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# Evapotranspiration with the Moretti-Jerszurki-Silva model for the Brazilian sub-tropical climate

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**ABSTRACT**

The objective of this study was to evaluate the performance of the reference evapotranspiration at the hourly and daily scale, using the Moretti-Jerszurki-Silva alternative approach (MJS; $ETo_{MJS}$), for the Brazilian sub-tropical climate. Data from 25 automatic weather stations were used for calibration and validation analyses. In the linear correlation between $ETo_{MJS.h}$ and $ETo_h$ (ASCE-PM), at the hourly scale, it was found that: (i) values of $ETo_h$ were higher than those of $ETo_{MJS.h}$ in the daytime, while the opposite occurred at night-time; (ii) hourly $ETo_{MJS.h}$ and $ETo_h$ curves had an average two-hour delay; and (iii) the delay correction improves the correlation between $ETo_{MJS.h}$ and $ETo_h$. Statistically, there was better efficiency between $ETo_h$ and $ETo_{MJS.h}$ in the summer for *Cfa* climate and in the spring for *Cfb* climate. The MJS showed better efficiency concerning the Hargreaves and Samani, modified parametric and Penman-Monteith temperature models, being the best alternative methodology to estimate *ETo* at the daily scale in the sub-tropical region of Brazil.

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## 1 Introduction

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Evapotranspiration (*ET*) consists of water loss to the atmosphere through soil evaporation, the ground surface and plant transpiration. It is one of the main components of the hydrological cycle, being fundamental in water planning and management in drainage basins and agricultural crops. For a better understanding of trends and interactions between climatic variables in *ET*, the term reference evapotranspiration (*ETo*) was idealized, considering a hypothetical grass reference crop, with uniform and fixed cultivation height (0.12 m for grass and 0.50 m for alfalfa), fixed surface resistance of 70 s $m^{-1}$ and albedo of 0.23. The reference surface resembles an extensive grassy surface, without water restriction, experiencing active growth and completely shading the ground (Allen *et al.* 1998).

*ETo* is a water component that is difficult to measure directly, due to the costs for equipment such as evapotranspirometers or lysimeters, as well as the requirement for qualified labour to operate and maintain the equipment. For this reason, numerous indirect *ETo* estimation methods have been developed based on meteorological variables, and can be found in the literature (Alves Sobrinho *et al.* 2011, Moura *et al.* 2013, Tegos *et al.* 2013, 2015, 2017, Fenner *et al.* 2019).

Among the indirect methods, the Penman model and its derivatives are widely studied due to their physical basis. In the current literature, the American Society of Civil Engineers (ASCE-PM) model, derived from the Food and Agriculture Organization (FAO) Penman-Monteith method, is considered to be the most suitable, recognized for presenting good precision and approximation with lysimeter data. However, the ASCE-PM model is complex and requires a large amount of meteorological data (air temperature, relative humidity, wind speed and solar radiation), which is not always available, or may not be available in sufficient quantities or quality for the activity to be performed (Moura *et al.* 2013, Maina *et al.* 2014, Nolz and Rodný 2019).

Due to the difficulty of using highly complex methods of calculation that require many input parameters, simpler alternative methods based on fewer input parameters and climatic variables have been formulated (Owusu-Sekyere *et al.* 2017). Among the models recommended in the literature, the Hargreaves and Samani (HS; Hargreaves and Samani 1985), Penman-Monteith temperature (PMT; Raziei and Pereira 2013, Paredes *et al.* 2020b) and modified parametric (PET; Tegos *et al.* 2017) models stand out due to the simplicity and precision in obtaining daily values of evapotranspiration. The PMT approach uses the Penman-Monteith equation as a base, and the input variables are estimated with equations that consider air temperature. The wind speed is considered using default or regional average values (Raziei and Pereira 2013, Paredes *et al.* 2020b). Tegos *et al.* (2017) introduced an innovative approach, the PET model for estimating potential evapotranspiration. The authors observed high efficiency of the model in relation to other important models for estimating evapotranspiration in different climatic regimes worldwide.

The ASCE-PM method (ASCE-EWRI 2005) allows the estimation of hourly evapotranspiration ($ETo_h$), including night-time periods. The sum over a 24-h period for $ETo_h$ integrates the values of daily evapotranspiration ($ETo_d$) (Alves Sobrinho *et al.* 2011, Treder and Klamkowski 2017). Yildirim *et al.* (2004) emphasize the importance of *ETo* analysis at the hourly scale, allowing estimates with higher precision and flexibility for agricultural

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management. In addition, it has an aspect focused on the physical understanding of this phenomenon. However, research with alternative methodologies that estimate *ETo* at the hourly scale is still in the initial phase for regions in Brazil.

Jerszurki *et al.* (2017) and Oliveira (2018) carried out interesting studies with an alternative method for estimating *ETo*, which considers the atmospheric water potential ($\Psi air$) as an input. Oliveira (2018) conducted preliminary studies indicating very satisfactory results in adapting the Moretti-Jerszurki-Silva method (MJS) developed by Jerszurki *et al.* (2017) to estimate *ETo* at the hourly scale. The $\Psi air$ calculation requires only the temperature and relative humidity. An interesting aspect is that the measurement of the two variables is easy and makes it possible to estimate *ETo* at night-time, something more complicated to solved by the alternative methods that consider solar radiation. The MJS model considers the atmospheric water potential ($\Psi air$) as the most sensitive and active component for the occurrence of *ETo* (Jerszurki *et al.* 2017). The $\Psi air$ calculation is based on the first and second laws of thermodynamics (Philip 1964, Hillel 1971).

Given the context presented, this study aims to evaluate the performance of the reference evapotranspiration at the hourly and daily scale, using the MJS approach ($ETo_{MJS}$), for the sub-tropical climate in Paraná State, Southern Brazil.

## 2 Material and methods

### 2.1 Study location

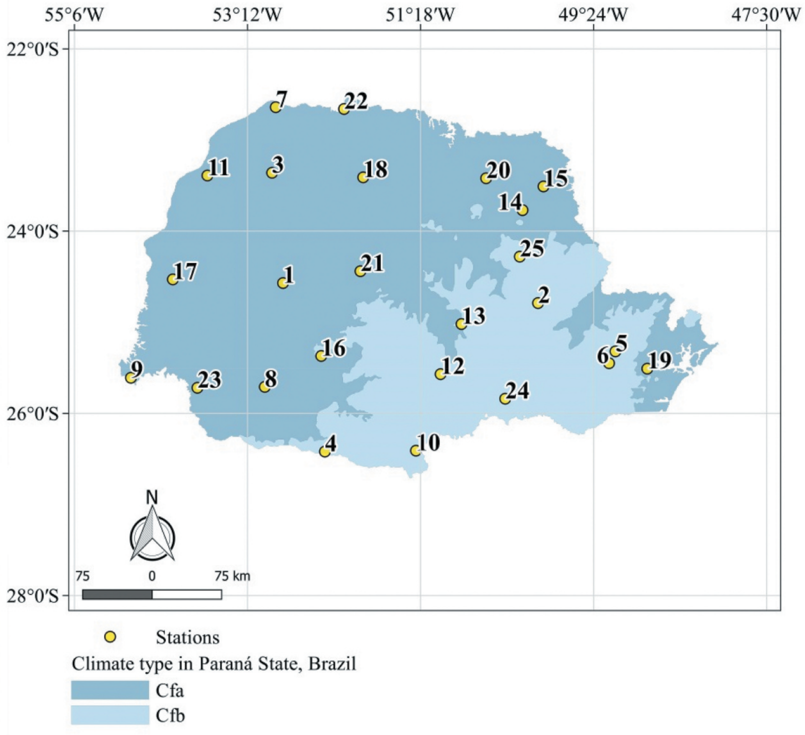
The present study was carried out for the Paraná State (Fig. 1), sub-tropical region of Southern Brazil, with an area of 199 307 922 km$^2$ and predominance *Cfa* and *Cfb* climate types, according to Maack (2012). The *Cfa* sub-tropical climate has a good rainfall distribution, with an average 1500 mm year$^{-1}$, and an average annual temperature of 19°C. The *Cfb* sub-tropical climate presents rainfall of more than 1200 mm year$^{-1}$, well distributed throughout the year, and a temperate summer, with an annual average temperature of 17°C (Alvares *et al.* 2013).

### 2.2 Weather data used

Data series from 25 automatic weather stations (Fig. 1) were used, obtained from the National Institute of Meteorology (INMET), covering the period from 1 December 2016 to 8 November 2018.

The following climate data were required to estimate the hourly and daily *ETo* with the ASCE-PM ($ETo_h$ and $ETo_d$, respectively) model: maximum and minimum air temperatures ($T$; °C); maximum and minimum relative humidity ($RH$; %); incident solar radiation ($Rs$; MJ m$^{-2}$ h$^{-1}$); and wind speed at 10 m height ($u_{10}$; m s$^{-1}$), which was later converted to 2 m height ($u_2$; m s$^{-1}$) at an hourly scale (Allen *et al.* 1998).

The total number of hours analysed is 424 800, or 2 548 800 data points in total (6 variables × 424 800 h = 2 548 800 data), for the 25 stations analysed. However, it was decided to exclude periods with climatic input variable that presented failure on readings data to estimate *ETo*, as well as out-of-normal values or outliers. With this data correction, 331 344 hours or 1 988 064 data were effectively used in the $ETo_h$ and $ETo_{MJS.h}$ calculations, representing a 22% reduction in the total hours.



| Stations | Lat. | Lon. |
|---|---|---|
| 1 - Campina da Lagoa | -24.57 | -52.81 |
| 2 - Castro | -24.79 | -50.01 |
| 3 - Cidade Gaucha | -23.36 | -52.93 |
| 4 - Clevelandia | -26.42 | -52.35 |
| 5 - Colombo | -25.32 | -49.16 |
| 6 - Curitiba | -25.45 | -49.23 |
| 7 - Diamante do Norte | -22.64 | -52.89 |
| 8 - Dois Vizinhos | -25.71 | -53.01 |
| 9 - Foz do Iguacu | -25.61 | -54.48 |
| 10 - General Carneiro | -26.41 | -51.35 |
| 11- Icaraima | -23.39 | -53.64 |
| 12 - Inacio Martins | -25.57 | -51.08 |
| 13 - Ivai | -25.02 | -50.85 |
| 14 - Japira | -23.77 | -50.18 |
| 15 - Joaquim Tavora | -23.51 | -49.95 |
| 16 - Laranjeiras do Sul | -25.37 | -52.39 |
| 17 - Marechal Candido Rondon | -24.53 | -54.02 |
| 18 - Maringa | -23.41 | -51.93 |
| 19 - Morretes | -25.51 | -48.81 |
| 20 - Nova Fatima | -23.42 | -50.58 |
| 21 - Nova Tebas | -24.44 | -51.96 |
| 22 - Paranapoema | -22.66 | -52.14 |
| 23 - Planalto | -25.72 | -53.75 |
| 24 - Sao Mateus do Sul | -25.84 | -50.37 |
| 25 - Ventania | -24.28 | -50.21 |

**Figure 1.** Predominant climate types in Paraná State and location of weather stations. Source: Adapted from Paraná Agronomic Institute (IAPAR 2019); adapted from de Brazilian Institute of Geography and Statistics (IBGE 2010).

### 2.3 Estimation of reference evapotranspiration (ETo) at the hourly scale

The estimation of hourly *ETo* ($ETo_h$; standard) was performed with the standardized Penman-Monteith equation (Equation (1)), presented by the American Society of Civil Engineers (ASCE-EWRI 2005), using a short crop height of 0.12 m.

$$\boldsymbol{ETo_h} = \frac{0.408 \cdot (\boldsymbol{Rn} - \boldsymbol{G}) + \gamma \cdot \frac{\boldsymbol{Cn}}{(\boldsymbol{T}+273)} \cdot \boldsymbol{u}_2 \cdot (\boldsymbol{es} - \boldsymbol{ea})}{\Delta + \gamma \cdot (1 + \boldsymbol{Cd} \cdot \boldsymbol{u}_2)} \quad (1)$$

where $ETo_h$ is the reference evapotranspiration at each *i* hour (mm $h^{-1}$); Δ is the slope of the saturated water–vapour–pressure curve to the air temperature in the period considered (kPa $°C^{-1}$); 0.408 is the inverse value of the latent heat of vaporization (λ = 2.45 MJ $kg^{-1}$); *Rn* is the net radiation balance in the period considered (MJ $m^{-2}$ $h^{-1}$); *G* is the soil heat flux in the period considered (MJ $m^{-2}$ $h^{-1}$); *γ* is the psychrometric constant (kPa $°C^{-1}$); *Cn* is the constant related to the type of vegetation and time scale considered ($Cn_{hourly}$ = 37 K mm $s^3$ $Mg^{-1}$ $h^{-1}$ for soil cover with short grass); *T* is the average air temperature in the period considered (°C); $u_2$ is the wind speed at 2 m height in the period considered (m $s^{-1}$); *es* is the saturation vapour pressure in the period considered (kPa); *ea* is the actual vapour pressure in the period considered (kPa); and *Cd* is the constant related to the type of vegetation and time scale (considered $Cd_{\text{daytime}}$ = 0.24 s $m^{-1}$ for daytime period and short grass, or $Cd_{\text{nighttime}}$ = 0.96 s $m^{-1}$ for nighttime period and short grass).

The hourly $ETo_{MJS.h}$ was calculated using the MJS model, which considers only the atmospheric water potential *Ψair* ($ETo_{MJS}$ as a function of *Ψair*; Equations (2) and (3)):

$$\boldsymbol{ETo_{MJS.h}} = \boldsymbol{a} + \boldsymbol{b} \cdot \boldsymbol{\Psi air_h} \quad (2)$$

$$\boldsymbol{\Psi air_h} = \frac{\boldsymbol{R} \cdot \boldsymbol{T}}{\boldsymbol{M_v}} \cdot \ln\left(\frac{\boldsymbol{ea}}{\boldsymbol{es}}\right) \quad (3)$$

where $ETo_{MJS.h}$ is the reference evapotranspiration estimated with the atmospheric water potential (mm $h^{-1}$); *a* is the linear coefficient obtained from the linear regression equation, resulting from the relation between $Ψair_h$ and $ETo_h$ (mm $h^{-1}$); *b* is the angular coefficient obtained in the linear regression equation, resulting from the relation between $Ψair_h$ and $ETo_h$ (mm $h^{-1}$ $MPa^{-1}$; MPa is megapascal); $Ψair_h$ is the atmospheric water potential at each *i* hour (MPa); *R* is the gas constant (8.314 J $mol^{-1}$ $K^{-1}$); *T* is the average air temperature in the period considered (K); *Mv* is the partial molar volume of water ($18.10^{-6}$ $m^3$ $mol^{-1}$); *ea* is the actual vapour pressure in the period considered (MPa); and *es* is the saturation vapour pressure in the period considered (MPa).

The analysis with the model that estimates $ETo_{MJS.h}$ was carried out in two stages:

(i) The first stage, according to Jerszurki *et al.* (2017), consisted in calculating the values for the $Ψair_h$ (Equation (3)) and $ETo_h$ (Equation (1)) series. Then the calibration was performed by a simple linear regression analysis between $Ψair_h$ and $ETo_h$, to obtain the *a* and *b* coefficients to use in Equation (2) to estimate the $ETo_{MJS.h}$. Calibration was performed for 25 weather stations analysed in Paraná State, considering the climate data for the period from 1 December 2016 to 1 December 2017.

(ii) The second stage consisted in analysing the performance of the method that estimates $ETo_{MJS.h}$ (Equation (2)), performing a correlation between $ETo_{MJS.h}$ and $ETo_h$. Validation analyses were performed for 25 weather stations tested in Paraná State, considering the climate data for the period from 2 December 2017 to 8 November 2018.

### 2.4 Estimation of reference evapotranspiration (ETo) at the daily scale

The reference evapotranspiration estimates at the daily scale with the MJS, HS (Hargreaves and Samani 1985), PET (Tegos *et al.* 2017) and PMT methods were compared with the estimates performed by the ASCE-PM method. The estimation was performed for 24 weather stations in the Paraná State, considering the climate data for the period from 2 December 2017 to 8 November 2018.

The methods ASCE-PM ($ETo_h$; Equation (1)) and MJS ($ETo_{MJS.h}$; Equations (2) and (3)), calculated at the hourly scale, had the *ETo* of the 24 hours of the day added to compose the daily values: $ETo_d$ and $ETo_{MJS.d}$, respectively. The HS and PET methods were calculated using Equations (4) and (5). The PMT method was calculated with Equation (1), using as input, for each location, the maximum and minimum daily temperatures and the average normal wind speed at 2 m height (Raziei and Pereira 2013, Paredes *et al.* 2020a, 2020b). As the areas analysed have a humid climate (*Cfa* and *Cfb*), the $T_{dew}$ was considered equal to [$T_{mean}$ – 2°C] (Paredes *et al.* 2020b), and the incident solar radiation (*Rs*) was estimated with the Hargreaves and Samani equation (Equation (6)), adopting the coefficient $K_{Rs}$ = 0.16°$C^{-5}$, characteristic of inland sites proposed in FAO 56 (Allen *et al.* 1998).

$$\boldsymbol{ETo_{HS.d}} = 0.0023 \cdot \frac{\boldsymbol{Ra}}{\lambda} \cdot \sqrt{(\boldsymbol{T_{max}} - \boldsymbol{T_{min}})} \cdot (\boldsymbol{T} + 17.8) \quad (4)$$

$$\boldsymbol{PET_d} = \frac{\boldsymbol{a'} \cdot \boldsymbol{Ra}}{1 - \boldsymbol{c'} \cdot \frac{\boldsymbol{T_{min}} + \boldsymbol{T_{max}}}{2}} \quad (5)$$

$$\boldsymbol{Rs_{HS}} = \boldsymbol{k_{R_s}} \cdot (\boldsymbol{T_{max}} - \boldsymbol{T_{min}})^2 \cdot \boldsymbol{Ra} \quad (6)$$

where $ETo_{HS.d}$ is the evapotranspiration at each *i* day, estimated with the Hargreaves and Samani equation (mm $day^{-1}$); $PET_d$ is the potential evapotranspiration at each *i* day, estimated with the modified parametric model (mm $day^{-1}$; Tegos *et al.* 2017); $Rs_{HS}$ is the daily shortwave solar radiation (MJ $m^{-2}$ $d^{-1}$) directly expressed as influenced by $K_{Rs}$ (°$C^{-5}$), required in the calculation of the PMT; *λ* is the latent heat of vaporization (2.45 MJ $kg^{-1}$); *Ra* is the extraterrestrial radiation (MJ $m^{-2}$ $day^{-1}$); *T* is the temperature (°C), which can be maximum, minimum or medium; and *a'* and *c'* are the parameters of PET equation. The extraterrestrial radiation (*Ra*) was calculated according to Allen *et al.* (1998).

The parameters *a'* and *c'* of the PET equation were obtained using the inverse distance weighted (IDW) method, in the *R* software. Values of *a'* and *c'* obtained from Tegos *et al.* (2017) for the Paraná State (Maringá: *a'* = 0.0000875 and *c'* = 0.0037; Curitiba: *a'* = 0.0000570 and *c'* = 0.0153; and Ponta Grossa: *a'* = 0.0000547 and *c'* = 0.0166) were interpolated and extrapolated to the entire state.

### 2.5 Statistical analysis for comparison

The values of hourly and daily *ETo* obtained with the MJS ($ETo_{MJS.h}$ and $ETo_{MJS.d}$), HS ($ETo_{HS.d}$), PET ($ETo_{PET.d}$), PMT ($ETo_{PMT.d}$) and ASCE-PM ($ETo_h$ and $ETo_d$) methods were compared and verified in linear regression analysis, as well as the main error (root mean square error), index (Willmott's "*d*" agreement) and coefficient (Pearson's *r* correlation) recommended in the literature (Jacovides and Kontoyiannis 1995) and the model efficiency (Nash and Sutcliffe 1970):

$$\boldsymbol{RMSE} = \sqrt{\frac{1}{\boldsymbol{n}}\cdot\sum_{\boldsymbol{i}=1}^{\boldsymbol{n}}\left(\boldsymbol{ETo}_{\boldsymbol{p}_i} - \boldsymbol{ETo}_{\boldsymbol{a}_i}\right)^2}$$

$$\boldsymbol{r} = \frac{\sum_{\boldsymbol{i}=1}^{\boldsymbol{n}}\left[\left(\boldsymbol{ETo}_{\boldsymbol{p}_i} - \overline{\boldsymbol{ETo}}_{\boldsymbol{p}}\right)\cdot\left(\boldsymbol{ETo}_{\boldsymbol{a}_i} - \overline{\boldsymbol{ETo}}_{\boldsymbol{a}}\right)\right]}{\sqrt{\sum_{\boldsymbol{i}=1}^{\boldsymbol{n}}\left(\boldsymbol{ETo}_{\boldsymbol{p}_i} - \overline{\boldsymbol{ETo}}_{\boldsymbol{p}}\right)^2\cdot\sum_{\boldsymbol{i}=1}^{\boldsymbol{n}}\left(\boldsymbol{ETo}_{\boldsymbol{a}_i} - \overline{\boldsymbol{ETo}}_{\boldsymbol{a}}\right)^2}}$$

$$\boldsymbol{d} = 1 - \frac{\sum_{\boldsymbol{i}=1}^{\boldsymbol{n}}\left(\boldsymbol{ETo}_{\boldsymbol{a}_i} - \boldsymbol{ETo}_{\boldsymbol{p}_i}\right)^2}{\sqrt{\sum_{\boldsymbol{i}=1}^{\boldsymbol{n}}\left(\left|\boldsymbol{ETo}_{\boldsymbol{a}_i} - \overline{\boldsymbol{ETo}}_{\boldsymbol{p}}\right|\left|\boldsymbol{ETo}_{\boldsymbol{p}_i} - \overline{\boldsymbol{ETo}}_{\boldsymbol{p}}\right|\right)^2}}$$

$$\boldsymbol{NSE} = 1 - \frac{\sum_{\boldsymbol{i}=1}^{\boldsymbol{n}}\left(\boldsymbol{ETo}_{\boldsymbol{p}_i} - \boldsymbol{ETo}_{\boldsymbol{a}_i}\right)^2}{\sum_{\boldsymbol{i}=1}^{\boldsymbol{n}}\left(\boldsymbol{ETo}_{\boldsymbol{p}_i} - \overline{\boldsymbol{ETo}}_{\boldsymbol{p}}\right)^2}$$

where *RMSE* is the root mean square error (mm period$^{-1}$); *r* is the Pearson correlation coefficient (dimensionless); *d* is the agreement index of Willmott (1982) (dimensionless); *NSE* is the Nash-Sutcliffe model efficiency (dimensionless); $\boldsymbol{ETo}_{\boldsymbol{p}_i}$ is the reference evapotranspiration estimated with the standard ASCE-PM method at each *i* period (mm period$^{-1}$); $\boldsymbol{ETo}_{\boldsymbol{a}_i}$ is the reference evapotranspiration estimated with the alternative approach (MJS, HS, PET, PMT) at each *i* period (mm period-$^{-1}$); *n* is the number of days or hours analysed (dimensionless); $\overline{\boldsymbol{ETo}}_{\boldsymbol{p}}$ is the mean reference evapotranspiration estimated with the standard ASCE-PM method (mm period$^{-1}$); and $\overline{\boldsymbol{ETo}}_{\boldsymbol{a}}$ is the mean reference evapotranspiration estimated with the alternative approach (MJS, HS, PET or PMT; mm period$^{-1}$). The period considered varies according to the time scale (hourly or daily).

## 3 Results and discussion

### 3.1 Estimation of reference evapotranspiration (ETo) at the hourly scale

Twenty-five weather stations were analysed between 1 December 2016 and 8 November 2018, 15 in the *Cfa* climate type and 10 in *Cfb*. Air temperature (*T*), relative humidity (*RH*), incident solar radiation (*Rs*) and wind speed at 2 m height ($u_2$) in general showed very similar trends among the predominant climates of Paraná (Fig. 2). It was observed that: (i) *T* was higher in the spring (approximately 20°C for *Cfa* climate and 18°C for *Cfb*) and summer (24°C for *Cfa* and 19°C for *Cfb*); (ii) *RH* showed no high seasonal variations for either climate, being between 66% and 80% throughout the year, with winter displaying the lowest *RH* for *Cfa* (66%) and summer for *Cfb* (74.9%); (iii) *Rs* showed a similar trend to *T*, with higher *Rs* periods in the spring (0.84 MJ m$^2$ h$^{-1}$ for *Cfa* and 0.75 MJ m$^2$ h$^{-1}$ for *Cfb*) and summer (0.95 MJ m$^2$ h$^{-1}$ for *Cfa* and 0.94 MJ m$^2$ h$^{-1}$ for *Cfb*); and (iv) $u_2$ showed a similar trend to *RH*, with little seasonal variation, being between 0.95 and 1.45 m s$^{-1}$, with the highest values observed during the autumn period (1.45 m s$^{-1}$ for *Cfa* and 1.36 m s$^{-1}$ for *Cfb*).

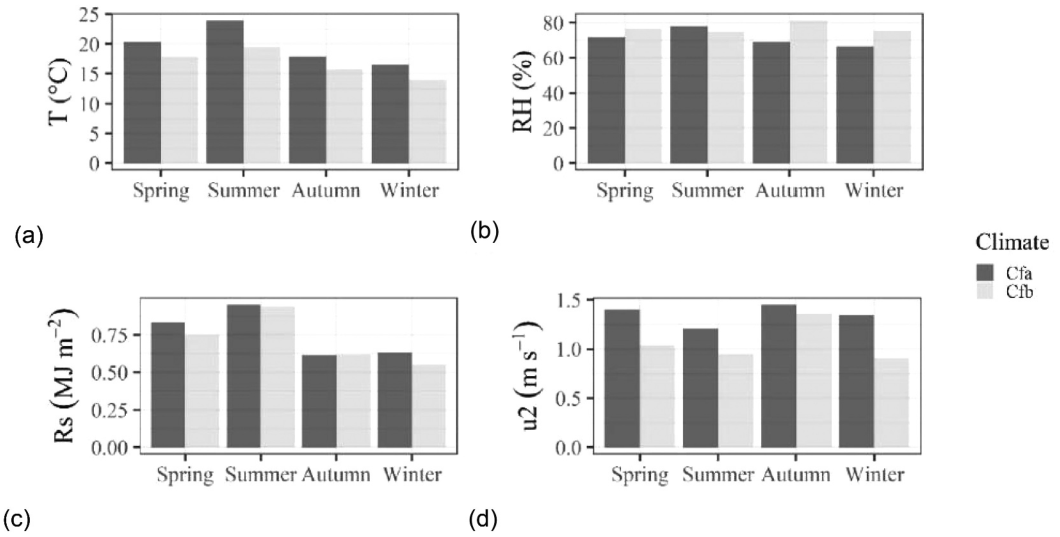


**Figure 2.** Seasonal average variation of the climatic variables of 15 and 10 weather stations in *Cfa* and *Cfb* climate types, respectively, in Paraná State, for the period 1 December 2016 to 8 November 2018: (a) air temperature (*T*; °C); (b) relative humidity (*RH*; %); (c) incident solar radiation (*Rs*; MJ m$^{-2}$ h$^{-1}$); (d) wind speed at 2 m height ($u_2$; m s$^{-1}$).

### 3.2 Calibration of the MJS model to obtain "a" and "b" parameters

As the hourly values of *ETo* are low, the "*a*" parameters (linear coefficient of the MJS model) were between −0.0079 and 0.0328 mm h$^{-1}$ for *Cfa* climate, and between −0.024 and 0.026 mm h$^{-1}$ for *Cfb* climate (Table 1). The "*b*" parameters (angular coefficient of the MJS model) were between −6.96E-09 and −2.61E-09 mm h$^{-1}$ MPa$^{-1}$ for locations with *Cfa* climate, and between −5.59E-09 and −2.9E-09 mm h$^{-1}$ MPa$^{-1}$ for *Cfb*. The coefficients obtained in the correlation between $\Psi air_h$ and $ETo_h$ were not as narrow as those obtained by Oliveira (2018), at the hourly scale, for *Cfa* ($0.81 \le r \le 0.96$) and *Cfb* ($0.84 \le r \le 0.90$) climates. However, Oliveira (2018) performed linear and quadratic adjustments in their analyses. The range of correlation coefficients in this study is wider and lower than those obtained by Oliveira (2018) due to the longer period analysed here. In the present study, in addition to making only linear adjustments, a one-year hourly data period was used, whereas Oliveira (2018) used only two months of hourly data in their calibration analyses. Thus, removing the Campina da Lagoa station ($r$ = 0.37), the correlation coefficients were $0.51 \le r \le 0.77$ for locations with *Cfa* climate, and $0.58 \le r \le 0.78$ for locations with *Cfb* climate.

The results of calibration performed with the MJS model in the present study are consistent with those obtained by Jerszurki *et al.* (2017) at the daily scale, and with Oliveira (2018) at daily and hourly scale. There is evidence that the MJS model has less sensitivity in humid sub-tropical climates, due to the small range between the lowest and highest value of the atmospheric water potential ($\Psi air$). The lower range, or amplitude, is due to the lower temperatures and higher *RH* values (Jerszurki *et al.* 2017). All of these aspects contributed to the fact that the correlation coefficient ($r$) values were not so narrow in the correlation between $\Psi air_h$ and $ETo_h$, as was verified in arid and semi-arid climates (Jerszurki *et al.* 2017, Oliveira 2018). In addition, the number of data used in the regression analysis for each location was very high ($4045 \le n \le 8614$; Table 1), which increases variability and generally tends to reduce the values of $r$ when working with climate data.

With the values of the parameters "*a*" and "*b*" of the MJS model for each one of the 25 weather stations analysed in the Paraná State, the results were interpolated and a map of the parameters values was developed (Fig. 3). Once established, the coefficients "*a*" and "*b*" from each type of climate can be extrapolated to locations that present the same climatic characteristics, without requiring new calibrations.

**Table 1.** Calibration of the MJS model for 25 weather stations located in *Cfa* and *Cfb* climate types, in Paraná State, for the period 1 December 2016 to 1 December 2017: linear coefficient ("*a*"); angular coefficient ("*b*"); correlation coefficient (*r*); and number of data in the analyses (*n*).

| Weather station | *a* | *b* | *r* | *n* |
|---|---|---|---|---|
| | (mm h$^{-1}$) | (mm h$^{-1}$ MPa$^{-1}$) | (dimensionless) | |
| | *Cfa* climate | | | |
| Campina da Lagoa | 0.0328 | −3.1307E-09 | 0.37 | 7487 |
| Cidade Gaúcha | −0.0079 | −2.9987E-09 | 0.57 | 7093 |
| Diamante do Norte | 0.0162 | −3.0102E-09 | 0.55 | 8509 |
| Dois Vizinhos | 0.0278 | −2.4630E-09 | 0.55 | 6524 |
| Foz do Iguaçu | 0.0098 | −3.9421E-09 | 0.68 | 6422 |
| Icaraíma | 0.0197 | −2.6140E-09 | 0.51 | 7651 |
| Japirá | 0.0153 | −2.6234E-09 | 0.51 | 7496 |
| Joaquim Távora | −0.0024 | −3.2096E-09 | 0.58 | 8389 |
| Marechal Cândido Rondon | 0.0020 | −3.5451E-09 | 0.69 | 7993 |
| Maringá | 0.0034 | −2.7126E-09 | 0.56 | 8371 |
| Morretes | 0.0008 | −6.9641E-09 | 0.77 | 4045 |
| Nova Fátima | 0.0085 | −4.1062E-09 | 0.73 | 6209 |
| Nova Tebas | 0.0151 | −3.0851E-09 | 0.57 | 8417 |
| Paranapoema | −0.0133 | −4.0179E-09 | 0.68 | 7182 |
| Planalto | 0.0208 | −3.1454E-09 | 0.61 | 7462 |
| Average for *Cfa* climate | 0.0099 | −3.4379E-09 | 0.60 | 7283 |
| | *Cfb* climate | | | |
| Castro | −0.011 | −3.486E-09 | 0.71 | 8614 |
| Clevelândia | −0.004 | −2.990E-09 | 0.69 | 4629 |
| Colombo | −0.009 | −4.580E-09 | 0.76 | 8378 |
| Curitiba | −0.024 | −3.595E-09 | 0.66 | 5697 |
| General Carneiro | −0.012 | −4.610E-09 | 0.78 | 8161 |
| Inácio Martins | −0.002 | −5.535E-09 | 0.73 | 5404 |
| Ivaí | −0.011 | −3.674E-09 | 0.68 | 8053 |
| Laranjeiras do Sul | −0.009 | −4.139E-09 | 0.73 | 7461 |
| São Mateus do Sul | −0.001 | −3.868E-09 | 0.73 | 7405 |
| Ventania | 0.026 | −3.165E-09 | 0.58 | 7042 |
| Average for *Cfb* climate | −0.006 | −3.964E-09 | 0.71 | 7084 |

### 3.3 Validation of the MJS model: variation and correlation between $ETo_{MJS.h}$ and $ETo_h$ in Paraná State

The *Cfa* and *Cfb* climates showed similar trends between the $ETo_{MJS.h}$ and $ETo_h$ methods. There was no considerable variation in the values of *ETo* ($ETo_{MJS.h}$ and $ETo_h$) between seasons. In the autumn period there were many input data errors (lack of data), and therefore, this seasonal period was not evaluated. Similarly, the months of February and March showed many failures in input data and, for this reason, these months were also not analysed (Table 2 and Fig. 4).

The averages of $ETo_{MJS.h}$ and $ETo_h$ for the seasonal and monthly periods were very close (Fig. 4(a) and (b)). The highest amplitudes between $ETo_{MJS.h}$ and $ETo_h$ occurred in the winter, a period in which the *RH* remains high and the values of *T* were lower. Jerszurki *et al.* (2017) and Oliveira (2018), analysing the MJS model as a function of only $\Psi air$, for several Brazilian climate types, also found that the model performance worsened in these conditions – in other words, for colder and wetter climates or periods. The highest discrepancies occurred in Dois Vizinhos and Nova Tebas cities for *Cfa* climate, and in Clevelândia for *Cfb* climate.

In the validation process of the 25 locations in Paraná State, excluding the autumn period (all locations) and Clevelândia and Nova Tebas stations, due to problems with the climatic data, the following statistical indicators of the MJS model were found in the correlation between $ETo_{MJS.h}$ and $ETo_h$ (Table 3):

- The correlation coefficients ($r$) were lower in winter for *Cfa* ($0.53 \le r \le 0.82$) and *Cfb* ($0.81 \le r \le 0.84$) climates, and higher in summer and spring for *Cfa* ($0.69 \le r \le 0.93$) and *Cfb* ($0.91 \le r \le 0.93$);
- The *NSE* was higher in the spring ($-2.29 \le NSE \le 0.82$) and lower in the winter ($-13.90 \le NSE \le 0.49$) for *Cfa* climate. Disregarding autumn, due to the lack of data, it was found in the *Cfb* climate that the mean value observed was a better predictor than the simulated value.

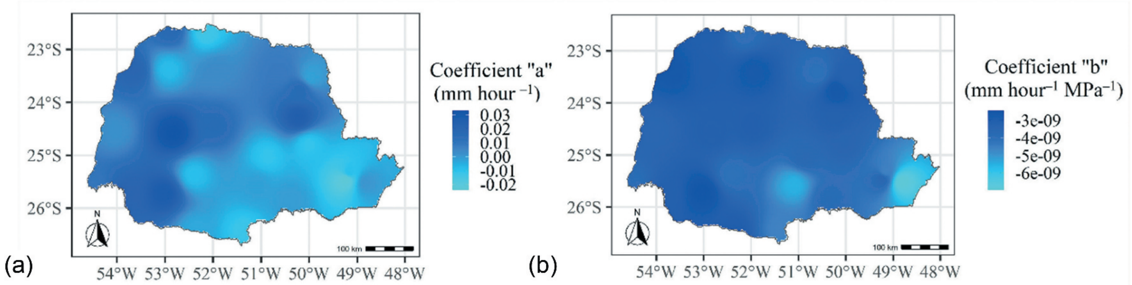


**Figure 3.** Spatialization of "*a*" and "*b*" coefficients of the Moretti-Jerszurki-Silva model, in Paraná State: (a) linear coefficient ("*a*"; mm $h^{-1}$); (b) angular coefficient ("*b*"; mm $h^{-1}$ $MPa^{-1}$).

**Table 2.** Seasonal averages[a] of $ETo_{MJS.h}$ and $ETo_h$ (mm $h^{-1}$) of 25 weather stations in Paraná State, for the period 2 December 2017 to 8 November 2018.

| Weather station | Spring | | Summer | | Autumn | | Winter | | Annual average | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $ETo_{MSJ.h}$ | $ETo_h$ | $ETo_{MSJ.h}$ | $ETo_h$ | $ETo_{MSJ.h}$ | $ETo_h$ | $ETo_{MSJ.h}$ | $ETo_h$ | $ETo_{MSJ.h}$ | $ETo_h$ |
| | (mm $h^{-1}$) | | | | | | | | | |
| | | | | *Cfa* climate | | | | | | |
| Campina da Lagoa | 0.10 | 0.10 | 0.10 | 0.12 | – | – | 0.10 | 0.07 | 0.10 | 0.10 |
| Cidade Gaúcha | 0.15 | 0.14 | 0.09 | 0.14 | – | – | 0.20 | 0.11 | 0.15 | 0.13 |
| Diamante do Norte | 0.10 | 0.11 | 0.09 | 0.12 | – | – | 0.10 | 0.07 | 0.10 | 0.10 |
| Dois Vizinhos | 0.10 | 0.11 | 0.09 | 0.12 | – | – | 0.10 | 0.07 | 0.10 | 0.10 |
| Foz do Iguaçu | 0.12 | 0.11 | 0.11 | 0.12 | – | – | 0.12 | 0.07 | 0.12 | 0.10 |
| Icaraíma | 0.08 | 0.09 | 0.09 | 0.13 | – | – | 0.09 | 0.07 | 0.09 | 0.10 |
| Japirá | 0.09 | 0.11 | 0.08 | 0.12 | – | – | 0.09 | 0.07 | 0.09 | 0.10 |
| Joaquim Távora | 0.09 | 0.11 | 0.08 | 0.12 | – | – | 0.09 | 0.07 | 0.08 | 0.10 |
| Marechal Cândido Rondon | 0.10 | 0.11 | 0.09 | 0.12 | – | – | 0.10 | 0.07 | 0.10 | 0.10 |
| Maringá | 0.08 | 0.11 | 0.07 | 0.12 | – | – | 0.08 | 0.07 | 0.08 | 0.10 |
| Morretes | 0.19 | 0.11 | 0.17 | 0.12 | – | – | 0.19 | 0.07 | 0.19 | 0.10 |
| Nova Fátima | 0.12 | 0.11 | 0.11 | 0.12 | – | – | 0.12 | 0.07 | 0.12 | 0.10 |
| Nova Tebas | 0.12 | 0.11 | 0.11 | 0.12 | – | – | 0.12 | 0.07 | 0.12 | 0.10 |
| Paranapoema | 0.10 | 0.11 | 0.09 | 0.12 | – | – | 0.10 | 0.07 | 0.09 | 0.10 |
| Planalto | 0.20 | 0.22 | 0.17 | 0.22 | – | – | 0.25 | 0.17 | 0.20 | 0.20 |
| Average for *Cfa* climate | 0.12 | 0.11 | 0.10 | 0.13 | – | – | 0.12 | 0.08 | 0.11 | 0.11 |
| | | | | *Cfb* climate | | | | | | |
| Castro | 0.11 | 0.12 | 0.09 | 0.14 | 0.08 | 0.07 | 0.11 | 0.08 | 0.10 | 0.11 |
| Clevelândia | 0.08 | 0.02 | 0.07 | 0.03 | – | – | 0.08 | 0.02 | 0.08 | 0.02 |
| Colombo | 0.12 | 0.11 | 0.11 | 0.12 | – | – | 0.12 | 0.07 | 0.11 | 0.10 |
| Curitiba | 0.08 | 0.11 | 0.07 | 0.12 | – | – | 0.08 | 0.07 | 0.07 | 0.10 |
| General Carneiro | 0.12 | 0.11 | 0.11 | 0.12 | – | – | 0.12 | 0.07 | 0.11 | 0.10 |
| Inácio Martins | 0.15 | 0.11 | 0.14 | 0.12 | – | – | 0.15 | 0.07 | 0.14 | 0.10 |
| Ivaí | 0.12 | 0.11 | 0.11 | 0.12 | – | – | 0.12 | 0.07 | 0.11 | 0.10 |
| Laranjeiras do Sul | 0.11 | 0.11 | 0.10 | 0.12 | – | – | 0.11 | 0.07 | 0.10 | 0.10 |
| São Mateus do Sul | 0.11 | 0.11 | 0.10 | 0.13 | – | – | 0.11 | 0.08 | 0.10 | 0.10 |
| Ventania | 0.11 | 0.11 | 0.11 | 0.12 | – | – | 0.11 | 0.07 | 0.11 | 0.10 |
| Average for *Cfb* climate | 0.11 | 0.10 | 0.10 | 0.11 | 0.08 | 0.07 | 0.11 | 0.07 | 0.11 | 0.09 |

[a] The seasons were considered to occur in the following periods: summer begins on 21 December and ends on 20 March; autumn begins on 21 March and ends on 20 June; winter begins on 21 June and ends on 22 September; and spring begins on 23 September and ends on 20 December.

- The "*d*" index, which measures the proximity of the associated values in relation to the 1:1 line, also indicated lower values in winter for both *Cfa* ($0.38 \le d \le 0.89$) and *Cfb* ($0.54 \le d \le 0.89$) climates, and higher values in summer and spring for *Cfa* ($0.5 \le d \le 0.95$) and *Cfb* ($0.73 \le d \le 0.97$).
- On average, the *RMSE* values obtained were also low. By season, winter also showed the highest errors for *Cfa* ($0.02 \le RMSE \le 0.13$) and *Cfb* ($0.02 \le RMSE \le 0.9$) climates, whereas the error was lower in summer and spring for *Cfa* ($0.02 \le RMSE \le 0.14$) and *Cfb* ($0.02 \le RMSE \le 0.06$).

In general, it was found that $ETo_{MJS.h}$ presented higher values on average than $ETo_h$ at night-time (Fig. 5(a) and (c)). With the sunrise, $ETo_h$ became progressively higher than the $ETo_{MJS.h}$. Considering the input variables in both models (MJS and ASCE-PM), the results are consistent. *T* and *RH* are considered directly or indirectly in both methodologies. The ASCE-MP method considers *Rs* and $u_2$ while the MJS method does not. Thus, at night-time there are no *Rs* and the $u_2$ is low, providing lower values of *ETo*. During the day, the opposite occurs, considering that *Rs* and $u_2$ are higher, favouring higher values of *ETo*.

In checks of all daily and average trends (Fig. 5(a) and (c)) of the hourly *ETo*, for 25 weather stations in Paraná State (*Cfa* and *Cfb* climates), we found the existence of a delay on the maximum *ETo* point obtained with the two methodologies (MJS and ASCE-PM). For the ASCE-PM model, the maximum $ETo_h$ occurred at between 12:00 and 14:00 hours (except for Clevelândia station), the time when the highest values of incident solar radiation are generally observed. For the MJS model,

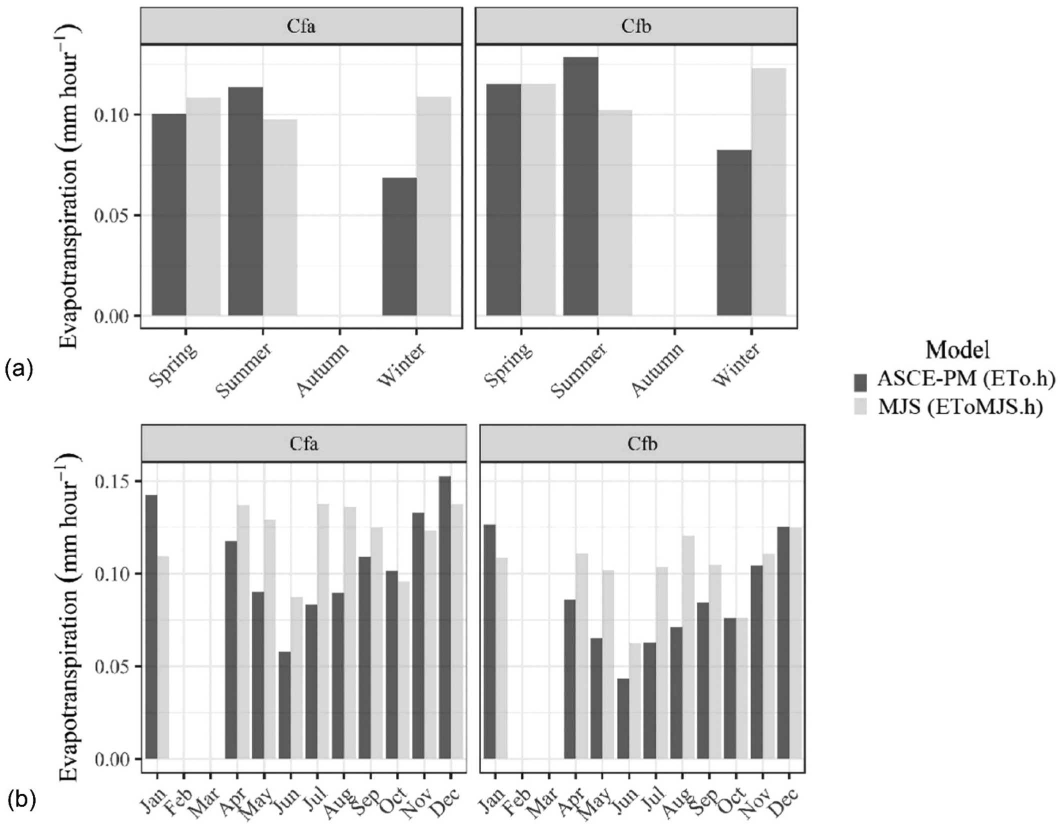


**Figure 4.** Averages of $ETo_{MJS.h}$ and $ETo_h$, at the hourly scale, from weather stations according to the *Cfa* and *Cfb* climate types, in Paraná State, for the period 2 December 2017 to 8 November 2018: (a) seasonal average; (b) monthly average.

the maximum $ETo_{MJS.h}$ occurred between 14:00 and 16:00 hours (Fig. 5(a) and (c)), a period in which the highest temperatures of the day and the lowest relative humidity generally occur. This aspect is interesting and deserves to be investigated. On average, there was a delay of approximately two hours delay in the curve of the hourly *ETo* value throughout the day, estimated using both methodologies (Fig. 5(a) and (c)).

Although the statistical results shown in Table 3 are very promising, the delay in the values of *ETo* estimated with both methodologies (MJS and ASCE-PM) certainly limited the statistical measures used to verify the validation process of the correlation between $ETo_{MJS.h}$ and $ETo_h$ (Tables 2 and 3). Thus, correcting the hours and analysing the effect of the delay on *ETo* estimates can lead to better and more promising statistical indicators for an alternative method as simple as the MJS, to estimate hourly *ETo*.

The correction of the two-hour delay between $ETo_{MJS.h}$ and $ETo_h$ on all days, at the 25 stations analysed in Paraná State, provided an average trend as shown in Fig. 5(b) and (d). With the correction, the occurrence time of maximum *ETo* estimated with the MJS model started to coincide with the ASCE-PM methodology. With the adjustment made, there was an improvement in the correlation between $ETo_{MJS.h}$ and $ETo_h$ (Fig. 6).

The existence of a delay between the values of $ETo_{MJS.h}$ and $ETo_h$ for *Cfa* and *Cfb* climates, in Paraná State, generated uncertainty regarding the existence of a similar trend for the *ETo* estimated with the two methodologies for the main climates in Brazil (*Af, Am, Aw, BSh; Cfa, Cfb, Cwa* and *Cwb*). This is an important aspect and will need to be investigated in more detail later, considering the findings obtained in the present study and the conclusions of Oliveira (2018). It would be interesting to verify the magnitude and time of occurrence of the highest and lowest hourly values of *ETo* estimated with the ASCE-PM and MJS methodologies, as well as the existence and cause of delays in the trends of the estimated values for $ETo_{MJS.h}$ and $ETo_h$.

### 3.4 Estimation of reference evapotranspiration (ETo) at the daily scale

In the analysed period (2 December 2017 to 8 November 2018), not all alternative approaches tested (MJS, HS, PET and PMT) showed average values of daily *ETo* very close to those obtained with the standard ASCE-PM model (Table 4). The average values of daily *ETo* estimated for the 24 weather stations in the Paraná State were interpolated and presented on maps (Fig. 7). The location of Clevelândia was excluded from the analyses as it had a lot of missing data.

The indexes, errors and statistical coefficients indicated better performance of the MJS model in the 24 locations and climates (*Cfa* and *Cfb*) analysed in the Paraná State (Table 5). Although the values of $ETo_{MJS.d}$ resulted from the 24-hour sum, as in the ASCE-PM ($ETo_d$), it is believed that the calibration of the "*a*" and "*b*" coefficients of the model contributed substantially to improving

**Table 3.** Seasonal[a] and annual values of Nash-Sutcliffe efficiency (*NSE*; dimensionless), "*d*" index (dimensionless), root mean square error (*RMSE*; mm $h^{-1}$) and correlation coefficient (*r*; dimensionless) between $ETo_{MJS.h}$ and $ETo_h$, of 15 and 10 weather stations in *Cfa* and *Cfb* climate types, respectively, in Paraná State, for the period 2 December 2017 to 8 November 2018.

| Weather station | Spring | | | | Summer | | | | Autumn | | | | Winter | | | | Annual average | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *NSE* | *d* | *RMSE* | *r* | *NSE* | *d* | *RMSE* | *r* | *NSE* | *d* | *RMSE* | *r* | *NSE* | *d* | *RMSE* | *r* | *NSE* | *d* | *RMSE* | *r* |
| *Cfa* climate | | | | | | | | | | | | | | | | | | | | |
| Campina da Lagoa | 0.73 | 0.90 | 0.03 | 0.88 | 0.52 | 0.81 | 0.04 | 0.89 | – | – | – | – | −0.45 | 0.67 | 0.04 | 0.71 | 0.27 | 0.79 | 0.04 | 0.83 |
| Cidade Gaúcha | 0.49 | 0.89 | 0.05 | 0.81 | 0.11 | 0.76 | 0.07 | 0.84 | – | – | – | – | −5.40 | 0.53 | 0.11 | 0.73 | −1.60 | 0.73 | 0.08 | 0.73 |
| Dois Vizinhos | 0.24 | 0.77 | 0.06 | 0.72 | −0.67 | 0.66 | 0.07 | 0.76 | – | – | – | – | −8.87 | 0.38 | 0.06 | 0.74 | −3.10 | 0.60 | 0.06 | 0.68 |
| Diamante do Norte | 0.82 | 0.94 | 0.02 | 0.93 | 0.55 | 0.85 | 0.04 | 0.92 | – | – | – | – | 0.06 | 0.79 | 0.03 | 0.81 | 0.48 | 0.86 | 0.03 | 0.83 |
| Foz do Iguaçu | 0.80 | 0.95 | 0.02 | 0.93 | 0.79 | 0.94 | 0.03 | 0.92 | – | – | – | – | −1.31 | 0.68 | 0.05 | 0.81 | 0.09 | 0.86 | 0.03 | 0.83 |
| Icaraíma | 0.76 | 0.91 | 0.02 | 0.92 | 0.47 | 0.81 | 0.05 | 0.93 | – | – | – | – | 0.38 | 0.83 | 0.03 | 0.81 | 0.54 | 0.85 | 0.03 | 0.83 |
| Joaquim Távora | 0.72 | 0.92 | 0.03 | 0.93 | 0.33 | 0.80 | 0.05 | 0.92 | – | – | – | – | 0.44 | 0.87 | 0.03 | 0.81 | 0.50 | 0.86 | 0.04 | 0.83 |
| Japirá | 0.68 | 0.89 | 0.03 | 0.93 | 0.29 | 0.77 | 0.05 | 0.92 | – | – | – | – | 0.49 | 0.85 | 0.02 | 0.81 | 0.49 | 0.84 | 0.03 | 0.83 |
| Marechal Cândido Rondon | 0.84 | 0.95 | 0.02 | 0.92 | 0.56 | 0.87 | 0.04 | 0.92 | – | – | – | – | −0.06 | 0.80 | 0.04 | 0.81 | 0.45 | 0.87 | 0.03 | 0.83 |
| Maringá | 0.55 | 0.86 | 0.04 | 0.93 | 0.06 | 0.73 | 0.06 | 0.92 | – | – | – | – | 0.06 | 0.89 | 0.02 | 0.81 | 0.23 | 0.83 | 0.04 | 0.83 |
| Morretes | −2.29 | 0.68 | 0.10 | 0.93 | 0.42 | 0.80 | 0.07 | 0.92 | – | – | – | – | −13.90 | 0.40 | 0.13 | 0.82 | −5.26 | 0.63 | 0.10 | 0.84 |
| Nova Fátima | 0.75 | 0.94 | 0.03 | 0.93 | 0.83 | 0.95 | 0.02 | 0.92 | – | – | – | – | −1.72 | 0.65 | 0.06 | 0.81 | −0.05 | 0.85 | 0.04 | 0.83 |
| Nova Tebas | 0.21 | 0.71 | 0.14 | 0.71 | −0.01 | 0.74 | 0.07 | 0.81 | – | – | – | – | 0.19 | 0.65 | 0.11 | 0.53 | 0.13 | 0.70 | 0.11 | 0.60 |
| Paranapoema | 0.80 | 0.95 | 0.02 | 0.92 | 0.40 | 0.85 | 0.04 | 0.89 | – | – | – | – | −0.13 | 0.80 | 0.04 | 0.80 | 0.36 | 0.87 | 0.03 | 0.82 |
| Planalto | 0.68 | 0.91 | 0.05 | 0.86 | −2.26 | 0.50 | 0.06 | 0.69 | – | – | – | – | −1.51 | 0.67 | 0.10 | 0.79 | −1.03 | 0.69 | 0.07 | 0.73 |
| Average for *Cfa* climate | 0.45 | 0.88 | 0.04 | 0.88 | 0.16 | 0.79 | 0.05 | 0.88 | – | – | – | – | −2.12 | 0.70 | 0.06 | 0.77 | −0.50 | 0.79 | 0.05 | 0.79 |
| *Cfb* climate | | | | | | | | | | | | | | | | | | | | |
| Castro | 0.74 | 0.94 | 0.03 | 0.9 | −0.07 | 0.73 | 0.06 | 0.91 | 0.71 | 0.03 | 0.03 | 0.65 | −0.29 | 0.81 | 0.05 | 0.84 | 0.27 | 0.82 | 0.04 | 0.83 |
| Clevelândia | −15.54 | 0.09 | 0.08 | −0.34 | −15.88 | 0.08 | 0.06 | −0.37 | – | – | – | – | −12.29 | 0.10 | 0.08 | −0.16 | −14.57 | 0.09 | 0.07 | −0.29 |
| Colombo | 0.77 | 0.95 | 0.03 | 0.93 | 0.79 | 0.94 | 0.03 | 0.92 | – | – | – | – | −1.42 | 0.69 | 0.05 | 0.81 | 0.05 | 0.86 | 0.04 | 0.89 |
| Curitiba | 0.55 | 0.88 | 0.04 | 0.93 | 0.02 | 0.76 | 0.06 | 0.92 | – | – | – | – | 0.49 | 0.89 | 0.02 | 0.81 | 0.36 | 0.84 | 0.04 | 0.89 |
| General C. | 0.76 | 0.95 | 0.03 | 0.93 | 0.8 | 0.95 | 0.03 | 0.93 | – | – | – | – | −1.47 | 0.69 | 0.05 | 0.81 | 0.03 | 0.86 | 0.04 | 0.89 |
| Inácio Martins | 0.13 | 0.86 | 0.05 | 0.93 | 0.74 | 0.94 | 0.03 | 0.93 | – | – | – | – | −5.22 | 0.54 | 0.09 | 0.83 | −1.45 | 0.78 | 0.06 | 0.90 |
| Ivaí | 0.77 | 0.94 | 0.03 | 0.93 | 0.40 | 0.84 | 0.05 | 0.92 | – | – | – | – | 0.24 | 0.85 | 0.03 | 0.81 | 0.47 | 0.88 | 0.04 | 0.89 |
| Laranjeiras do Sul | 0.83 | 0.96 | 0.02 | 0.92 | 0.70 | 0.91 | 0.03 | 0.92 | – | – | – | – | −0.05 | 0.76 | 0.04 | 0.81 | 0.49 | 0.88 | 0.03 | 0.88 |
| São Mateus do Sul | 0.86 | 0.97 | 0.02 | 0.93 | 0.63 | 0.90 | 0.04 | 0.92 | – | – | – | – | −0.43 | 0.76 | 0.04 | 0.81 | 0.35 | 0.88 | 0.03 | 0.89 |
| Ventania | 0.84 | 0.95 | 0.02 | 0.93 | 0.71 | 0.90 | 0.03 | 0.91 | – | – | – | – | −0.80 | 0.69 | 0.05 | 0.81 | 0.25 | 0.85 | 0.03 | 0.88 |
| Average for *Cfb* climate | −0.93 | 0.85 | 0.04 | 0.87 | −1.12 | 0.80 | 0.04 | 0.79 | 0.71 | 0.03 | 0.03 | 0.65 | −2.12 | 0.68 | 0.05 | 0.72 | −1.40 | 0.77 | 0.04 | 0.71 |

[a] The seasons were considered to occur in the following periods: summer begins on 21 December and ends on 20 March; autumn begins on 21 March and ends on 20 June; winter begins on 21 June and ends on 22 September; and spring begins on 23 September and ends on 20 December.

the performance. The result is interesting, since Jerszurki *et al.* (2017) considered that the MJS model presents good results at the daily scale, with lower performance in regions with higher *RH* and low temperatures, as occurs in *Cfa* and *Cfb* climates. Therefore, there is an expectation that the spatialization of $ETo_{MJS.d}$ in hot and dry regions will be even better.

The statistical results of the HS method (Table 5) did not indicate good performance in some locations, mainly in Dois Vizinhos, Diamante do Norte, Icaraíma, Japirá and Colombo. The HS and PMT models underestimated the values of daily *ETo* in relation to the ASCE-PM model for *Cfa* climate. For *Cfb*, the HS model had the highest underestimation in relation to all tested models (Fig. 7 and Table 4). Several locations presented $NSE < 0$, indicating that the average values of $ETo_d$ (ASCE-PM) result in better prediction than the HS model ($ETo_{HS.d}$). The opposite results were observed by Todorovic *et al.* (2013), which in Mediterranean climates observed overestimation of *ETo* with the HS method in relation to the standard ASCE-PM. As the HS method does not consider the relative humidity, which has high value for *Cfa* and *Cfb* climates, the method was less accurate in humid climates, with low performance in relation to the other analysed methods.

There was an overestimation of the daily values of *ETo* with the PET model in relation to the ASCE-PM model (Fig. 7 and Table 4), in *Cfa* and *Cfb* climates, indicating less efficiency for the sub-tropical region of Brazil. In addition, 16 locations presented $NSE < 0$. The lowest efficiencies (*NSE*) occurred in Morretes, Joaquim Távora, Ventania, Ivaí, São Mateus do Sul and Inácio Martins (Table 5). The few parameters *a'* and *c'* available for IDW extrapolation may have contributed to the model's low performance. However, Tegos *et al.* (2017), evaluating evapotranspiration with the PET model for 4088 stations worldwide, also found less precision with the model in the equatorial regions of South America, Africa, Indonesia and the Indian Peninsula. The authors considered that the poor performance was probably because the model does not account for the relative humidity and wind speed. The two variables are not considered in the PET model, but are very active in the evapotranspiration process in the mentioned areas, influencing the net solar radiation and the evaporation demand.

The PMT model underestimated the $ETo_d$, presenting results similar to the HS model for the *Cfa* climate. However, in the *Cfb* climate, the PMT was not the model that had the lowest underestimations in relation to the ASCE-PM (Fig. 7; Table 4). Considering the 1:1 line, PMT and HS (Fig. 8(b) and (d)) also

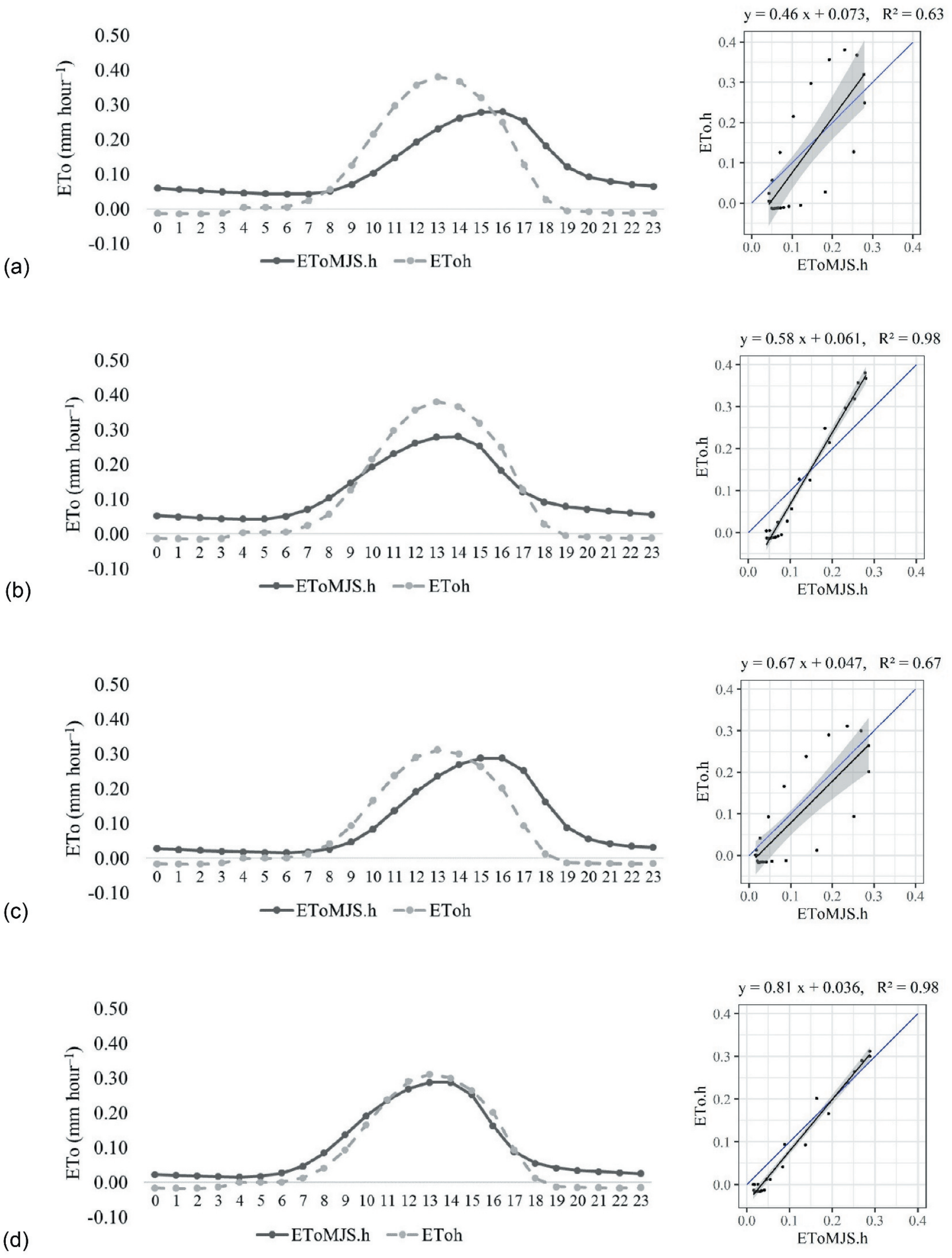


**Figure 5.** Variation and correlation between $ETo_{MJS.h}$ and $ETo_h$, at the hourly scale, of 15 and 10 weather stations in *Cfa* and *Cfb* climate types, respectively, in Paraná State, for the period 2 December 2017 to 8 November 2018: (a) hourly *ETo* without delay adjustment, in *Cfa* climate; (b) hourly *ETo* with 2-h delay adjusted, in *Cfa* climate; (c) hourly *ETo* without delay adjustment, in *Cfb* climate; (d) hourly *ETo* with 2-h delay adjusted, in *Cfb* climate.

produced similar results, presenting the lowest adjustment and performance in the analyses (Table 5) for the sub-tropical region of Brazil.

## 4 Conclusions

In the calibration, the "*a*" coefficients of the MJS model were between −0.0133 and 0.0328 mm h$^{-1}$ for *Cfa* climate, and between −0.024 and 0.026 mm h$^{-1}$ for *Cfb* climate. The "*b*" parameters were between −6.96E-0.9 and −2.46E-0.9 mm h$^{-1}$ MPa$^{-1}$ for *Cfa* climate, and between −5.53E-0.9 and −2.99E −0.9 mm h$^{-1}$ MPa$^{-1}$ for *Cfb* climate.

The values of $ETo_{MJS.h}$ are higher than $ETo_h$ at night-time. With the sunrise, the opposite occurs, and the $ETo_h$ becomes progressively higher than $ETo_{MJS.h}$.

The curve of hourly *ETo* value, estimated using the ASCE-PM and MJS methodologies, presents, on average, a two-hour delay between the maximum values of hourly

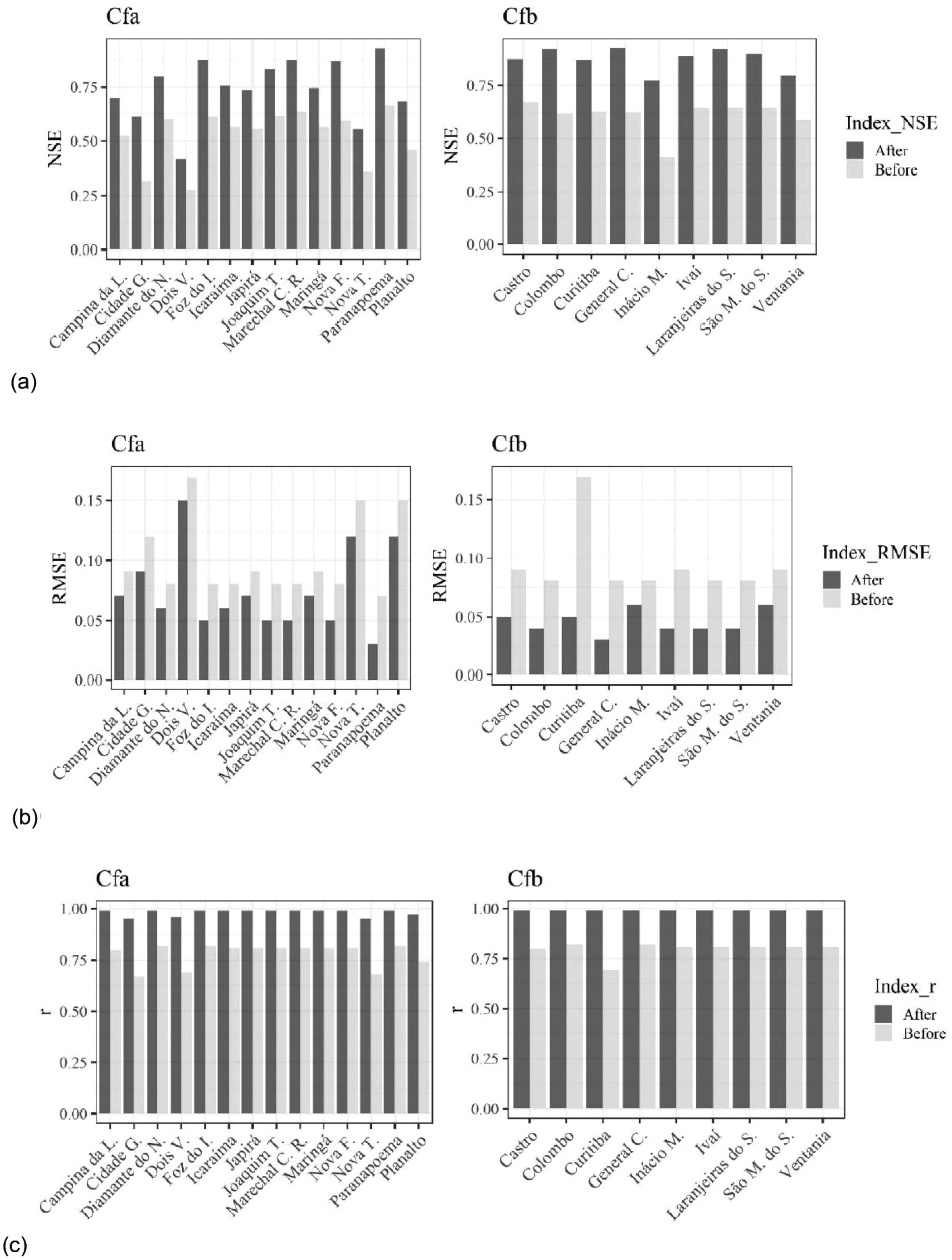


**Figure 6.** Indexes and errors before and after the correction of the delay observed in the correlation between $ETo_{MJS.h}$ and $ETo_h$, at the hourly scale, of 25 weather stations, 15 and 10 in climate types *Cfa* and *Cfb*, respectively, in Paraná State, for the period 2 December 2017 to 8 November 2018: (a) Nash-Sutcliffe efficiency (*NSE*; dimensionless); (b) root mean square error (*RMSE*; mm day$^{-1}$); (c) correlation (*r*; dimensionless).

$ETo$ throughout the day. The correction of the two-hour delay improved the $ETo_{MJS.h}$ estimates in relation to $ETo_h$ for *Cfa* and *Cfb* climates, in Paraná State.

On average, the values of $ETo_{MJS.h}$ and $ETo_h$ were close and well associated statistically in Paraná State. The highest amplitudes and less narrow correlations occurred in the winter season, a period when the $RH$ remains high and the values of $T$ are lower. Summer and spring had equivalent values of $ETo_{MJS.h}$ and $ETo_h$, with smaller amplitudes and closer correlations.

The Moretti-Jerszurki-Silva alternative approach showed better efficiency in relation to the Hargreaves and Samani, modified parametric and Penman-Monteith temperature models, being the best alternative

Table 4. Average daily values of reference evapotranspiration (*ETo*; mm day$^{-1}$) of 24 weather stations in Paraná State, for the period 2 December 2017 to 8 November 2018.

| Weather station | *ETo* (mm day$^{-1}$) | | | | |
|---|---|---|---|---|---|
| | ASCE-PM | MJS | HS | PET | PMT |
| | | *Cfa* climate | | | |
| Campina da Lagoa | 2.38 | 2.14 | 2.08 | 2.58 | 2.10 |
| Cidade Gaúcha | 3.22 | 3.09 | 2.90 | 2.10 | 2.49 |
| Diamante do Norte | 2.48 | 2.21 | 1.23 | 1.97 | 1.36 |
| Dois Vizinhos | 4.23 | 3.77 | 1.44 | 4.12 | 1.49 |
| Foz do Iguaçu | 2.43 | 2.50 | 1.20 | 3.20 | 1.37 |
| Icaraíma | 2.27 | 2.09 | 1.15 | 1.89 | 1.40 |
| Japirá | 2.51 | 2.37 | 1.22 | 3.57 | 1.26 |
| Joaquim Távora | 2.49 | 2.14 | 1.22 | 4.55 | 1.34 |
| Marechal Cândido Rondon | 2.46 | 2.21 | 1.21 | 2.91 | 1.39 |
| Maringá | 2.42 | 2.27 | 2.14 | 1.30 | 2.32 |
| Morretes | 2.30 | 2.40 | 2.07 | 4.49 | 1.86 |
| Nova Fátima | 2.40 | 2.45 | 2.11 | 3.58 | 2.24 |
| Nova Tebas | 3.52 | 3.25 | 2.71 | 3.65 | 2.32 |
| Paranapoema | 2.36 | 2.12 | 2.11 | 1.31 | 2.38 |
| Planalto | 3.97 | 3.76 | 3.14 | 3.44 | 2.55 |
| Average for *Cfa* climate | 2.76 | 2.58 | 1.86 | 2.98 | 1.86 |
| | | *Cfb* climate | | | |
| Castro | 2.59 | 2.19 | 2.22 | 3.23 | 1.94 |
| Colombo | 2.59 | 2.80 | 1.22 | 3.85 | 1.94 |
| Curitiba | 2.59 | 2.30 | 1.23 | 3.53 | 1.73 |
| General Carneiro | 1.84 | 1.92 | 0.97 | 3.75 | 1.18 |
| Inácio Martins | 2.41 | 2.67 | 1.20 | 4.49 | 1.20 |
| Ivaí | 2.50 | 2.71 | 1.21 | 5.15 | 1.17 |
| Laranjeiras do Sul | 2.44 | 2.27 | 1.19 | 2.24 | 1.28 |
| São Mateus do Sul | 2.38 | 2.31 | 2.06 | 4.47 | 1.29 |
| Ventania | 2.31 | 2.39 | 2.08 | 5.18 | 1.85 |
| Average for *Cfb* climate | 2.41 | 2.40 | 1.49 | 3.99 | 1.51 |

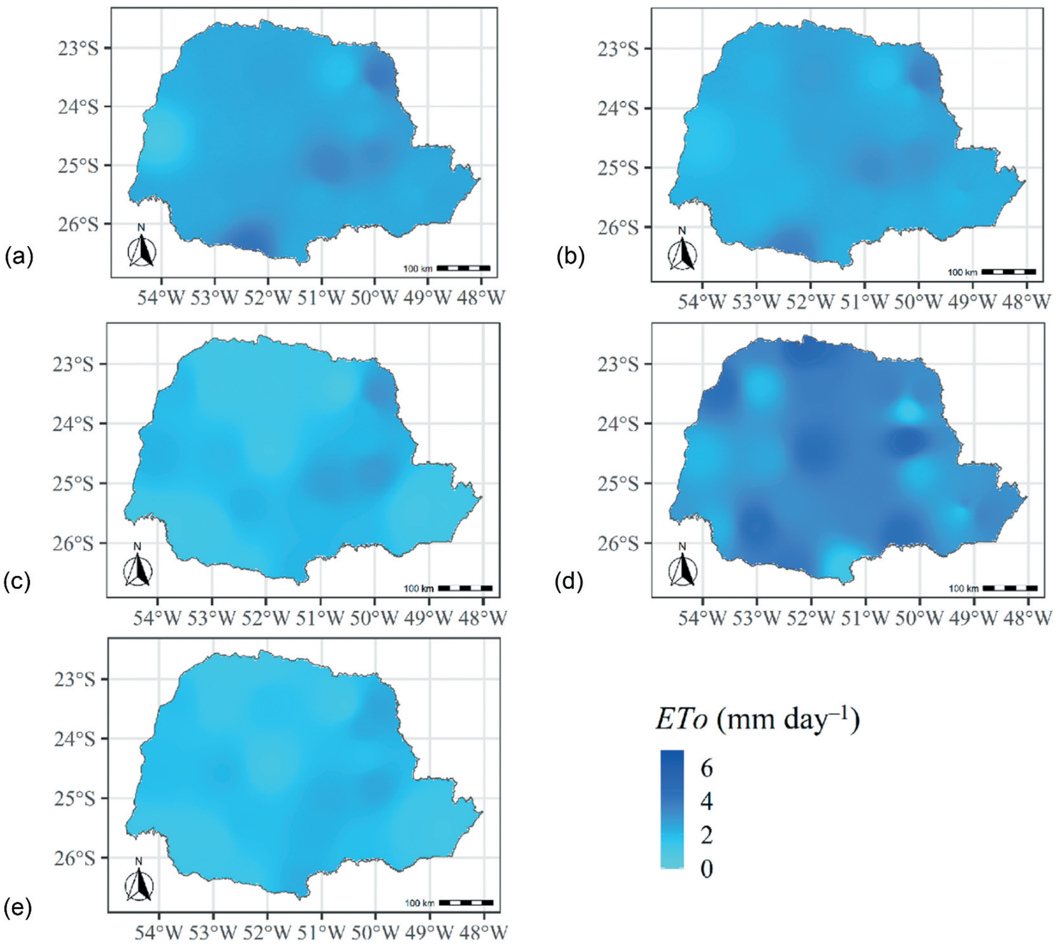


Figure 7. Daily reference evapotranspiration (*ETo*; mm day$^{-1}$) of 24 weather stations in Paraná State, obtained with the inverse distance weighting (IDW) method, for the following models: (a) ASCE-PM ($ETo_d$); (b) Moretti-Jerszurki-Silva ($ETo_{MJS.d}$); (c) Hargreaves and Samani ($ETo_{HS.d}$); (d) modified parametric ($ETo_{PET.d}$); and (e) Penman-Monteith temperature ($ETo_{PMT.d}$).

**Table 5.** Daily values of Nash-Sutcliffe efficiency (*NSE*), root mean square error (*RMSE*) and correlation coefficient (*r*; dimensionless) in the correlations between "$ETo_{MJS.d}$ and $ETo_d$," "$ETo_{HS.d}$ and $ETo_d$," "$ETo_{PET.d}$ and $ETo_d$" and "$ETo_{PMT.d}$ and $ETo_d$" of 15 and nine weather stations in *Cfa* and *Cfb* climate types, respectively, in Paraná State, for the period 2 December 2017 to 8 November 2018.

| Weather station | Interaction between the evaluated models (*ETo*; mm day$^{-1}$) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $ETo_{MJS.d}$ and $ETo_d$ | | | | $ETo_{HS.d}$ and $ETo_d$ | | | | $ETo_{PET.d}$ and $ETo_d$ | | | | $ETo_{PMT.d}$ and $ETo_d$ | | | |
| | *RMSE* | *d* | *r* | *NSE* | *RMSE* | *d* | *r* | *NSE* | *RMSE* | *d* | *r* | *NSE* | *RMSE* | *d* | *r* | *NSE* |
| | (mm day$^{-1}$) | (dimensionless) | | | (mm day$^{-1}$) | (dimensionless) | | | (mm day$^{-1}$) | (dimensionless) | | | (mm day$^{-1}$) | (dimensionless) | | |
| *Cfa* climate | | | | | | | | | | | | | | | | |
| Campina da Lagoa | 0.64 | 0.92 | 0.96 | 0.50 | 0.40 | 0.94 | 0.97 | 0.80 | 0.46 | 0.91 | 0.91 | 0.74 | 1.23 | 0.75 | 0.89 | 0.27 |
| Cidade Gaúcha | 0.78 | 0.87 | 0.80 | 0.62 | 0.61 | 0.93 | 0.92 | 0.77 | 1.39 | 0.71 | 0.76 | −0.20 | 1.31 | 0.75 | 0.86 | 0.26 |
| Diamante do Norte | 0.47 | 0.92 | 0.92 | 0.74 | 1.38 | 0.56 | 0.96 | −1.27 | 0.75 | 0.74 | 0.91 | 0.33 | 2.63 | 0.53 | 0.81 | −1.09 |
| Dois Vizinhos | 0.77 | 0.83 | 0.81 | 0.46 | 2.89 | 0.41 | 0.88 | −6.61 | 0.71 | 0.87 | 0.76 | 0.53 | 2.70 | 0.52 | 0.78 | −1.42 |
| Foz do Iguaçu | 0.37 | 0.95 | 0.94 | 0.85 | 1.36 | 0.58 | 0.96 | −1.09 | 0.86 | 0.80 | 0.91 | 0.17 | 2.40 | 0.54 | 0.79 | −0.71 |
| Icaraíma | 0.35 | 0.92 | 0.94 | 0.77 | 1.20 | 0.56 | 0.95 | −1.67 | 0.55 | 0.81 | 0.90 | 0.45 | 2.78 | 0.51 | 0.60 | −0.76 |
| Japirá | 0.40 | 0.95 | 0.92 | 0.81 | 1.42 | 0.56 | 0.96 | −1.29 | 1.14 | 0.71 | 0.91 | −0.47 | 2.12 | 0.53 | 0.77 | −1.06 |
| Joaquim Távora | 0.50 | 0.91 | 0.96 | 0.71 | 1.40 | 0.57 | 0.96 | −1.26 | 2.12 | 0.53 | 0.91 | −4.20 | 2.08 | 0.54 | 0.78 | −1.15 |
| Marechal C. Rondon | 0.48 | 0.92 | 0.92 | 0.74 | 1.38 | 0.57 | 0.96 | −1.18 | 0.60 | 0.87 | 0.91 | 0.59 | 2.45 | 0.54 | 0.82 | −0.82 |
| Maringá | 0.45 | 0.94 | 0.90 | 0.78 | 0.37 | 0.96 | 0.98 | 0.85 | 1.32 | 0.56 | 0.89 | −0.88 | 1.16 | 0.81 | 0.90 | 0.43 |
| Morretes | 0.32 | 0.97 | 0.94 | 0.87 | 0.35 | 0.96 | 0.97 | 0.85 | 2.24 | 0.51 | 0.92 | −5.28 | 0.98 | 0.78 | 0.86 | 0.38 |
| Nova Fátima | 0.33 | 0.96 | 0.94 | 0.86 | 0.38 | 0.95 | 0.98 | 0.82 | 1.24 | 0.68 | 0.91 | −0.95 | 1.35 | 0.75 | 0.88 | 0.36 |
| Nova Tebas | 0.44 | 0.94 | 0.94 | 0.79 | 0.90 | 0.78 | 0.94 | 0.09 | 0.43 | 0.94 | 0.90 | 0.79 | 1.54 | 0.69 | 0.86 | −0.01 |
| Paranapoema | 0.43 | 0.93 | 0.92 | 0.76 | 0.37 | 0.95 | 0.97 | 0.82 | 1.22 | 0.57 | 0.91 | −0.95 | 1.37 | 0.77 | 0.9 | 0.34 |
| Planalto | 0.37 | 0.96 | 0.95 | 0.85 | 0.84 | 0.83 | 0.95 | 0.22 | 0.61 | 0.89 | 0.90 | 0.59 | 1.49 | 0.71 | 0.87 | 0.01 |
| Average | 0.47 | 0.93 | 0.92 | 0.74 | 1.02 | 0.74 | 0.95 | −0.61 | 1.04 | 0.74 | 0.89 | −0.58 | 1.84 | 0.65 | 0.82 | −0.33 |
| *Cfb* climate | | | | | | | | | | | | | | | | |
| Castro | 0.78 | 0.71 | 0.90 | 0.39 | 0.46 | 0.94 | 0.97 | 0.79 | 0.75 | 0.58 | 0.93 | 0.43 | 0.79 | 0.84 | 0.90 | 0.56 |
| Colombo | 0.57 | 0.92 | 0.88 | 0.74 | 1.55 | 0.56 | 0.96 | −0.95 | 1.36 | 0.70 | 0.88 | −0.51 | 1.63 | 0.55 | 0.39 | 0.15 |
| Curitiba | 0.48 | 0.92 | 0.94 | 0.76 | 1.49 | 0.57 | 0.97 | −1.34 | 1.01 | 0.77 | 0.87 | −0.08 | 1.74 | 0.56 | 0.85 | −0.74 |
| General Carneiro | 0.28 | 0.98 | 0.98 | 0.94 | 1.37 | 0.63 | 0.99 | −0.42 | 1.85 | 0.69 | 0.97 | −1.58 | 1.56 | 0.59 | 0.89 | −0.47 |
| Inácio Martins | 0.42 | 0.95 | 0.94 | 0.79 | 1.34 | 0.58 | 0.96 | −1.06 | 2.13 | 0.54 | 0.91 | −4.23 | 1.67 | 0.56 | 0.83 | −0.40 |
| Ivaí | 0.43 | 0.95 | 0.92 | 0.80 | 1.43 | 0.57 | 0.96 | −1.25 | 2.71 | 0.47 | 0.91 | −7.08 | 1.89 | 0.55 | 0.85 | −0.95 |
| Laranjeiras do Sul | 0.38 | 0.94 | 0.93 | 0.80 | 1.35 | 0.57 | 0.96 | −1.50 | 0.44 | 0.91 | 0.92 | 0.74 | 1.96 | 0.56 | 0.86 | −0.72 |
| São Mateus do Sul | 0.40 | 0.95 | 0.91 | 0.81 | 0.42 | 0.94 | 0.97 | 0.79 | 2.15 | 0.54 | 0.92 | −4.46 | 3.26 | 0.52 | 0.63 | −0.08 |
| Ventania | 0.35 | 0.95 | 0.93 | 0.84 | 0.34 | 0.96 | 0.97 | 0.85 | 2.92 | 0.43 | 0.91 | −10.08 | 1.07 | 0.76 | 0.88 | 0.31 |
| Average | 0.45 | 0.92 | 0.93 | 0.76 | 1.08 | 0.70 | 0.97 | −0.45 | 1.70 | 0.63 | 0.91 | −2.98 | 1.73 | 0.61 | 0.79 | −0.26 |

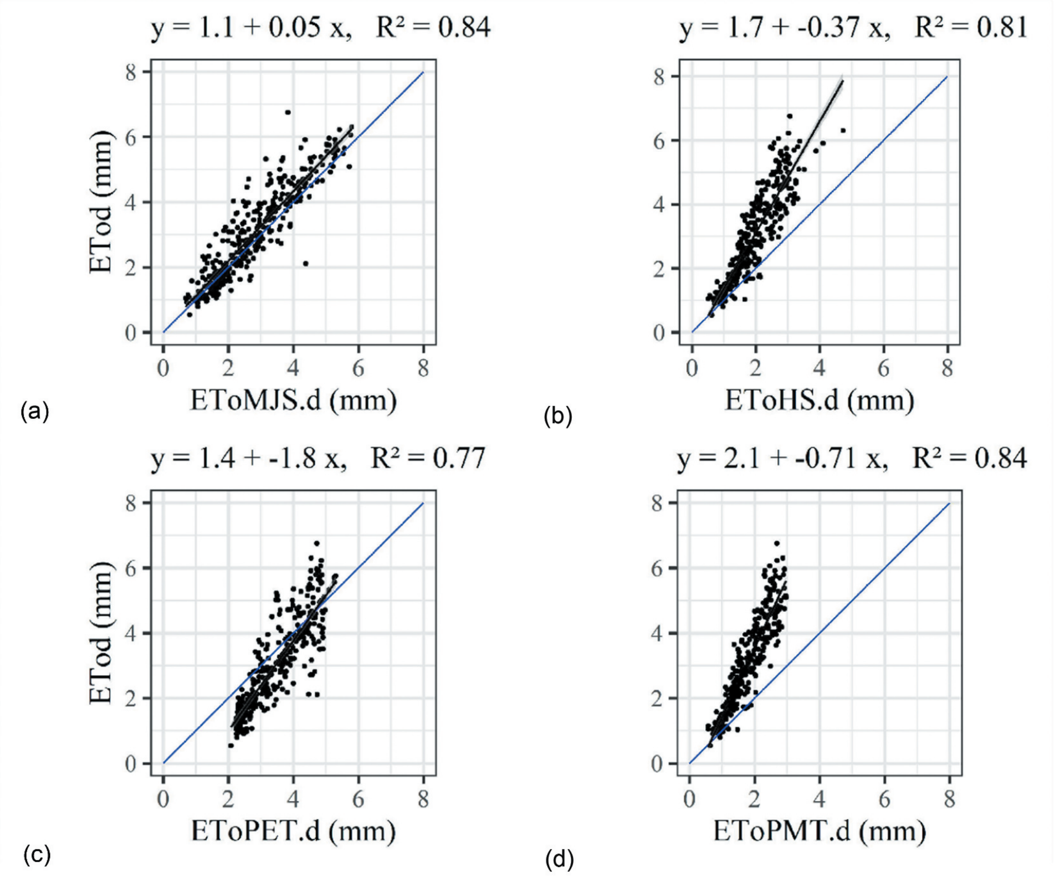


**Figure 8.** Simple linear regression analysis of the values of daily reference evapotranspiration (*ETo*; mm day$^{-1}$) of 24 weather stations in Paraná State, for the period 2 December 2017 to 8 November 2018, for the correlation between: (a) $ETo_{MJS.d}$ and $ETo_d$; (b) $ETo_{HS.d}$ and $ETo_d$; (c) $ETo_{PET.d}$ and $ETo_d$; (d) $ETo_{PMT.d}$ and $ETo_d$.

methodology to produce accurate evapotranspiration estimates at a daily scale, for *Cfa* and *Cfb* climate types, in the sub-tropical region of Brazil.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

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