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Hourly reference evapotranspiration by Moretti-Jerszurki-Silva method using data from alternative station[1]

Estimativa da evapotranspiração de referência horária pelo método Moretti-Jerszurki-Silva usando dados de estação alternativa

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HIGHLIGHTS:
Moretti-Jerszurki-Silva (MJS) models can estimate the hourly ETo.
Atmospheric water potential and solar radiation at the top of the atmosphere allows a reliable estimate of the hourly ETo.
The hourly ETo estimation over the hours of the day can be satisfactorily performed using alternative methods.

ABSTRACT: Reliable measures of climate variables and the availability of alternative and safe methods are fundamental in estimating reference evapotranspiration (ETo) under unfavorable technical and financial conditions. The objective of this study was to evaluate the performance of the reference evapotranspiration estimation, in hourly periodicity, using the Moretti-Jerszurki-Silva models ($ETo_{MJS(\psi air)}$; $ETo_{MJS(\psi air;Ra)}$), which considers air temperature (T) and relative air humidity (RH) data measured in an alternative station. The calibration and validation of the alternative station measurements were performed using data from automatic meteorological stations in Curitiba in Paraná (climate type Cfb) and Santa Rita de Cássia in Bahia (climate type Aw), Brazil. The use of the alternative station for hourly measurements of air temperature and relative air humidity in the analyzed climate types and locations were promising. The Moretti-Jerszurki-Silva models were robust in the analyzed locations, indicating satisfactory performance for the hourly periodicity. The Moretti-Jerszurki-Silva method that uses atmospheric water potential and solar radiation ($ETo_{MJS(\psi air;Ra)}$) provided better adjustments and estimates of the hourly reference evapotranspiration, as opposed to the standard Penman-Monteith model.

Key words: water relations, water requirements, alternative methods, weather stations

RESUMO: Medidas confiáveis de variáveis climáticas e a disponibilidade de métodos alternativos seguros são fundamentais para estimar a evapotranspiração de referência (ETo) em condições técnicas e financeiras desfavoráveis. Objetivou-se no presente estudo avaliar o desempenho da estimativa da evapotranspiração de referência, na periodicidade horária, com os modelos Moretti-Jerszurki-Silva ($ETo_{MJS(\psi air)}$; $ETo_{MJS(\psi air;Ra)}$), utilizando dados de temperatura (T) e umidade relativa (UR) do ar, medidos em estação alternativa. A calibração e validação das leituras da estação alternativa foram realizadas com dados de estações meteorológicas automáticas de Curitiba no Paraná (tipo climático Cfb), e Santa Rita de Cássia na Bahia (tipo climático Aw). O uso da estação alternativa para medições horárias da temperatura e umidade relativa do ar dos locais e tipos climáticos analisados foi promissor. Os modelos Moretti-Jerszurki-Silva foram robustos nos locais analisados, indicando desempenho satisfatório para a periodicidade horária. O modelo Moretti-Jerszurki-Silva que considera o uso do potencial hídrico atmosférico e radiação solar ($ETo_{MJS(\psi air;Ra)}$) proporcionou melhores ajustes e estimativas da evapotranspiração de referência horária, considerando o modelo padrão Penman-Monteith.

Palavras-chave: relações hídricas, necessidades hídricas, métodos alternativos, estações meteorológicas

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Introduction

The quality of climate variable measurements obtained at meteorological stations are fundamental in estimating the reference evapotranspiration using the Penman-Monteith-ASCE ($ETo_{PM\text{-}ASCE}$) model. $ETo_{PM\text{-}ASCE}$ estimates can be obtained in daily or hourly periodicity, where the hourly evapotranspiration (ETo) estimates have provided a better performance with regard to assessment of irrigation management (Yildirim et al., 2004). Models that predict ETo on an hourly scale aid in estimating crop water requirements (Tawegoum et al., 2015) and provide a better understanding of the dynamic processes in river basins (Debele et al., 2009).

Meteorological stations use equipment with a high level of accuracy to provide climatic data components that allow the characterization of local weather and climate. However, acquisition cost, maintenance, and operation may restrict their use (Bier & Ferraz, 2017; Vianna et al., 2017). The use of simplified ETo models, based on a few variables of easy measurement, holds significant potential in improving ETo estimates worldwide.

As a result of the lack in quantity and quality of available climate data for daily estimates of $ETo_{PM\text{-}ASCE}$ and due to its high sensitivity to air temperature (T) and relative air humidity (RH; Jerszurki et al., 2019), simplified alternative ETo models have been developed (ETo_{MJS}; Moretti-Jerszurki-Silva) and tested over different Brazilian climatic conditions (Jerszurki et al., 2017), resulting in reliable estimates. Similar results were also obtained for hourly ETo estimates in Brazil (Oliveira, 2018). The results obtained by Jerszurki et al. (2017) and Oliveira (2018) were promising; the input variables needed for ETo estimates were accurately obtained using psychrometers (Cunha, 2013; Cunha & Volpe, 2014) and electronic sensors (Carvalho & Amorim, 2014; Enokela & Othoigbe, 2016), which are inexpensive, easily calibrated, and easy to operate.

Alternative stations have been considered to obtain weather variables in areas where accurate weather-observed data are not available (Lorite et al., 2018). Mobile monitoring systems are being used more frequently because of their advantages such as fast data collection and the capability to forecast environmental conditions of a determined location (Morón et al., 2018).

Accordingly, the objective of this study is to evaluate the performance of the ETo estimation, in hourly periodicity, using the Moretti-Jerszurki-Silva models, based on "atmospheric water potential ($ETo_{MJS(\psi air)}$)" and "atmospheric water potential and solar radiation ($ETo_{MJS(\psi air;Ra)}$)" considering air temperature (T) and relative air humidity (RH) data measured at a low-cost alternative weather station, developed for this purpose.

Material and Methods

The analysis of the present study was performed at the Agricultural Systems Modeling Laboratory (LAMOSA), Federal University of Paraná (UFPR). The estimates of hourly ETo with alternative (Moretti-Jerszurki-Silva models) and standard (Penman-Monteith model) methods were performed in Curitiba, PR (25° 26' 52.8" S latitude, 49° 13' 12" W longitude and altitude 923 m) and Santa Rita de Cássia, BA (11° 0' 7.2" S latitude, 44° 31' 26.4" W longitude and altitude 450 m), Brazil.

The Moretti-Jerszurki-Silva methodology that considers only the atmospheric water potential ($ETo_{MJS(\psi air)}$) was selected as linear (Eq. 1; Jerszurki et al., 2017) and quadratic (Eq. 2; Oliveira, 2018) functions to represent the associations of the calibration process:

$$ETo_{MJS(\psi_{air})_i} = a + b\ \psi_{air_i} \quad (1)$$

$$ETo_{MJS(\psi_{air})_i} = a\ \psi_{air_i}^{\ 2} + b\ \psi_{air_i} + c \quad (2)$$

where:

$ETo_{MJS(\psi air)}i$ - calibrated reference evapotranspiration estimated by atmospheric water potential at each i-hour, mm h^{-1};

ψ_{air_i} - atmospheric water potential at each i-hour, MPa; and,

a, b, and c - coefficients obtained in regression analysis of the relation between "ψ_{air} versus $ETo_{PM\text{-}ASCE}$" from calibration process (Eq. 1: coefficient a is in mm h^{-1} and b is in mm h^{-1} MPa^{-1}; Eq. 2: coefficient a is in mm h^{-1} MPa^{-2}, b is in mm h^{-1} MPa^{-1}, and c is in mm h^{-1}).

The Moretti-Jerszurki-Silva methodology that considers the atmospheric water potential and solar extraterrestrial radiation ($ETo_{MJS(\psi air;Ra)}$) were also selected as linear (Eq. 3; Jerszurki et al., 2017) and quadratic (Eq. 4; Oliveira, 2018) functions to represent the associations of the calibration process, based on equivalent evaporation (Eq. 5) and coefficient of proportionality of the atmospheric water potential (Eq. 6):

$$ETo_{MJS(\psi_{air};Ra)_i} = a + b\ Ee_i \quad (3)$$

$$ETo_{MJS(\psi_{air};Ra)_i} = a\ Ee_i^2 + b\ Ee_i + c \quad (4)$$

$$Ee_i = K_{\psi_{air_i}} \frac{Ra_i}{\lambda \cdot \rho_a} \quad (5)$$

$$K_{\psi_{air_i}} = \left| \frac{\psi_{air_i} - \psi_{air \cdot min}}{\psi_{air \cdot max} - \psi_{air \cdot min}} \right| \quad (6)$$

where:

$ETo_{MJS(\psi air;Ra)i}$ - reference evapotranspiration estimated using the Moretti-Jerszurki-Silva method with ψ_{air_i} and Ra_i at each i-hour, mm h^{-1};

a, b, and c - coefficients obtained in regression analysis of the relation between "Ee versus $ETo_{PM\text{-}ASCE}$" from calibration process (Eq. 3: coefficient a is in mm h^{-1} and b is dimensionless; Eq. 4: coefficient a is in (mm $h^{-1})^{-1}$, b is dimensionless, and c is in mm h^{-1});

Ee_i - equivalent evaporation at each i-hour, mm h^{-1};

Ra_i - extraterrestrial radiation at each i-hour, MJ m^{-2} h^{-1};

λ - latent heat of vaporization, 2.45 MJ kg^{-1};

$K\psi_{air_i}$ - coefficient of proportionality of atmospheric water potential at each i-hour, dimensionless;

ρ_a - density of water, kg L^{-1};

ψ_{airi} - atmospheric water potential at each i-hour, MPa; and,

$\psi_{air\ max}$ and $\psi_{air\ min}$ - maximum and minimum atmospheric water potential obtained in the experimental period, MPa.

The Moretti-Jerszurki-Silva methods estimate ETo based on atmospheric water potential (ψ_{air}), which can be calculated for hourly periods according to the following equation (Jerszurki et al., 2017):

$$\psi_{air_i} = \frac{R\ T_i}{M_v} \ln\left(\frac{ea_i}{es_i}\right) \tag{7}$$

where:

$\psi_{air.i}$ - atmospheric water potential at each i-hour, MPa;

R - gas constant, 8.314 J mol^{-1} K^{-1};

M_v - partial molar volume of water, 18×10^{-6} m^3 mol^{-1};

T_i - absolute temperature at each i-hour, K;

ea_i - actual vapor pressure at each i-hour, MPa; and,

es_i - saturated vapor pressure at each i-hour, MPa.

The extraterrestrial radiation (Ra) was estimated according to the ASCE-EWRI (2005) methodology:

$$\begin{aligned} Ra &= \frac{12}{\pi} G_{SC}\ dr\ \left[(\omega_2 - \omega_1)\ sen(\varphi)\ sen(\delta) + \right. \\ &+ \left. \cos(\varphi)\ \cos(\delta)\ \left(sen(\omega_2) - sen(\omega_1)\right)\right] \end{aligned} \tag{8}$$

where:

Ra - extraterrestrial radiation, MJ m^{-2} h^{-1};

G_{sc} - solar constant, 4.92 MJ m^{-2} h^{-1};

dr - relative distance of Earth-Sun, dimensionless;

ω_1 - hourly angle corresponding to period beginning, rad;

ω_2 - hourly angle corresponding to the period end, rad;

ϕ - latitude, rad; and,

δ - sun inclination, rad.

The $K_{\psi air_i}$ coefficients range from 0 to 1.0, establishing the proportionality between Ra (MJ m^{-2} h^{-1}) and Ee_i (mm h^{-1}). The standard unit conversion of solar radiation (Ra; MJ m^{-2} day^{-1}) to equivalent evaporation (mm h^{-1}) was performed using the conversion factor (0.408) defined by the inverse of latent heat of vaporization $1/\lambda$ (Pereira et al., 1997; Allen et al., 1998).

The standard hourly ETo was estimated using the Penman-Monteith equation presented by the American Society of Civil Engineers (Allen et al., 1998; ASCE-EWRI, 2005):

$$ETo_{PM-ASCE} = \frac{0.408\ \Delta\ (Rn - G) + \gamma\ \dfrac{Cn}{(T + 273)}\ u_2\ (es - ea)}{\Delta + \gamma\ (1 + Cd\ u_2)} \tag{9}$$

where:

$ETo_{PM\text{-}ASCE}$ - reference evapotranspiration, mm h^{-1};

Δ - slope of the saturated water vapor pressure curve, kPa °C^{-1};

Rn - net radiation at the crop surface, MJ m^{-2} h^{-1};

G - soil heat flux, MJ m^{-2} h^{-1};

γ - psychrometric constant, kPa °C^{-1};

T - average daily air temperature, °C;

u_2 - wind speed at 2 m height, m s^{-1};

es - saturation vapor pressure, kPa;

ea - actual vapor pressure, kPa; and,

Cn and Cd - constants that changes with reference type and calculation time step (Cn = 37 K mm s^3 Mg^{-1} h^{-1} for soil cover with short grass; $Cd_{daytime}$ - 0.24 s m^{-1} for daytime period; and, $Cd_{nighttime}$ - 0.96 s m^{-1} for nighttime period).

Analyses using the Penman-Monteith standard method (ASCE-EWRI, 2005) were conducted for a set of two National Meteorological Institute stations (INMET) distributed in two representative Brazilian climate types: i) Station A807, Curitiba, Paraná State, Brazil, Cfb climate type (Koppen classification), 25° 26' 52.8" S latitude, 49° 13' 12" W longitude, and altitude 923 m; and, ii) Station A415, Santa Rita de Cássia, Bahia State, Brazil, Aw climate type (Koppen classification), 11° 0' 7.2" S latitude, 44° 31' 26.4" W longitude, and altitude 450 m. The obtained hourly observations were from the spring and summer periods (October 2017 to January 2018), which considered maximum and minimum air temperature (T; °C), maximum and minimum relative air humidity (RH; %), incident solar radiation (h) and wind speed at 10 m height (m s^{-1}). The average T at each i-hour was obtained using the hourly maximum and minimum temperatures.

Hourly wind speed was obtained at a height of 10 m using an anemometer Vaisala WT521, and the wind speed was calculated using the wind profile relationship for a height of 2 m (Allen et al., 1998). Only daytime ETo was used in the analyses. Therefore, solar radiation data were considered for periods in which the sun was 17° above the horizon, by following the limits established for cloud cover function (f_{cd}) (ASCE-EWRI, 2005), to not cover nighttime values.

Analyses with the Moretti-Jerszurki-Silva method (Jerszurki et al., 2017) were carried out for an alternative meteorological station, located next to the two analyzed INMET stations (installed in the same tower with the automatic station), with hourly observations of T (°C) and RH (%), from spring to summer (October 2017 to January 2018).

An alternative meteorological station was built using simple technologies. It consisted of a set of humidity, air temperature, and pressure sensors, as well as a microcontroller. Hourly T was obtained with BMP180 sensor, with an amplitude of -40 to 85 °C for temperature and 300 to 1100 hPa for pressure, with an accuracy of 2 °C and 2.5 hPa, respectively. Relative air humidity was obtained with DTH11 sensor, with an amplitude of 20 to 100% and an accuracy of 5%. The estimates from the alternative station were interpreted using LUA programing language, a free and open source software (Ierusalimschy, 2006).

The data were recorded at predetermined time intervals of 15, 30, 45, and 60 min, stored in an SD card, and accessed over a wireless connection. Power was supplied with a 5-V voltage source, and an LED sensor indicated the station operation assisting the user in verification. The sensors were placed in a closed structure that allowed air circulation and protected them from being exposed to sun and rain.

The calibration of the alternative station consisted of performing linear regression analysis between T and RH data obtained at the "alternative" and "INMET automatic" stations, representing each location (Table 1). With the regression parameters obtained in the calibration, the alternative station was validated using a data set different from those applied during the calibration. Hourly data from Curitiba, PR (between October 10, 2017, to October 31, 2017) and Santa Rita de Cássia, BA (between January 1, 2018, to January 31, 2018) were used for the calibration and validation (Table 1) of alternative station and tested methods ($ETo_{MJS(\psi air)}$ and $ETo_{MJS(\psi air;Ra)}$).

After calibration and validation, the weather data (T and RH) obtained at the alternative station was analyzed using the Moretti-Jerszurki-Silva methods. The calibration and validation of Moretti-Jerszurki-Silva models were performed (Table 1) according to Jerszurki et al. (2017) and Oliveira (2018).

Hourly weather data (T and RH) obtained at the "alternative and INMET stations" and ETo estimates obtained using "Moretti-Jerszurki-Silva and standard PM-ASCE methods" were compared by regression analysis, root mean square error (RMSE), "d" (Willmott) and "c" (Camargo & Sentelhas) indexes (Souza, 2018).

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (E_i - O_i)^2}{\sum_{i=0}^{n} \left(|E_i - \bar{O}| + |Oi - \bar{O}| \right)^2} \right] \quad (10)$$

$$c = |r\ d| \quad (11)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (E_i - O_i)^2} \quad (12)$$

where:

d - agreement index of Willmott, dimensionless;

E_i - variable estimated by alternative methods at each i-hour, variable dimension;

O_i - variable estimated by standard method (Penman-Monteith or INMET station) at each i-hour, variable dimension;

$\bar{O}$ - mean of the variable estimated by standard method (Penman-Monteith or INMET station), variable dimension;

n - number of observations, dimensionless;

c - performance index of Camargo & Sentelhas, dimensionless;

r - correlation coefficient, dimensionless; and,

RMSE - root mean square error, variable dimension.

The interpretation criteria in terms of performance "c" was classified as "excellent" ("c" > 0.85), "very good" (0.75 < "c" ≤ 0.85), "good" (0.65 < "c" ≤ 0.75), "medium" (0.60 < "c" 0.65), "tolerable" (0.50 < "c" 0.60), "bad" (0.40 < "c" ≤ 0.50), and "terrible" ("c" ≤ 0.40).

Table 1. Associations performed in the calibration and validation analysis of the alternative station and Moretti-Jerszurki-Silva models

Specification	Analyzed association [(1)]
Calibration and validation of the alternative station developed	
Calibration	$T_{alternative\_station}$ vs $T_{INMET\_station}$ $RH_{alternative\_station}$ vs $RH_{INMET\_station}$
Validation	$T_{alternative\_station}$ vs $T_{INMET\_station}$ $RH_{alternative\_station}$ vs $RH_{INMET\_station}$
Calibration and validation of the Moretti-Jerszurki-Silva model considering only ψ_{air}	
Calibration	ψ_{air} vs $ETo_{PM-ASCE}$
Validation	$ETo_{MJS(\psi air)}$ vs $ETo_{PM-ASCE}$
Calibration and validation of the Moretti-Jerszurki-Silva model considering ψ_{air} and Ra	
Calibration	Ee vs $ETo_{PM-ASCE}$
Validation	$ETo_{MJS(\psi air;\ Ra)}$ vs $ETo_{PM-ASCE}$

(1) T - Air temperature; RH - Relative air humidity; ψ_{air} - Atmospheric water potential; Ee - Equivalent evaporation; Ra - extraterrestrial radiation

Results and Discussion

The calibration of the alternative station presented the coefficients of determination (R^2) to be higher than 0.80, considered satisfactory (Table 2) for T and RH in the analyzed locations. T and RH records for Curitiba, PR, Cfb climate type, had angular coefficient (b) approximately 1. For Santa Rita de Cássia, BA, Aw climate type, the angular coefficient (b) were >1.

The literature reports calibration processes for sensors that measure climate variables for several purposes. The calibration of the alternative station (Table 2) presented similar coefficients of determination as the normal range. While evaluating different regression methods to calibrate particulate matter sensors in Poland, Baduda et al. (2019) observed that the addition of T and RH measurements in the models resulted in good adjustments ($R^2 > 0.87$). Munir et al. (2019) evaluated the concentrations of NO and NO_2 (ppb) measured by calibrated sensors, along with meteorological data (wind speed, T and RH) in England, obtained $R^2 > 0.92$ for NO_2 concentration. Hojaiji et al. (2017) calibrated and validated T and RH sensors to monitor air quality and obtained values in the range of $0.45 \le R^2 \le 0.96$. Good results were also achieved by Yamamoto et al. (2017) while calibrating temperature sensors in Japan, with mean absolute errors of 0.19. Despite the diversity in the use of sensors, few studies involve the measurement of climate data with alternative and low-cost stations focused on ETo estimation.

The alternative station was not able to provide a unique calibration function for the variables and climatic environments

Table 2. Calibration of air temperature (°C) and relative air humidity (%) sensors: linear coefficient (a), angular coefficient (b), and coefficient of determination (R^2)

Location	Station	Climate	a	b	R^2
Air temperature (°C)					
Curitiba, PR	A807	Cfb	0.813	0.903	0.827
Santa Rita de Cássia, BA	A415	Aw	–15.533	1.656	0.835
Relative air humidity (%)					
Curitiba, PR	A807	Cfb	3.713	0.937	0.807
Santa Rita de Cássia, BA	A415	Aw	–5.946	1.125	0.836

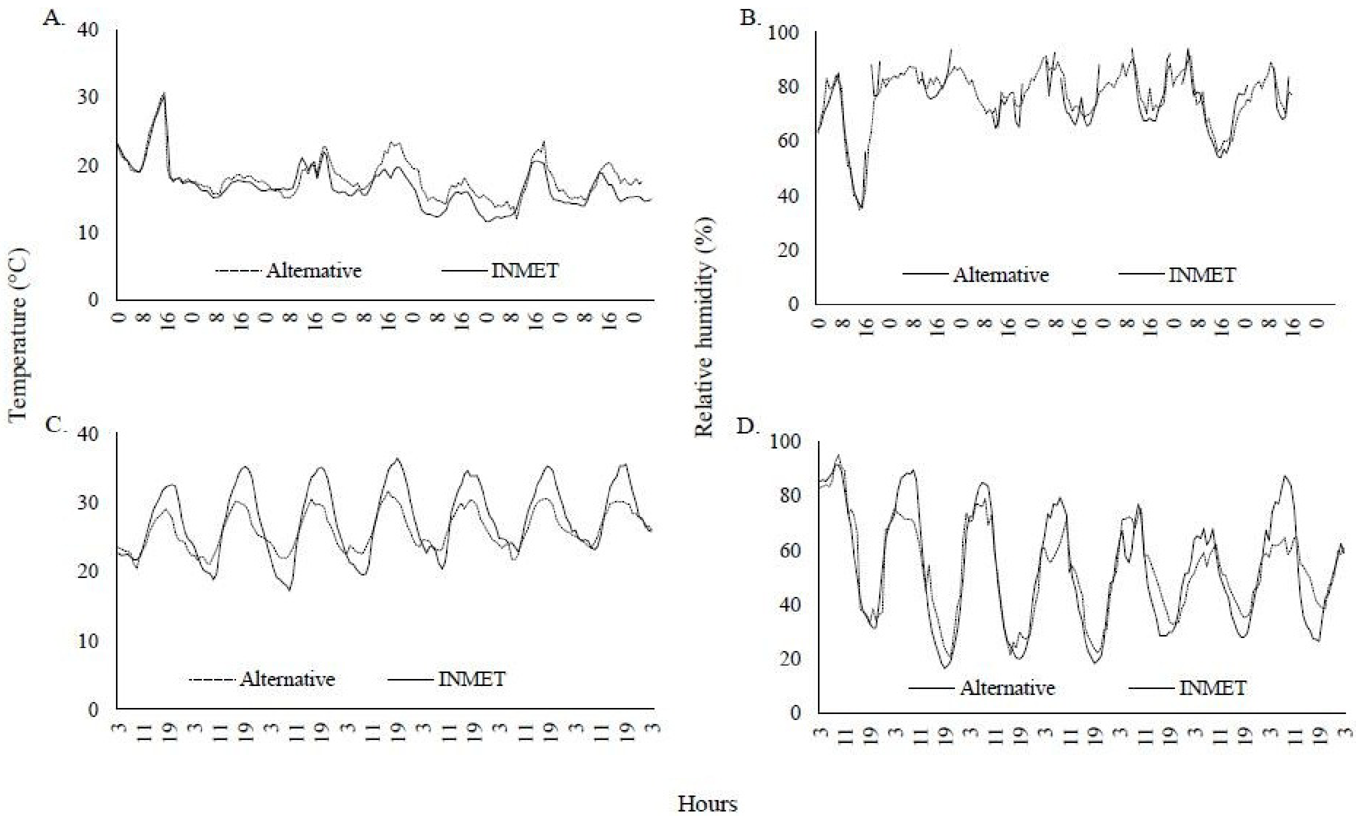
studied (Cfb and Aw climates, Table 2). Notably, the alternative station was the same in the two locations evaluated; however, the INMET stations were different, and it is normal that the coefficients of the calibration equation were not the same. In addition, the variability and intrinsic characteristics of each climatic type have to be considered (Aw - tropical; Cfb - subtropical). However, evidently, the coefficients of determination (R^2) were higher in the Aw climate, indicating better adjustment of the model and the measurements obtained in the alternative station.

In Aw climate type (Santa Rita de Cássia, BA), the lowest differences in T between the alternative and automatic stations occurred between 0:00 and 8:00 a.m. When T was above 25 °C, underestimations were made up to 5 °C between 7:00 and 9:00 p.m. For RH, better results occurred between 2:00 and 6:00 a.m. (Figures 1C and D). In Cfb climate type (Curitiba, PR), the highest similarities between the values measured in the alternative and automatic stations occurred between 6:00 and 12:00 a.m. and between 7:00 and 11:00 a.m. for T and RH, respectively (Figures 1A and B). It was not possible to identify a consistent reason that explained the variations occurring in the two locations. However, it is considered that the highest variation in Santa Rita de Cássia was due to the higher temperatures in this location, affecting the humidity and temperature sensors used.

The measured T and RH obtained from the INMET stations were used as standard data series during the validation of the alternative station for both Aw and Cfb climate types. Notably, the INMET station in Curitiba, PR (A807), presented failures in the RH data series during the validation period (Figure 2B). Thus, failure periods were identified and omitted from the statistical analyses. The temporal trends of the data series from the alternative station followed the hourly variation of T and RH, which indicates satisfactory responses to abrupt changes in these variables (Figures 2 and 3).

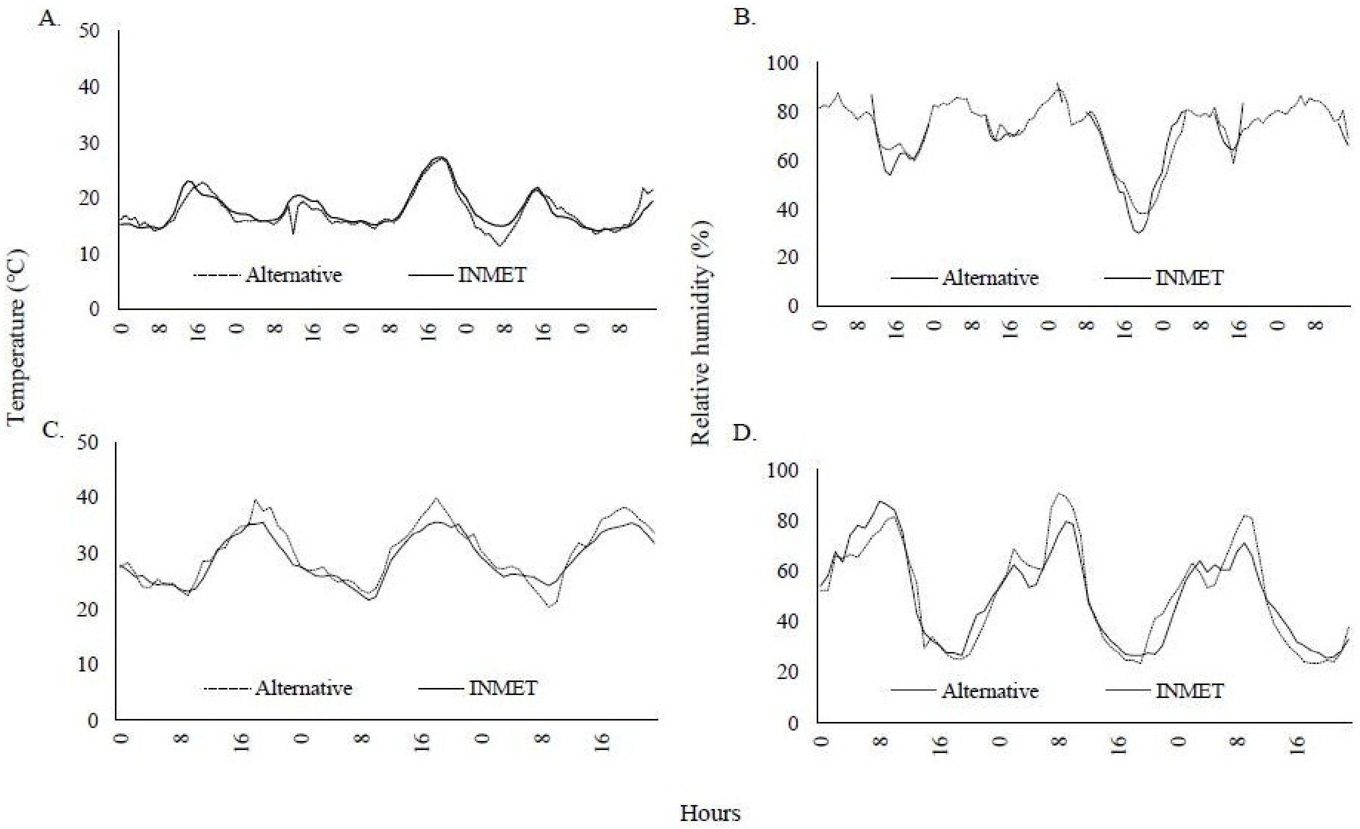
Good associations were observed for T and RH measurements ($r > 0.9$) between alternative and automatic stations (Figure 3), which confirmed the promising use of the alternative station in the analyzed climatic types. During the analyzed period, the amplitude of air temperature variation was up to 14 °C and 19 °C in the Cfb and Aw climate type, respectively. Sousa et al. (2015) studied the DHT22 sensor in Aw climate (Barra do Garça City, Mato Grosso State, Brazil) and performed calibration with data measured in an official automatic station, and found a strong association between T ($r = 0.94$) and RH ($r = 0.93$). The RH amplitude ranged from 30 to 61% in the Cfb climate type. In Aw climate type, minimum RH of 16% that resulted in an amplitude of up to 75% for the analyzed period was verified. On an average, RH was overestimated by 0.15% in the Cfb climate and 2.40% in the Aw climate. The highest underestimations recorded in the alternative station were verified under the conditions of higher RH in Santa Rita de Cássia, BA.

The RMSE of the T measurements was 1.4 °C in the Cfb climate and 1.94 °C in the Aw climate (Figure 3). For RH, the RMSE was verified as 3.75% for the Cfb climate and 5.56% for the Aw climate. Largest errors generally occurred for the extreme values (minimum and maximum) verified for the



Data measured between October 10, 2017 and October 31, 2017, in Curitiba, PR; and between January 1, 2018 and January 31, 2018, in Santa Rita de Cássia, BA

Figure 1. Air temperature and relative air humidity during the calibration, measured in the alternative and automatic stations: (A) Air temperature in Curitiba, PR; (B) Relative air humidity in Curitiba, PR; (C) Air temperature in Santa Rita de Cássia, BA; and, (D) Relative air humidity in Santa Rita de Cássia, BA



Data measured between October 10, 2017, and October 31, 2017, in Curitiba, PR; and between January 1, 2018 and January 31, 2018, in Santa Rita de Cássia, BA

Figure 2. Air temperature and relative air humidity measures in the alternative and automatic stations: (A) Air temperature in Curitiba, PR; (B) Relative air humidity in Curitiba, PR; (C) Air temperature in Santa Rita de Cássia, BA; and, (D) Relative air humidity in Santa Rita de Cássia, BA

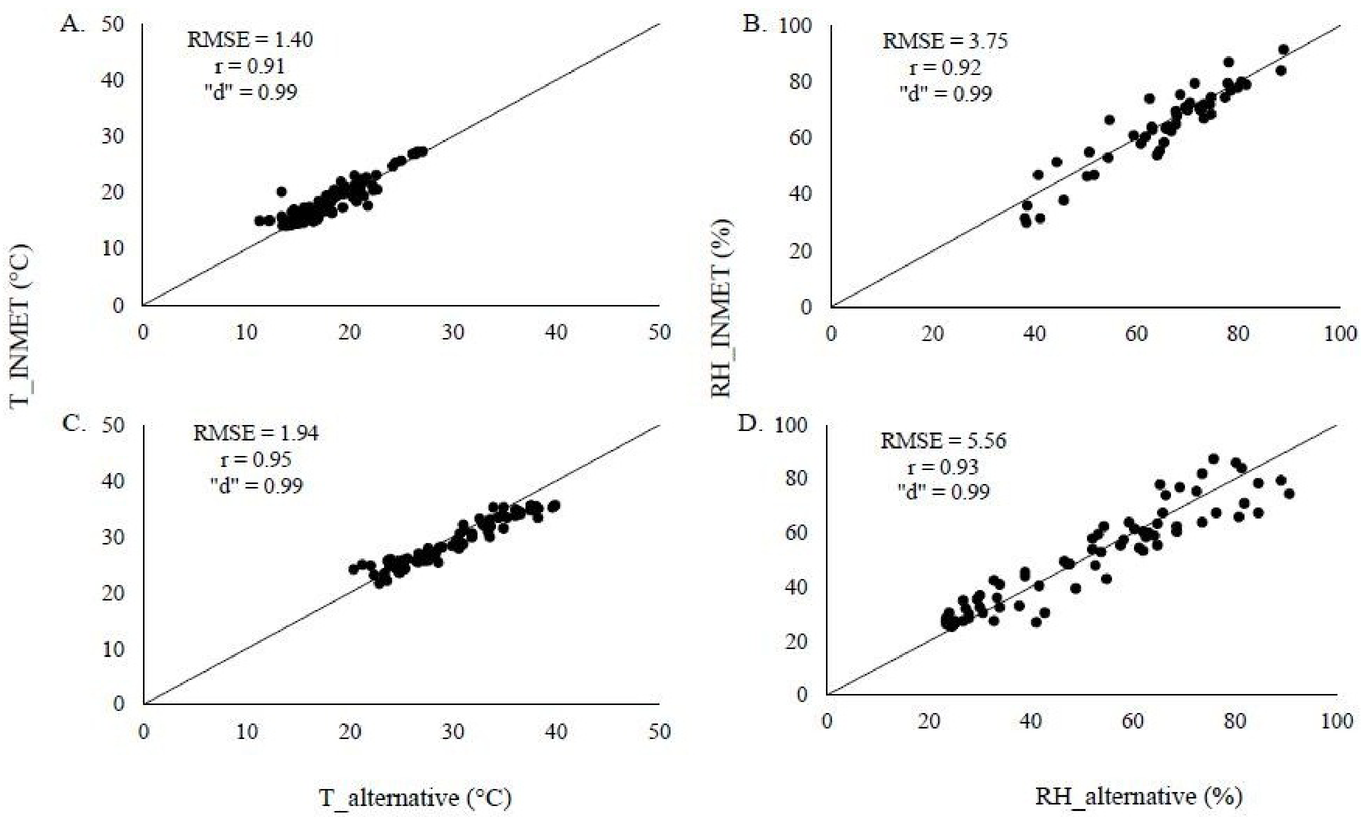


Figure 3. Correlation coefficient (r), root mean square error (RMSE) and "d" index, obtained in the validation of the mean air temperature and mean relative air humidity measured in the alternative and automatic stations: (A) "$T_{\_alternative}$ vs $T_{\_INMET\ (A807)}$", in Curitiba, PR; (B) "$RH_{\_alternative}$ vs $RH_{\_INMET\ (A807)}$", in Curitiba, PR; (C) "$T_{\_alternative}$ vs $T_{\_INMET\ (A415)}$", in Santa Rita de Cássia, BA; and, (D) "$RH_{\_alternative}$ vs $RH_{\_\ INMET\ (A415)}$", in Santa Rita de Cássia, BA

two variables (Figure 2). The RMSE obtained was promising because the sensitivity of the DHT11 sensor presented by sensor manufacturers is ± 5% for RH and ± 2 °C for T. The differences between the observed data from conventional and alternative instruments in electronic equipment are as expected (Silva et al., 2007; Miranda & Pereira, 2011; Torres et al., 2015). Palmieri et al. (2014) reported that errors up to 2.23 °C verified in electronic sensors for T can be considered irrelevant, and the results are reliable for physical process analyses in agricultural environments.

Several authors (Silva et al., 2007; Miranda & Pereira, 2011; Palmieri et al., 2014; Torres et al., 2015) consider that small variations between climatic data measured at different stations are normal. Thus, the use of low-cost alternative stations, such as the one tested in the present study, are appropriate for obtaining climatic data to estimate hourly ETo.

The results are considered satisfactory because of the simplicity and cost (US$ 150.00) of the alternative station for research, which could be used daily. The results obtained with r coefficient and "d" index indicate that the measurements obtained with the alternative station may be valid for using in hourly reference evapotranspiration estimation with Moretti-Jerszurki-Silva models (Figure 3).

Associations between "ψ_{air} versus $ETo_{PM\text{-}ASCE}$" and "Ee versus $ETo_{PM\text{-}ASCE}$" were established to verify the possibility of using T and RH values, measured in the alternative station. ψ_{air} and Ee were estimated with the same observed T and RH data measured at the alternative station. Climatic data obtained from the INMET automatic stations were used to estimate $ETo_{PM\text{-}ASCE}$.

The linear equation had a better adjustment for "Ee versus $ETo_{PM\text{-}ASCE}$" with a strong association (r = 0.89 in Cfb, and r = 0.94 in Aw climate type; Table 3). For "ψ_{air} versus $ETo_{PM\text{-}ASCE}$" association, the correlations were weak, and a better linear adjustment was observed in Cfb climate (r = 0.83) and quadratic adjustment in Aw climate type (r = 0.71). Oliveira (2018) also observed quadratic adjustment for some Brazilian locations for analyses considering hourly ETo. The result is interesting, and the adoption of a linear model provided small estimation errors in many validation situations.

In the validation of Moretti-Jerszurki-Silva models using data from the alternative station (Table 4 and Figure 4), the relation between "$ETo_{MJS(\psi air)}$ versus $ETo_{PM\text{-}ASCE}$" and "$ETo_{MJS(\psi air;Ra)}$ versus $ETo_{PM\text{-}ASCE}$" had smaller RMSE values, generally less than 0.021 mm h^{-1}. According to Zhang et al. (2017), RMSE < 0.186 mm h^{-1} is considered acceptable. In Curitiba, PR (Cfb climatic type), the highest errors occurred in the late afternoon, starting at 4:00 p.m.

With the exception of the association between "$ETo_{MJS(\psi air)}$ versus $ETo_{PM\text{-}ASCE}$", in Aw climate (Figure 4C), the proximity of the points to line of best fit in the other regression analyzes performed indicates the quality of results obtained (Table 4 and Figure 4), mainly in the association between "$ETo_{MJS(\psi air;Ra)}$ vs $ETo_{PM\text{-}ASCE}$" in Curitiba, PR, which provided "good" to "excellent" association. The performances were very promising and partly reflected the same aspects of the calibration process. The "$ETo_{MJS(\psi air)}$ versus $ETo_{PM\text{-}ASCE}$" association in Aw climate type, with measurements from the alternative station, presented "bad" performance, which was related to the weak correlation coefficient (r = 0.42), indicating high dispersion in relation to the regression line.

The results of the MJS(ψ_{air}) model in Santa de Cássia, BA were unexpected, as a similar dispersion as the other analysis was expected (Figure 4). Jerszurki et al. (2019) evaluated the sensitivity of daily ASCE Penman-Monteith reference evapotranspiration and observed that Brazilian climatic types, including Aw and Cfb, have variations in vapor pressure deficit (VPD) as the most sensitive variable for estimating daily ETo. The same authors concluded that VPD, calculated from the measurements of RH and T, is essential for accurately predicting ETo_{PM} across tropical and subtropical climates. Oliveira (2018) associated the estimated ETo with the "MJS(ψ_{air}) and MJS($\psi_{air;Ra}$) versus ASCE-PM" models in hourly periodicity and obtained index "c" ≥ 0.6 ("Good" performance) for Cristalina, GO, Brazil (Aw climate type), in seasonal periods, using data from INMET. The results obtained in the present study (Table 4 and Figure 4) indicated that Ra improved the ETo estimate in Santa Rita de Cássia. It is generally considered that the better performance of the MJS(ψ_{air}) and MJS($\psi_{air;Ra}$) models in Curitiba is related to the better association between T and RH data of the alternative station, obtained after calibration (Figure 2). In Santa Rita de Cássia, the amplitude of the hourly data readings was higher, mainly for RH (Figure 2). However, this aspect needs to be investigated in future by considering the main Brazilian climate types, more locations, and seasons of the year.

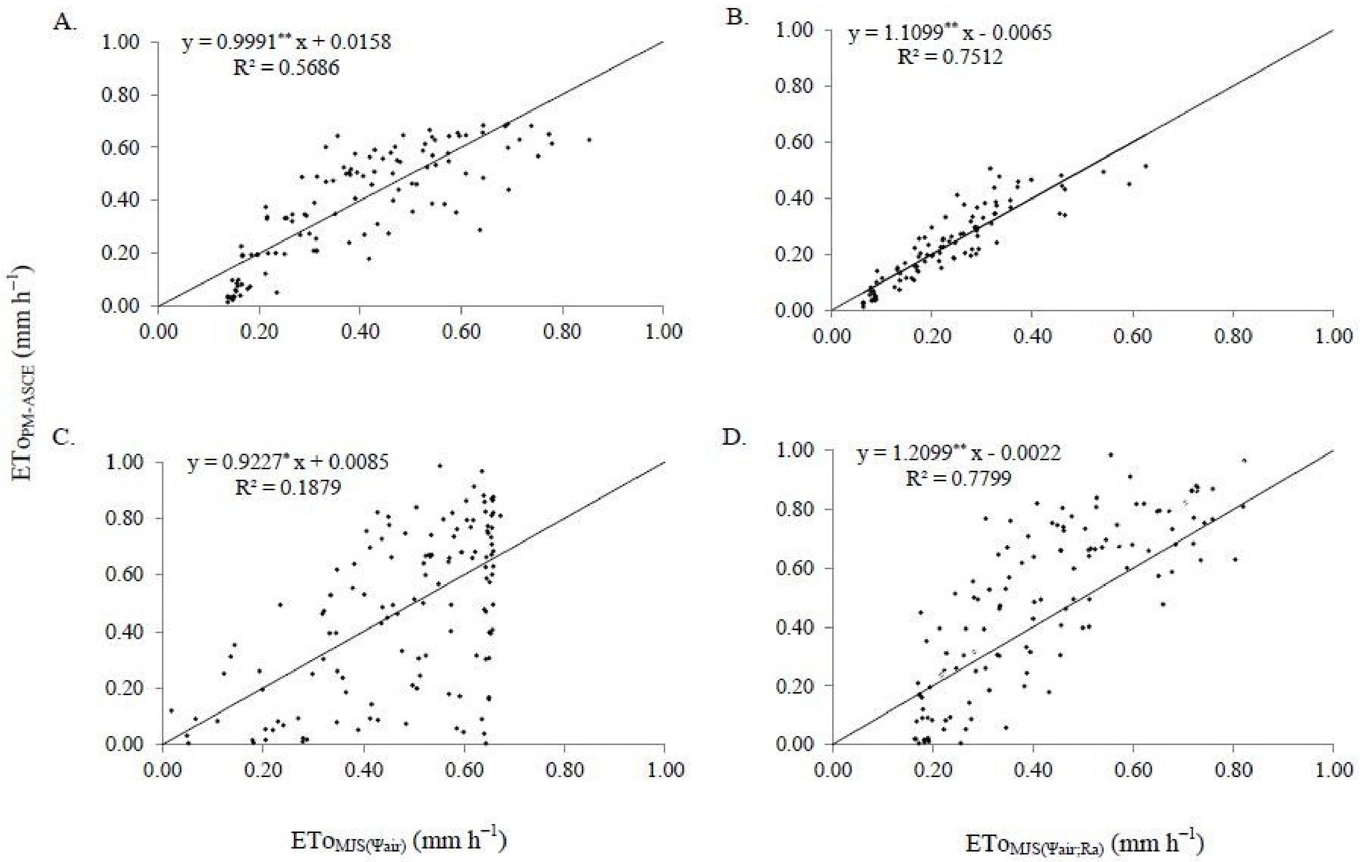
Table 3. Adjusted parameters of Moretti-Jerszurki-Silva (a, b, and c) models and correlation coefficient (r) obtained in calibration with the association between "ψ_{air} vs $ETo_{PM\text{-}ASCE}$" and "Ee vs $ETo_{PM\text{-}ASCE}$"

Location	$ETo_{MJS(\psi air)}$: association "ψ_{air} vs $ETo_{PM\text{-}ASCE}$"					$ETo_{MJS(\psi air;Ra)}$: association "Ee vs $ETo_{PM\text{-}ASCE}$"			
	Equation	a	b	c	r	Equation	a	b	r
Curitiba, PR	Linear	-0.039	0.053	—	0.83	Linear	0.024	0.471	0.89
Santa Rita de Cássia, BA	Quadratic	-3E-05	0.010	-0.175	0.71	Linear	0.108	0.607	0.94

Table 4. Validation of ETo estimated with Moretti-Jerszurki-Silva models using data measured at the alternative station, for the associations between "$ETo_{MJS(\psi air)}$ versus $ETo_{PM\text{-}ASCE}$" and "$ETo_{MJS(\psi air;Ra)}$ versus $ETo_{PM\text{-}ASCE}$"

Location	"$ETo_{MJS(\psi air)}$ vs $ETo_{PM\text{-}ASCE}$"					"$ETo_{MJS(\psi air;Ra)}$ vs $ETo_{PM\text{-}ASCE}$"				
	RMSE	r	"d"	"c"	Performance	RMSE	r	"d"	"c"	Performance
Curitiba, PR	0.011	0.75	0.90	0.68	good	0.009	0.87	0.98	0.85	excellent
Santa Rita de Cássia, BA	0.020	0.42	0.93	0.40	terrible	0.011	0.88	0.94	0.83	very good

RMSE - Root mean square error (mm h^{-1}); r - Correlation coefficient (dimensionless); "d" - "d" index (dimensionless); "c" - Performance index (dimensionless)



**, * - Significant at p ≤ 0.01 and p ≤ 0.05 by t test, respectively

Figure 4. Regression analysis and respective coefficient of determination (R^2) obtained for the associations: (A) "$ETo_{MJS(\psi air)}$ vs $ETo_{PM-ASCE}$" in Curitiba, PR; (B) "$ETo_{MJS(\psi air;Ra)}$ vs $ETo_{PM-ASCE}$", in Curitiba, PR; (C) "$ETo_{MJS(\psi air)}$ vs $ETo_{PM-ASCE}$" in Santa Rita de Cássia, BA; and, (D) "$ETo_{MJS(\psi air;Ra)}$ vs $ETo_{PM-ASCE}$", in Santa Rita de Cássia, BA

Jerszurki et al. (2017) considered that methods based on solar radiation have performed better in relation to the Penman-Monteith method in humid environments, as solar radiation is the main factor contributing to evapotranspiration (Allen et al., 1998). Thus, a better performance of the MJS($\psi_{air;Ra}$) model in the two locations analyzed (Table 4 and Figure 4) was expected.

Owing to the accuracy of "c" index, it is possible to affirm that the properly calibrated Moretti-Jerszurki-Silva models can provide acceptable estimates, even with the use of an alternative station designed to measure T and RH (Table 4). The methodologies tested (models and alternative station) can also be used in more sophisticated studies in the future, aiming to evaluate and quantify the dynamics and spatial variability of the reference evapotranspiration in fields or watersheds, with the assembly of sampling meshes for collecting data. Research of this nature will allow more detailed estimation of water movement in the soil-plant-atmosphere system.

Conclusions

1. The alternative station has performed exceptionally in obtaining hourly measurements of air temperature and relative air humidity in the subtropical Cfb (Curitiba, Paraná State) and tropical Aw (Santa Rita de Cássia, Bahia State) climate types.

2. With the exception of the model that considers only the atmospheric water potential in Santa Rita de Cássia, (MJS(ψ_{air})), the Moretti-Jerszurki-Silva models were robust in the analyzed locations, indicating satisfactory performance for the hourly periodicity. In particular, the use of atmospheric water potential and solar radiation in the simplified method MJS($\psi_{air;Ra}$) provided better adjustments and improved the accuracy of ETo estimates.

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