borges and Mediondo, 2007; Oliveira *et al.*, 2008; Trajkovic and Kolakovic, 2009), with few studies analyzing the adjustment of *ETo* methods under different climatic types (Todorovic *et al.*, 2013.). Therefore, given the existing climate variability in Brazil, such studies are important, because they allow to identify trends and limitations of the alternative methods and to choose the best suited method for each region.

Accordingly, here we test, adjust and evaluate the main alternative methods of reference evapotranspiration for different climate types in Brazil.

2. Material and Methods

Analyzes were carried out in a set of 45 years of daily historical data (January 1970 to December 2015) of maximum, minimum and average air temperature (°C), relative humidity (%), daily sunshine hours (MJ m^{-2} d^{-1}) and wind speed at ten meters height (m s^{-1}), available by the National Institute of Meteorology (INMET, 2016) from two automatic weather stations located in the cities of Petrolina and Curitiba (Table 1), under the climate types Bsh and Cfb, respectively. According to Koppen (1936), the Bsh climate is characterized as dry semi-arid, occurring in low latitude and altitude locations with high average annual temperatures above 26 °C and average precipitation of 522.3 mm $year^{-1}$. The Cfb climate is characterized as a subtropical without dry season, with temperate summers and average precipitation of 1500 mm $year^{-1}$ (Alvares *et al.*, 2013).

Daily reference evapotranspiration was estimated by Penman-Monteith method, parameterized by American Society of Civil Engineers (ASCE) (ASCE EWRI, 2005).

$$ETo_{PM} = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma_{psy} \cdot \dfrac{C_n}{(T + 273)} \cdot u_2 \cdot (e_s - e_a)}{\Delta \cdot \gamma_{psy} \cdot (1 + C_d \cdot u_2)} \quad (1)$$

where ETo_{PM} - reference evapotranspiration (mm d^{-1}); Δ - slope of the saturated water-vapor-pressure curve

Table 1 - Climatic classification, location and assessed weather stations.

Climatic classification	State	Station	Latitude (degrees)	Longitude (degrees)	Altitude (m)
Bsh	Pernambuco	Petrolina	-9.38	-40.48	370.46
Cfb	Paraná	Curitiba	-25.43	-49.26	923.50

(kPa °C^{-1}); R_n - net radiation at the crop surface (MJ m^{-2} d^{-1}); G - soil heat flux (MJ m^{-2} d^{-1}); γ_{psy} - psychrometric constant (kPa °C^{-1}); T - daily average air temperature (°C); U_2 - wind speed at 2 m height (m s^{-1}); e_s - saturation vapor pressure (kPa); e_a - actual vapor pressure (kPa); C_n - constant related to the reference type and calculation time step, considered equal to 900 for grass (dimensionless); C_d - constant related to the reference type and calculation time step, considered equal to 0.34 for grass (dimensionless).

Daily vapor pressure deficit (e_s - e_a) was estimated by difference between saturated and actual vapor pressure. Saturated vapor pressure was calculated using air temperature based on the Tetens formula. Actual vapor pressure was obtained by saturated vapor pressure multiplied by fractional humidity. Daily net radiation (*Rn*) was estimated by the difference between net longwave and shortwave radiation. The net longwave radiation (*Rnl*) was obtained by relative shortwave radiation (*Rs*/*Rso*), air temperature and actual vapor pressure. The net shortwave radiation (*Rns*) was obtained by solar radiation (*Rs*), which was estimated by relation between extraterrestrial radiation (*Ra*) and relative sunshine duration (*n*/*N*) (Pereira, 2015). The soil heat flux (*G*) was calculated using air temperature (Pereira *et al.*, 1997). The wind speed measurements were transformed to wind speed at 2 m height by the wind profile relationship (Allen *et al.*, 1998).

Alternative *ETo* methods consisted of the following empirical models: Thornthwaite (1948), Camargo (1971), Budyko (1974), Linacre (1977) and Hargreaves and Samani (1985).

a) Thornthwaite (1948):

Thornthwaite (1948) method uses daily average air temperature (*T*), considering a month of 30 days and 12 hours of photoperiod:

$$ETo_{THi} = \frac{N_i}{12} \cdot \frac{1}{30} \cdot 16 \cdot \left(\frac{10 \cdot T}{I} \right), \quad \text{for:} T > 0^{\circ} C \tag{2}$$

where ETo_{THi} - reference evapotranspiration by Thornthwaite (1948) method for the i-th day (mm day^{-1}); N_i - photoperiod in i-th day (h); T - daily average air temperature (°C).

$$\begin{aligned} a = 6.75 \cdot 10^{-7} \cdot I^3 - 7.71 \cdot 10^{-5} \cdot I^2 \\ +1.7912 \cdot 10^{-2} \cdot I + 0.49239 \end{aligned} \tag{3}$$

where a - cubic function of the heat index (I) of the region (dimensionless); I - heat index in the region (dimensionless).

$$I = \sum_{i=1}^{12} (0.2 \cdot T_a)^{1.514}, \quad \text{for} \quad T_a > 0 \tag{4}$$

where T_a - average normal temperature of the m-th month of the year (°C).

b) Camargo (1971):

$$ETo_{Ci} = Qo_i \cdot F \cdot T \tag{5}$$

where ETo_{Ci} - reference evapotranspiration by Camargo (1971) method for the i-th day (mm day^{-1}); Qo_i - extraterrestrial radiation of the i-th day, calculated as evaporation (mm day^{-1}); F - adjustment factor varying according to the site of the annual average temperature; T - daily average air temperature (°C).

The extraterrestrial radiation of the i-th day in equivalent evaporation (*Qoi* - mm day^{-1}) was transformed from the latent heat of evaporation (λ = 2.45 MJ kg^{-1}):

$$Qo_{i(\text{mm. day}^{-1})} = \frac{R_a}{2.45} \tag{6}$$

where $Qo_{I(\text{mm day}^{-1})}$ - extraterrestrial radiation of the i-th day in equivalent of evaporation (mm day^{-1}); R_a - extraterrestrial radiation of the i-th day (MJ m^{-2} day^{-1}).

c) Hargreaves and Samani (1985):

$$ETo_{HSi} = 0.0023 \cdot Qo_i \cdot (T + 17.8) \cdot (T_{MAXi} - T_{MINi})^{0.5} \tag{7}$$

where ETo_{HSi} - reference evapotranspiration by Hargreaves and Samani (1985) method for the i-th day (mm day^{-1}); Qo_i - extraterrestrial radiation of the i-th day, calculated as evaporation (mm day^{-1}); T - daily average air temperature (°C); T_{MAXi} - maximum air temperature in the i-th day (°C); T_{MINi} - minimum air temperature in the i-th day (°C).

The transformation of the extraterrestrial radiation of the i-th day in equivalent of evaporation (Qo_i - mm day^{-1}) was from the latent heat of evaporation (λ = 2.45 MJ kg^{-1}), as proposed by Camargo (1971).

d) Linacre (1977):

$$ETo_{Li} = \frac{700 \cdot \frac{T + 0.006z}{100 - \varphi} + 15 \cdot (T - Td_i)}{80 - T} \tag{8}$$

where ETo_{Li} - reference evapotranspiration by Linacre method for the i-th day (mm dia^{-1}); T - daily average air temperature (°C); z - local altitude (m); ϕ - site latitude (degrees); Td_i - dew point temperature in the i-th day (°C).

e) Budyko (1974):

$$ETo_{Bi} = 0.20 \cdot T \tag{9}$$

where ETo_{Bi} - reference evapotranspiration by Budyko (1985) method for the i-th day (mm day^{-1}); T - daily average air temperature in the i-th day (°C).

The daily values of *ETo* estimated by alternative methods were adjusted from linear regression analyzes in a monthly and annual basis, between 01/01/1970 and 12/31/2005 (35 years). The linear regression analysis to verify the performance and association between ETo_{PM} and calibrated $ETo_{\text{alternative}}$ were held for the last ten years of data series (01/01/2006 to 12/31/2015). The calibrated $ETo_{\text{alternative}}$ values were obtained using the adjustment coefficients "a" and "b" obtained from the relation $ETo_{\text{alternative}}$ and ETo_{PM} (1970 to 2005).

$$ETo_{alternative\ i} = a + b \cdot ETo_{PMi} \tag{10}$$

where: $ETo_{alternative\ i}$ is the reference evapotranspiration estimated by calibrated alternative methods at each *i*-day (mm d^{-1}); ETo_{PMi} - reference evapotranspiration by Penman-Monteith method in the i-th day (mm day^{-1}); *a* is the linear coefficient (mm d^{-1}); *b* is the angular coefficient (dimensionless).

Daily reference evapotranspiration obtained with alternative methods and standard Penman-Monteith method were compared by linear regression analysis using R^2 as an index of precision, agreement index *"d"* (Willmott *et al.*, 1985) as an index of accuracy and confidence index *"c"* (Camargo and Sentelhas, 1997) as a general index to evaluate both precision and accuracy. The agreement index is a measure of the effectiveness with which the alternative method estimates the Penman-Monteith reference evapotranspiration, considering the dispersion of the relative data to the 1:1 line.

The interpretation criteria of *"c"* performance, was classified by great (*"c"* > 0.85); very good (0.75 < *"c"* ≤ 0.85); good (0.65 < *"c"* ≤ 0.75); average (0.60 < *"c"* ≤ 0.65); tolerable (0.50 < *"c"* ≤ 0.60); bad (0.40 < *"c"* ≤ 0.50); and, very bad (*"c"* ≤ 0.40).

For further comparison, root mean squared error (*RMSE*) and mean error (*ME*) were used to evaluate the reference evapotranspiration estimated by alternative methods:

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (E_i - O_i)^2}{\sum_{i=1}^{n} \left(\left| E_i - \bar{O}_i \right| + \left| O_i - \bar{O}_i \right| \right)^2} \right] \tag{9}$$

$$c = \left| R \cdot d \right| \tag{10}$$

$$RMSE = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} (E_i - O_i)^2} \tag{11}$$

$$ME = \frac{E_i - O_i}{O_i} \cdot 100 \tag{12}$$

where *d* - agreement index of Willmott *et al.* (1985) (dimensionless); *Ei* - *ETo* estimated by alternative methods in the i-th day (mm day^{-1}); O_i - *ETo* estimated by Penman-Monteith method in the i-th day (mm day^{-1}); O_i - mean of the *ETo* estimated by Penman-Monteith method (mm day^{-1}); n - number of observations (dimensionless); *R* - correlation coefficient (dimensionless); *RMSE* - root mean square error (mm day^{-1}); *ME* - mean error (%).

3. Results and Discussion

Contrasting performances were observed between methods for all climate types (Tables 2 and 3). The calibration process resulted in improved estimations in the annual period for some methods, showing better performances in the monthly period.

Comparatively, several authors have been demonstrating the influence of climate type on the estimated *ETo*, as well as on the performance of alternative methods (Lemos Filho *et al.*, 2010; Silva *et al.*, 2011). In this sense, the results showed that the evaluation of performance of alternative methods estimating *ETo* for different climate types is essential when climatic data required for ETo_{PM} are unavailable or unreliable.

The ETo_{HS} method showed the best performance and lower estimation errors for the climate Cfb in the monthly and annual periods. The ETo_L showed similar trends to ETo_{HS} in a monthly period (Table 2). Similar results were obtained by Syperreck *et al.* (2008), when the ETo_{HS} was a better suited method for subtropical climate ($R = 0.86$, $d = 0.85$, $c = 0.73$).

Camargo and Sentelhas (1997), comparing 20 alternative methods with ET obtained by evapotranspirometers in different Brazilian climate types, observed better estimates for ETo_C and ETo_{TH} for the subtropical and dry tropical climate types, respectively. The ETo_{HS}, ETo_C and ETo_{TH} use solar radiation or daily insolation as input variables of the model, which can improve the estimative of *ETo*, mainly under warm and dry climates (Gardiman *et al.*, 2012).

The use of solar radiation in alternative methods to estimate *ETo* is well-recognized in the literature, providing good results in the analyzed regions (Irmak *et al.*, 2006). According to Hupet and Vanclooster (2001), solar radiation has great influence on ETo_{PM} in extremely cold and wet climates, due to lower magnitude and influence of other climatic variables. According to Camargo and Sentelhas (1997), the easiest use of ETo_C and ETo_{TH} stands out among other alternative methods. However, ETo_{TH} method presents particularities in the estimative, as the need for the normal monthly average temperature of the year, which is considered a difficult information to access because it is not provided by weather stations, which makes it even more difficult spreading the method.

According to Souza *et al.* (2014), the use of solar radiation in alternative methods results in consistent estimates of *ETo* for both warm and dry as to cold and wet climates. For these authors, ETo_{HS} tends to perform better estimations in warm climates with high average temperatures throughout the year, since the method was based on the average temperature and maximum temperature of the day. Opposite trend was observed in this study, with the worst performance observed for ETo_{HS} in Bsh climate (Table 3).

The ETo_L method is a simplification of the Penman (1948) model, which uses air temperature functions, such as the difference between the average temperature and dew point temperature, being proposed in Africa and South America (Souza *et al.*, 2014). In this sense, the best performance of the method occurred for Bsh, given the similarity

Table 2 - Coefficient of determination (R^2), correlation (R), root mean square error ($RMSE$), mean error (ME), indexes *"d"* and *"c"* and performance of alternative methods, calibrated (C) or not (NC), compared to standard (ETo_{PM}) for climate type "Cfb", in monthly and annual periods, between 1970 and 2005.

Month	R^2		R		*"d"*		*"c"*		*RMSE* (mm day^{-1})		*ME* (%)		*a* (mm day^{-1})		*b* (dimensionless)	
	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C
								Thornthwaite (1948)								
Annual	0.55	0.55	0.74	0.74	0.81	0.84	0.60	0.62	0.90	0.77	-14.60	9.99	0.79	1.34	0.87	0.55
January	0.20	0.32	0.45	0.56	0.79	0.88	0.35	0.50	0.93	0.90	-8.60	15.17	1.48	3.38	0.70	0.20
February	0.18	0.41	0.42	0.64	0.76	0.87	0.32	0.56	0.83	0.86	-5.32	12.87	1.22	3.09	0.73	0.24
March	0.21	0.35	0.46	0.59	0.64	0.73	0.29	0.43	0.71	0.82	-6.20	15.21	1.32	2.84	0.63	0.19
April	0.13	0.14	0.36	0.38	0.76	0.62	0.27	0.23	0.69	0.59	-7.23	15.13	1.63	2.41	0.37	0.10
May	0.10	0.07	0.31	0.26	0.93	0.94	0.29	0.24	0.62	0.52	-10.44	17.96	1.33	1.87	0.30	0.06
June	0.07	0.45	0.26	0.67	0.96	0.97	0.25	0.64	0.57	0.47	-9.38	13.68	1.23	1.62	0.23	0.04
July	0.23	0.22	0.48	0.47	0.94	0.93	0.45	0.43	0.67	0.53	-19.82	24.52	1.01	1.74	0.53	0.20
August	0.32	0.39	0.57	0.63	0.84	0.72	0.48	0.45	0.90	0.60	-27.71	16.05	1.18	1.96	0.66	0.29
September	0.29	0.33	0.54	0.57	0.72	0.61	0.39	0.35	1.01	0.80	-25.88	17.44	1.39	2.31	0.63	0.25
October	0.20	0.23	0.45	0.48	0.50	0.69	0.22	0.33	1.10	0.89	-21.81	16.29	1.77	2.88	0.56	0.17
November	0.17	0.13	0.41	0.36	0.50	0.78	0.21	0.28	1.29	1.03	-21.75	21.55	2.11	3.53	0.56	0.13
December	0.14	0.18	0.38	0.43	0.69	0.87	0.26	0.37	1.10	0.97	-13.83	15.80	2.05	3.63	0.57	0.15
								Camargo (1971)								
Annual	0.63	0.58	0.79	0.76	0.86	0.84	0.68	0.64	0.76	0.81	-8.96	-7.47	0.56	0.68	0.91	0.65
January	0.19	0.30	0.44	0.55	0.86	0.88	0.38	0.48	0.81	0.84	0.21	8.46	-0.13	3.09	1.08	0.22
February	0.17	0.42	0.42	0.65	0.81	0.86	0.34	0.56	0.76	0.81	1.02	5.18	-0.26	2.73	1.11	0.26
March	0.21	0.36	0.46	0.60	0.62	0.70	0.28	0.42	0.65	0.77	-2.99	6.17	0.47	2.49	0.91	0.22
April	0.15	0.17	0.39	0.41	0.79	0.77	0.31	0.32	0.63	0.54	-8.64	7.04	1.13	2.13	0.61	0.14
May	0.11	0.09	0.33	0.30	0.95	0.95	0.31	0.29	0.57	0.48	-13.53	7.45	1.05	1.66	0.50	0.08
June	0.05	0.03	0.23	0.18	0.97	0.97	0.22	0.17	0.53	0.47	-15.71	4.48	1.10	1.49	0.35	0.03
July	0.23	0.22	0.48	0.47	0.94	0.96	0.45	0.45	0.66	0.45	-20.74	4.81	0.60	1.37	0.88	0.22
August	0.31	0.40	0.56	0.63	0.85	0.82	0.47	0.52	0.82	0.59	-22.08	-1.01	0.67	1.54	0.94	0.31
September	0.26	0.26	0.51	0.51	0.73	0.61	0.37	0.31	0.81	0.81	-12.28	3.66	0.74	2.02	0.86	0.23
October	0.20	0.23	0.44	0.48	0.57	0.64	0.25	0.31	0.81	0.85	-5.96	6.94	0.97	2.55	0.77	0.19
November	0.18	0.13	0.42	0.36	0.71	0.77	0.30	0.28	0.97	0.95	-7.81	14.21	1.03	3.25	0.82	0.14
December	0.14	0.18	0.38	0.42	0.83	0.86	0.31	0.36	0.88	0.91	-2.77	10.11	0.82	3.39	0.85	0.16
								Hargreaves and Samani (1985)								
Annual	0.72	0.71	0.85	0.85	0.81	0.84	0.69	0.71	1.09	1.01	36.54	31.18	0.10	0.93	0.74	0.93
January	0.41	0.55	0.64	0.74	0.86	0.91	0.55	0.68	1.34	0.69	34.01	2.10	0.32	2.16	0.71	0.42
February	0.41	0.58	0.64	0.76	0.83	0.90	0.54	0.69	1.22	0.70	33.17	-1.25	0.13	1.75	0.75	0.48
March	0.45	0.60	0.67	0.77	0.74	0.82	0.50	0.64	1.01	0.63	30.49	0.64	0.49	1.72	0.66	0.43
April	0.38	0.39	0.62	0.62	0.54	0.87	0.33	0.54	0.81	0.46	29.80	3.34	0.53	1.51	0.62	0.38
May	0.27	0.34	0.52	0.58	0.81	0.97	0.42	0.56	0.74	0.42	38.20	1.86	0.57	1.22	0.52	0.29

Table 2 - cont.

Month	R^2		R		"*d*"		"*c*"		*RMSE* (mm day^{-1})		*ME* (%)		*a* (mm day^{-1})		*b* (dimensionless)	
	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C
June	0.12	0.17	0.35	0.41	0.88	0.97	0.31	0.40	0.73	0.45	44.84	1.34	0.80	1.32	0.35	0.12
July	0.28	0.43	0.53	0.65	0.84	0.97	0.45	0.63	0.75	0.40	41.41	-1.19	0.37	0.99	0.59	0.39
August	0.36	0.46	0.60	0.68	0.62	0.85	0.37	0.57	0.94	0.59	39.22	-5.37	0.49	1.26	0.59	0.39
September	0.46	0.48	0.68	0.69	0.58	0.75	0.40	0.52	1.14	0.71	41.27	-2.00	0.53	1.50	0.58	0.38
October	0.47	0.44	0.69	0.66	0.70	0.78	0.48	0.52	1.30	0.73	40.25	1.88	0.57	1.77	0.60	0.41
November	0.40	0.46	0.63	0.68	0.84	0.87	0.53	0.59	1.32	0.73	34.16	5.11	0.52	2.03	0.67	0.42
December	0.42	0.40	0.65	0.63	0.86	0.90	0.56	0.57	1.37	0.77	34.20	3.11	0.46	2.32	0.68	0.39
Linacre (1977)																
Annual	0.46	0.53	0.68	0.73	0.76	0.81	0.52	0.59	0.87	0.81	-3.67	0.84	0.29	1.19	1.02	0.51
January	0.35	0.47	0.59	0.69	0.62	0.92	0.37	0.63	1.12	0.74	-20.13	9.37	1.08	2.37	0.93	0.43
February	0.30	0.53	0.55	0.72	0.64	0.91	0.35	0.66	0.94	0.72	-15.08	6.59	1.04	2.23	0.86	0.42
March	0.28	0.48	0.53	0.70	0.61	0.82	0.32	0.57	0.71	0.68	-9.27	9.06	0.97	2.09	0.78	0.38
April	0.26	0.31	0.51	0.55	0.80	0.81	0.41	0.45	0.54	0.50	3.83	7.61	1.06	1.90	0.57	0.24
May	0.25	0.38	0.50	0.62	0.92	0.97	0.46	0.60	0.57	0.41	19.30	8.63	0.91	1.36	0.43	0.27
June	0.28	0.36	0.53	0.60	0.92	0.98	0.49	0.59	0.64	0.39	31.10	5.47	0.82	1.15	0.36	0.27
July	0.48	0.52	0.69	0.72	0.93	0.98	0.65	0.71	0.60	0.35	21.87	4.47	0.65	0.90	0.53	0.50
August	0.52	0.53	0.72	0.73	0.90	0.88	0.64	0.64	0.63	0.51	3.06	-0.93	0.95	1.04	0.56	0.53
September	0.44	0.51	0.66	0.72	0.82	0.81	0.54	0.58	0.74	0.65	-9.09	3.46	1.16	1.38	0.61	0.47
October	0.29	0.35	0.53	0.59	0.60	0.73	0.32	0.43	0.95	0.78	-17.07	5.84	1.46	2.15	0.65	0.31
November	0.33	0.41	0.58	0.64	0.56	0.86	0.32	0.55	1.21	0.79	-22.81	12.06	1.50	2.49	0.79	0.35
December	0.24	0.42	0.49	0.65	0.54	0.91	0.26	0.59	1.25	0.79	-22.21	10.67	1.70	2.59	0.75	0.38
Budyko (1974)																
Annual	0.44	0.46	0.67	0.68	0.71	0.70	0.47	0.47	1.08	1.14	39.81	42.06	-0.58	2.38	0.96	0.44
January	0.19	0.31	0.44	0.56	0.89	0.88	0.39	0.49	0.88	0.84	15.49	8.38	-0.08	3.08	0.93	0.22
February	0.17	0.39	0.41	0.62	0.84	0.86	0.35	0.53	0.99	0.83	24.04	5.38	-0.39	2.82	0.94	0.24
March	0.19	0.31	0.44	0.55	0.67	0.68	0.29	0.37	1.11	0.79	35.51	6.39	0.12	2.59	0.74	0.19
April	0.11	0.13	0.33	0.36	0.21	0.76	0.07	0.27	1.31	0.55	54.18	7.19	1.15	2.23	0.36	0.10
May	0.08	0.05	0.28	0.22	0.26	0.95	0.07	0.21	1.36	0.49	78.17	7.64	1.09	1.71	0.23	0.05
June	0.05	0.03	0.23	0.18	0.39	0.97	0.09	0.17	1.42	0.47	94.34	4.50	1.10	1.49	0.15	0.03
July	0.20	0.18	0.44	0.42	0.52	0.96	0.23	0.41	1.21	0.46	73.62	5.19	0.65	1.43	0.38	0.19
August	0.27	0.34	0.52	0.59	0.56	0.81	0.29	0.47	0.99	0.61	42.60	-0.49	0.64	1.61	0.53	0.28
September	0.26	0.29	0.51	0.54	0.58	0.63	0.30	0.34	0.92	0.79	31.32	3.91	0.65	1.97	0.60	0.25
October	0.18	0.21	0.43	0.46	0.71	0.63	0.30	0.29	0.87	0.86	20.43	7.27	0.92	2.61	0.61	0.17
November	0.17	0.13	0.41	0.36	0.85	0.77	0.35	0.28	0.87	0.95	8.20	14.29	1.05	3.26	0.70	0.14
December	0.14	0.18	0.38	0.42	0.89	0.86	0.34	0.36	0.86	0.91	10.46	10.14	0.80	3.40	0.75	0.16

Table 3 - Coefficient of determination (R^2), correlation (R), root mean square error (*RMSE*), mean error (*ME*), indexes *"d"* and *"c"* and performance of alternative methods, calibrated (C) or not (NC), compared to standard (ETo_{PM}) for climate type "Bsh", in monthly and annual periods, between 1970 and 2005.

Month	R^2		R		*"d"*		*"c"*		*RMSE* (mm day^{-1})		*ME* (%)		*a* (mm day^{-1})		*b* (dimensionless)	
	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C
									Thornthwaite (1948)							
Annual	0.45	0.49	0.67	0.70	0.72	0.79	0.48	0.55	1.55	1.28	-17.46	-10.13	2.75	0.14	0.65	0.87
January	0.49	0.32	0.70	0.56	0.79	0.84	0.55	0.48	1.15	1.04	-6.60	9.41	1.31	3.38	0.86	0.20
February	0.57	0.41	0.75	0.64	0.81	0.88	0.61	0.57	1.05	0.90	-8.26	10.98	1.29	3.09	0.87	0.24
March	0.61	0.35	0.78	0.59	0.88	0.84	0.69	0.49	0.90	0.92	-5.53	9.62	1.03	2.84	0.88	0.19
April	0.50	0.14	0.71	0.38	0.88	0.80	0.62	0.30	0.94	0.90	-9.67	11.56	1.21	2.41	0.86	0.10
May	0.44	0.07	0.67	0.26	0.88	0.88	0.59	0.23	1.14	0.71	-15.97	9.02	1.92	1.87	0.73	0.06
June	0.36	0.45	0.60	0.67	0.83	0.88	0.50	0.59	1.56	0.77	-28.78	11.95	2.01	1.62	0.82	0.04
July	0.22	0.22	0.47	0.47	0.75	0.86	0.35	0.40	1.97	0.72	-36.23	10.67	2.78	1.74	0.68	0.20
August	0.24	0.39	0.49	0.63	0.38	0.51	0.19	0.32	2.46	0.76	-39.69	9.76	3.66	1.96	0.62	0.29
September	0.19	0.33	0.43	0.57	0.22	0.87	0.10	0.50	2.30	0.74	-30.95	6.66	4.75	2.31	0.41	0.25
October	0.26	0.23	0.51	0.48	0.56	0.89	0.28	0.42	1.64	0.92	-16.72	7.24	4.08	2.88	0.50	0.17
November	0.44	0.13	0.67	0.36	0.77	0.84	0.52	0.31	1.33	1.20	-8.31	9.78	2.08	3.53	0.77	0.13
December	0.44	0.18	0.66	0.43	0.78	0.84	0.52	0.36	1.17	1.06	-6.61	12.96	2.41	3.63	0.68	0.15
									Camargo (1971)							
Annual	0.45	0.47	0.67	0.69	0.52	0.56	0.35	0.38	2.18	1.92	-29.60	-27.29	2.75	1.99	0.65	0.35
January	0.49	0.37	0.70	0.61	0.46	0.20	0.33	0.13	1.99	1.49	-21.45	-13.21	1.31	4.67	0.86	0.09
February	0.57	0.70	0.75	0.84	0.50	0.44	0.37	0.37	1.85	1.29	-21.17	-6.71	1.29	4.26	0.87	0.16
March	0.61	0.59	0.78	0.77	0.66	0.54	0.51	0.42	1.65	1.32	-18.72	-10.56	1.03	3.97	0.88	0.15
April	0.50	0.44	0.71	0.66	0.73	0.76	0.52	0.50	1.64	1.08	-23.66	-6.27	1.21	3.84	0.86	0.14
May	0.44	0.30	0.67	0.55	0.78	0.90	0.52	0.49	1.75	0.77	-28.45	-3.38	1.92	3.89	0.73	0.10
June	0.36	0.30	0.60	0.55	0.77	0.92	0.46	0.51	1.92	0.68	-35.46	3.80	2.01	4.09	0.82	0.09
July	0.22	0.30	0.47	0.55	0.73	0.88	0.34	0.48	2.05	0.69	-37.07	8.46	2.78	4.49	0.68	0.08
August	0.24	0.30	0.49	0.55	0.35	0.26	0.17	0.14	2.55	0.73	-40.92	8.55	3.66	5.18	0.62	0.11
September	0.19	0.31	0.43	0.56	0.13	0.83	0.05	0.46	2.77	0.72	-38.87	2.28	4.75	5.83	0.41	0.09
October	0.26	0.20	0.51	0.45	0.12	0.77	0.06	0.34	2.71	0.97	-34.59	-2.80	4.08	5.92	0.50	0.06
November	0.44	0.26	0.67	0.51	0.27	0.23	0.18	0.12	2.50	1.39	-28.22	-12.10	2.08	5.02	0.77	0.09
December	0.44	0.59	0.66	0.77	0.30	0.28	0.20	0.22	2.20	1.36	-26.50	-4.34	2.41	4.86	0.68	0.10
									Hargreaves and Samani (1985)							
Annual	0.45	0.49	0.67	0.70	0.70	0.78	0.47	0.55	1.37	1.09	-15.90	-12.92	2.75	0.14	0.65	0.87
January	0.49	0.32	0.70	0.56	0.65	0.80	0.46	0.45	1.24	0.87	-8.07	-0.78	1.31	3.38	0.86	0.20
February	0.57	0.41	0.75	0.64	0.65	0.72	0.49	0.46	1.19	0.97	-8.88	5.71	1.29	3.09	0.87	0.24
March	0.61	0.35	0.78	0.59	0.79	0.73	0.62	0.43	1.07	0.87	-7.27	-0.14	1.03	2.84	0.88	0.19
April	0.50	0.14	0.71	0.38	0.83	0.86	0.59	0.32	1.13	0.74	-14.19	1.67	1.21	2.41	0.86	0.10
May	0.44	0.07	0.67	0.26	0.87	0.93	0.58	0.24	1.20	0.59	-18.20	3.82	1.92	1.87	0.73	0.06

Table 3 - cont.

Month	R^2		R		"*d*"		"*c*"		*RMSE* (mm day^{-1})		*ME* (%)		*a* (mm day^{-1})		*b* (dimensionless)	
	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C	NC	C
June	0.36	0.45	0.60	0.67	0.86	0.88	0.51	0.59	1.32	0.74	-22.99	14.00	2.01	1.62	0.82	0.04
July	0.22	0.22	0.47	0.47	0.83	0.67	0.39	0.31	1.36	0.92	-22.87	18.73	2.78	1.74	0.68	0.20
August	0.24	0.39	0.49	0.63	0.51	0.34	0.25	0.21	1.58	1.11	-24.37	19.56	3.66	1.96	0.62	0.29
September	0.19	0.33	0.43	0.57	0.22	0.86	0.10	0.49	1.68	0.84	-21.59	10.07	4.75	2.31	0.41	0.25
October	0.26	0.23	0.51	0.48	0.34	0.90	0.17	0.43	1.60	0.81	-18.45	5.91	4.08	2.88	0.50	0.17
November	0.44	0.13	0.67	0.36	0.53	0.86	0.35	0.31	1.53	0.86	-12.87	0.66	2.08	3.53	0.77	0.13
December	0.44	0.18	0.66	0.43	0.53	0.75	0.35	0.32	1.32	1.00	-12.05	5.24	2.41	3.63	0.68	0.15
Linacre (1977)																
Annual	0.36	0.21	0.60	0.46	0.31	0.32	0.19	0.15	4.09	3.80	-61.09	-59.05	10.18	2.89	-2.12	-0.13
January	0.56	0.39	0.75	0.62	0.28	0.82	0.21	0.51	4.13	1.03	-58.62	-1.90	12.33	2.24	-2.85	0.61
February	0.51	0.47	0.71	0.69	0.29	0.80	0.21	0.55	3.88	0.94	-56.99	2.65	12.32	3.03	-2.80	0.48
March	0.54	0.47	0.74	0.68	0.43	0.80	0.32	0.55	3.43	0.93	-52.14	-2.25	12.42	2.24	-2.94	0.56
April	0.51	0.34	0.71	0.59	0.53	0.82	0.38	0.48	3.10	0.88	-51.55	1.28	10.56	2.90	-2.32	0.41
May	0.46	0.26	0.68	0.51	0.63	0.91	0.43	0.46	2.93	0.72	-51.73	1.43	9.75	2.70	-2.27	0.41
June	0.40	0.33	0.63	0.57	0.65	0.93	0.41	0.53	2.92	0.64	-55.61	5.89	8.65	2.87	-1.93	0.40
July	0.40	0.29	0.63	0.54	0.60	0.92	0.38	0.50	3.17	0.61	-59.27	4.95	8.49	2.95	-1.92	0.39
August	0.33	0.23	0.57	0.48	0.23	0.59	0.13	0.28	4.17	0.68	-68.28	6.39	8.78	4.19	-1.67	0.27
September	0.42	0.17	0.65	0.42	0.07	0.85	0.04	0.35	4.94	0.74	-71.85	2.99	10.17	4.63	-2.03	0.29
October	0.42	0.40	0.65	0.63	0.06	0.92	0.04	0.58	5.27	0.74	-71.96	1.74	10.91	3.52	-2.17	0.47
November	0.58	0.42	0.76	0.65	0.15	0.88	0.11	0.57	5.00	0.93	-66.64	-2.16	12.27	1.96	-2.84	0.67
December	0.48	0.41	0.69	0.64	0.17	0.81	0.12	0.52	4.55	1.05	-64.08	1.13	11.67	2.94	-2.51	0.49
Budyko (1974)																
Annual	0.36	0.21	0.60	0.46	0.33	0.35	0.20	0.16	2.88	2.55	-33.56	-30.32	10.91	4.74	-1.44	-0.20
January	0.56	0.38	0.75	0.62	0.27	0.82	0.20	0.51	2.88	1.02	-30.19	-1.75	13.57	2.27	-2.01	0.60
February	0.50	0.48	0.71	0.69	0.31	0.80	0.22	0.55	2.57	0.94	-27.72	2.66	13.71	3.04	-2.02	0.47
March	0.54	0.47	0.74	0.68	0.46	0.80	0.34	0.55	2.18	0.93	-19.97	-2.17	14.00	2.25	-2.14	0.56
April	0.51	0.35	0.71	0.59	0.61	0.82	0.43	0.48	1.84	0.88	-18.64	1.37	11.71	2.91	-1.67	0.41
May	0.45	0.27	0.67	0.52	0.72	0.91	0.49	0.47	1.74	0.71	-17.91	1.43	10.68	2.73	-1.58	0.41
June	0.40	0.33	0.63	0.57	0.77	0.93	0.48	0.54	1.69	0.63	-23.46	5.93	9.27	2.89	-1.30	0.39
July	0.39	0.29	0.63	0.54	0.70	0.92	0.44	0.50	1.96	0.61	-29.24	4.96	8.99	2.99	-1.25	0.38
August	0.32	0.23	0.57	0.48	0.27	0.59	0.15	0.28	2.94	0.67	-44.51	6.32	9.13	4.22	-1.07	0.27
September	0.41	0.17	0.64	0.41	0.07	0.85	0.04	0.35	3.69	0.74	-50.81	2.90	10.65	4.65	-1.31	0.28
October	0.41	0.39	0.64	0.62	0.06	0.91	0.04	0.57	4.01	0.75	-51.28	1.83	11.44	3.67	-1.41	0.45
November	0.57	0.41	0.76	0.64	0.13	0.88	0.10	0.56	3.79	0.94	-42.88	-2.10	13.14	2.07	-1.90	0.65
December	0.48	0.39	0.69	0.62	0.16	0.80	0.11	0.50	3.25	1.08	-38.81	1.71	12.67	2.96	-1.74	0.50

with the climatic characteristics of the regions where the method was adjusted and validated (Irmak *et al.*, 2006). Compared to our results, Mendonça *et al.* (2003), Choi Junior *et al.* (2011) and Todorovic *et al.* (2013) also observed better adjustment of methods based only on air temperature in warm and dry climates, justifying its use when there is unavailability of climate data.

Thus, it is observed the link between the performance of each alternative method with climatic conditions of the region where it is being used, highlighting the importance of detailed study of tendency of *ETo* and input variables in climate models.

Furthermore, the best performance of the calibrated alternative methods emphasizes the importance of calibration of models to the region of interest (Garcia *et al.*, 2007; Pandey *et al.*, 2016).

It was found similar trend of estimated *ETo* by alternative methods in relation to the standard method of Penman-Monteith for Cfb climate (Fig. 1a), especially after the calibration of the methods (Fig. 1b). The highest values observed occurred in the summer, reflecting the greater availability of energy in the soil-plant-atmosphere system at this period (Syperreck *et al.*, 2008).

Similar results were observed for the Bsh climate type (Fig. 2), but with less seasonality of *ETo* throughout the year, characteristic of this climate type. However, the smaller values of *ETo* remained in the winter period. Prior to calibration, all alternative methods underestimated ETo_{PM}, and it was observed great variation between estimations (Fig. 2a). The same trend was observed by Cai *et al.* (2007) in warm and dry regions, due to overestimation of actual vapor pressure, resulting in inconsistent estimations of some alternative methods.

Although confirmed the possibility of using alternative methods to estimate *ETo* in conditions where climatic variables required for the standard method are not available, the results obtained in this study demonstrate the need for obtaining alternative consistent estimations for all Brazilian climatic conditions, from the simplified generation of alternative methods. In this sense, it stands out the under-

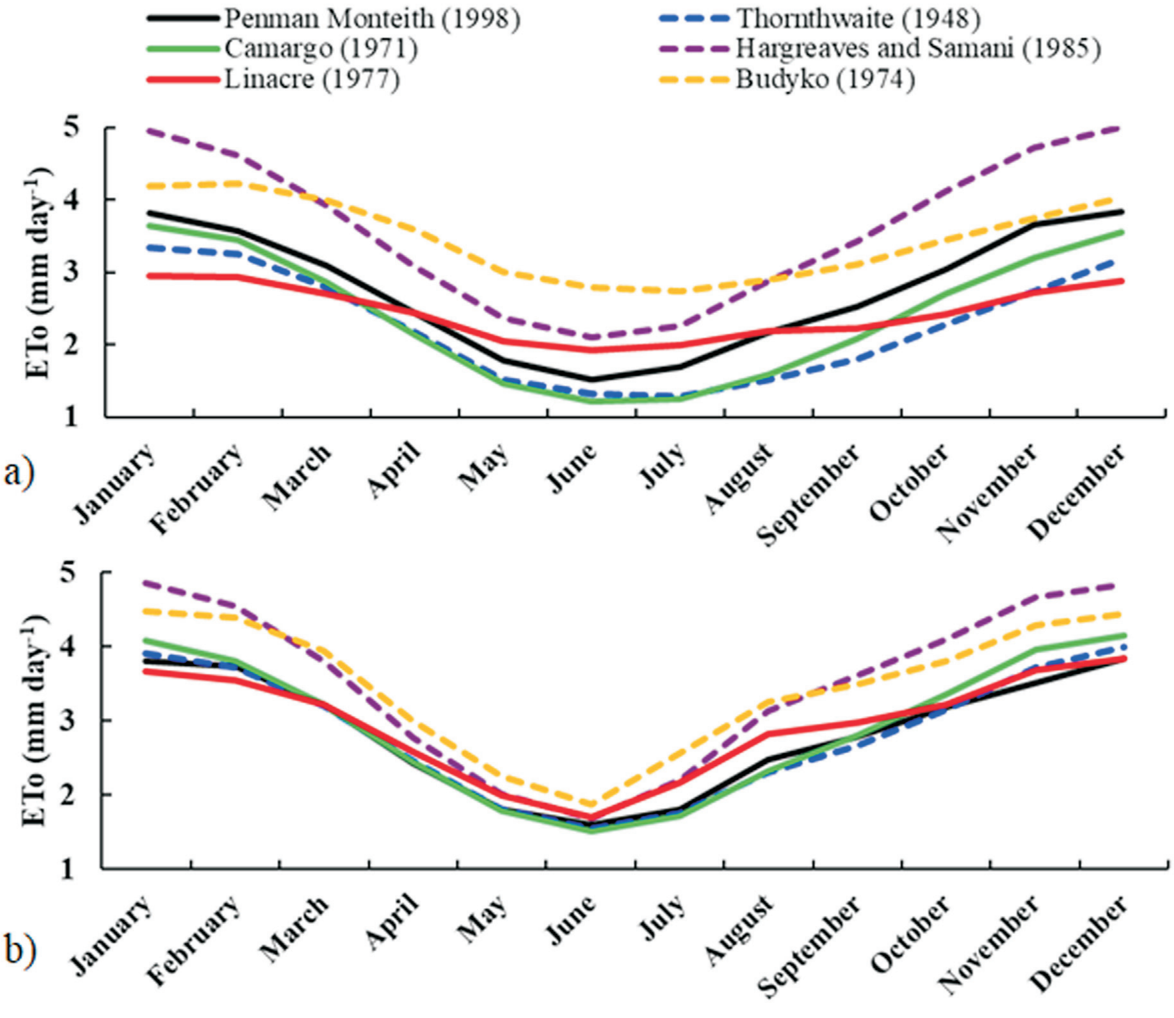

Figure 1 - Monthly average reference evapotranspiration (*ETo*) estimated by the standard method (ETo_{PM}) for climate type "Cfb" between 1970 and 2005, compared to alternative methods uncalibrated (a) and calibrated (b).

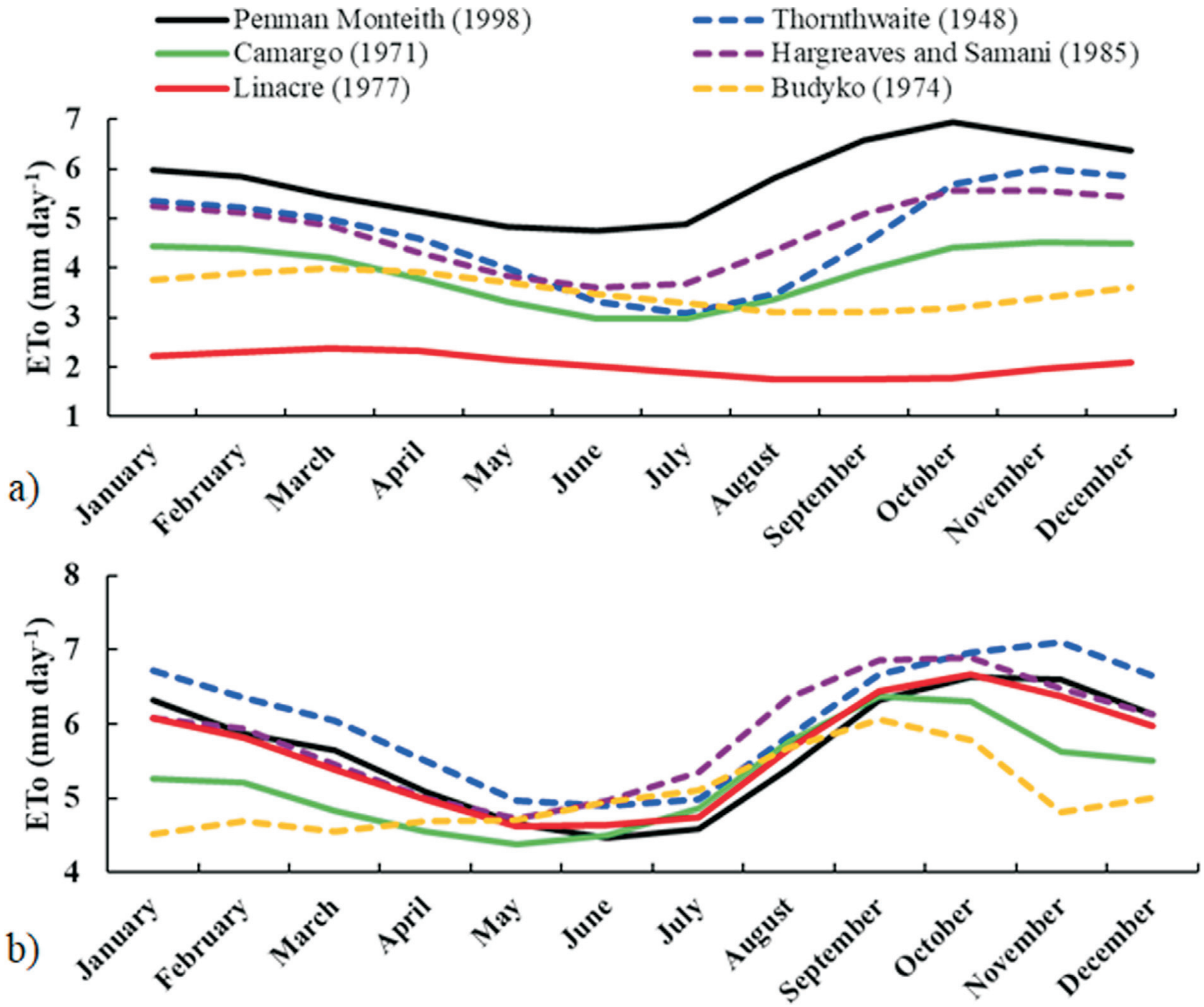

Figure 2 - Monthly average reference evapotranspiration (*ETo*) estimated by the standard method (ETo_{PM}) for climate type "Bsh" between 1970 and 2005, compared to alternative methods uncalibrated (a) and calibrated (b).

standing of the real influence of climate variables on the trend of *ETo*, which will form the basis for the simplification of the estimation. Therefore, given the territorial extension of Brazil and the great variability of latitude and altitude over regions, which result in different climate types, the sensitivity study of *ETo* is interesting and necessary. The study enables trends identification, constraints, to develop simplifications of the standard method and to propose alternative methods with a possible decrease of the number of input variables needed for an accurate estimation.

4. Conclusions

1. In order of importance, the Hargreaves and Samani, and Linacre methods showed a strong linear association with standard ETo_{PM} in the subtropical and semi-arid climate, respectively.

2. The Linacre and Budyko methods were particularly robust in subtropical and semi-arid climates, outlining the importance of continuous measurements of the air temperature used in the ETo_L and ETo_B modeling effort.

3. The results presented here showed the importance to calibrate the alternative methods on evapotranspiration estimative and outlined the need for improvement and proposition of new *ETo* methods based on a limited number of climatic variables commonly available in subtropical and semi-arid climates in Brazil.

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