Revista Brasileira de Meteorologia, **v. 36, n. 1,** 1−13, 2021 rbmet.org.br
DOI: http://dx.doi.org/10.1590/0102-77863610009

Artigo

Hourly and Daily Reference Evapotranspiration with ASCE-PM Model for Paraná State, Brazil

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Received: 12 June 2020 - Revised: 17 July 2020 - Accepted: 9 August 2020

Abstract

The objective of this study was to verify the magnitude and trend of hourly reference evapotranspiration (ETo_h), as well as associate and analyze daily *ETo* (ETo_d) series and the sum of hourly *ETo* (ETo_{24h}) in 24 h, estimated with the Penman-Monteith ASCE model for Paraná State (*Cfa* and *Cfb* climate type). Relative humidity (*RH*), temperature (*T*), solar radiation (*Rs*) and wind speed (u_2) data were obtained from 25 meteorological stations from the National Meteorological Institute (INMET), between December 1, 2016 to November 8, 2018. The analyzes were performed by linear regression and associations considering the root mean square error, correlation coefficient and index of agreement. The ETo_h trend has a Gaussian distribution, with the highest values between 12:00 p.m. and 2:00 p.m., with the maximum average being 0.44 mm h^{-1} (*Cfa* climate type) and 0.35 mm h^{-1} (*Cfb* climate type). The average difference between the ETo_{24h} and ETo_d values was small (5.1% for *Cfa* and 7.4% for *Cfb*), resulting in close linear associations. The results obtained indicate that ETo_h has good potential to be used in planning and management in the field of soil and water engineering, in Paraná State.

Keywords: hydrological cycle, water relations, water resources, models, precision.

Evapotranspiração de referência horária e diária pelo modelo ASCE-PM para o Estado do Paraná, Brasil

Resumo

Teve-se por objetivo no presente trabalho verificar a magnitude e tendência da evapotranspiração de referência horária (ETo_h), bem como associar e analisar as séries diárias de *ETo* (ETo_d) e a soma da *ETo* horária (ETo_{24h}) em 24 h, estimada pelo modelo Penman-Monteith ASCE para o Estado do Paraná (tipos climáticos *Cfa* e *Cfb*). Dados de umidade relativa (*UR*), temperatura (*T*), radiação solar (*Rs*) e velocidade do vento (u_2) foram obtidos de 25 estações meteorológicas do Instituto Nacional de Meteorologia, entre 01/12/2016 e 08/11/2018. As análises foram realizadas por meio de regressão linear e associações considerando a raiz quadrada do erro quadrado médio, coeficiente de correlação e índice de concordância. A tendência da ETo_h teve distribuição gaussiana, com valores mais altos entre as 12:00 e 14:00 h, com média máxima de 0.44 mm h^{-1} (para o clima *Cfa*) e 0.5 mm h^{-1} (em clima *Cfb*). A diferença média entre os valores de ETo_{24h} e ETo_d foi pequena (5.1% para *Cfa* e 7.4% para *Cfb*), resultando em estreitas associações lineares. Os resultados obtidos indicam que a ETo_h tem bom potencial para ser utilizada no planejamento e manejo na área de engenharia de água e solo, no Estado do Paraná.

Palavras-chave: ciclo hidrológico, relações hídricas, recursos hídricos, modelos, precisão.

1. Introduction

The Evapotranspiration (*ET*) is the term used to describe the loss of water by the soil surface evaporation and plant transpiration. Evapotranspiration researches are important for water resources planning and management, as well as the understanding of environmental and climate changes (Nolz & Rodný, 2019).

The *ET* depends on several factors, such as: water supply for plants; interaction between meteorological variables, such as solar radiation, wind speed, relative

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humidity and air temperature; and physiological issues such as stomatal movement, leaf area and the presence or absence of trichomes. The term reference evapotranspiration (*ETo*) originated from estimates using a hypothetical reference crop, with a height of 0.12 m, fixed surface resistance of 70 s m^{-1} and albedo of 0.23. The reference surface closely resembles to an extensive green grass surface, with uniform height, adequate water, in active growth and completely shading the soil surface (Allen *et al.* 1994; Allen *et al.* 1998).

The *ETo* can be measured directly with specific equipment, called lysimeters or evapotranspirometers. These methods are considered accurate and direct, but have high costs, requiring time and specialized labor. Indirect methods are an alternative form to determine *ETo*, which provide satisfactory results and minimize costs and time, compared to direct methods (Howell *et al.*, 1991; Dhungel *et al.*, 2019).

The time interval considered for *ETo* calculation may vary according to the purpose of the study. In the literature is common to use monthly, daily or even hourly intervals. The periodicity choice depends on the precision and data availability for use in the models. In areas where there are large changes in wind speed, cloudiness or dew point throughout the day, the calculation of evapotranspiration in hourly periodicity is more accurate (Noia *et al.*, 2014; Lopes & Leal, 2016). The models most recommended and used in the literature for this purpose are Penman-Monteith FAO N° 56 (Allen *et al.*, 1998) and Penman-Monteith ASCE (ASCE-EWRI, 2005).

The PM-ASCE method is a modification of the model presented by Food and Agriculture Organization of the United Nations (FAO), which has adjustments that enable even more accurate results. Currently, the PM-ASCE model is considered the standard for estimating *ETo*. In addition to estimates *ETo* for daily and hourly periodicity, the model also considers two types of reference surfaces: short grass (low height crop; 0.12 m) and alfalfa (tallest and harshest crop; 0.50 m) (ASCE-EWRI, 2005).

The reference evapotranspiration in hourly periodicity (ETo_h) can allow higher precision for *ETo* estimates, and offer better perspectives for water and soil resources planning and management (Treder & Klamkowski, 2017; Althoff *et al.*, 2019; Nolz & Rodný, 2019). In particular, the subtropical region where the Paraná State is located has scarce information regarding hourly reference evapotranspiration (ETo_h). In general, studies already carried out deal with *ETo* only on a daily periodicity, considering few locations and seasons for the predominant *Cfa* or *Cfb* climates of the State, which makes its spatialization difficult (Costa *et al.*, 2015; Jerszurki *et al.*, 2017).

In this context, we verify the magnitude and trend (daily and seasonal) of hourly reference evapotranspiration (ETo_h), as well as associate and analyze series of daily *ETo* (ETo_d) and the sum of hourly *ETo* in 24 h (ETo_{24h}), estimated with the Penman-Monteith ASCE model for Paraná State, considering the predominant *Cfa* and *Cfb* climate types.

2. Material and Methods

The present study was carried out for Paraná State, Southern region of Brazil, with an area of 199.307.922 km^2, according to Maack (2012). The region is comprised between 22°30’58” S and 26°43’00” S latitude, 48°05’37” W and 54°37’08” W longitude (Fig. 1), with hight variation in altitude, with the locations analyzed in the present study included between 1 and 994 meters. Paraná has a predominance of *Cfa* and *Cfb* climate type, according Köppen's climate classification for Brazil. The *Cfa* subtropical climate has a great rainfall distribution throughout the year, on average 1500 mm $year^{-1}$, and average annual temperature of 19 °C. The *Cfb* subtropical climate presents rainfall well distributed throughout the year, being over 1200 mm $year^{-1}$, temperate summer and annual average temperature of 17 °C (Alvares *et al.*, 2013).

The estimation of hourly (ETo_h) and daily (ETo_d) evapotranspiration was calculated with the standardized Penman-Monteith equation, presented by the American Society of Civil Engineers (ASCE-EWRI, 2005) (Eq. (1)), using a short crop having an approximate height of 0.12 m:

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

where $ETo_{PM\text{-}ASCE}$ is the hourly or daily reference evapotranspiration (ETo_h in mm h^{-1} or ETo_d in mm day^{-1}, respectively); 0.408 is the coefficient equation (m^2 mm MJ^{-1}); Δ is the slope of the saturated water-vapor-pressure curve to the air temperature in the period considered (kPa $°C^{-1}$); *Rn* is the net radiation balance in the period considered (MJ m^{-2} h^{-1} or MJ m^{-2} day^{-1}); *G* is the soil heat flux in the period considered (MJ m^{-2} h^{-1} or MJ m^{-2} day^{-1});γ is the psychrometric constant (kPa $°C^{-1}$); *Cn* and *Cd* are the constants related to the type of vegetation and time scale considered (K mm s^3 Mg^{-1} h^{-1} and s m^{-1}, respectively); *T* is the average air temperature in the period considered (°C); u_2 is the wind speed at 2 meters height in the period considered (m s^{-1}); *es* is the saturation vapor pressure in the period considered (kPa); *ea* is the actual vapor pressure in the period considered (kPa).

The daily *ETo* (ETo_d) was calculated using the ASCE-PM equation, according to recommendations and coefficients of the ASCE Manual of Practice N° 70 (ASCE-EWRI, 2005; p.09-26), for soil cover with short grass: Cn_{daily} = 900 K mm s^3 Mg^{-1} h^{-1} and Cd_{daily} = 0.34 s m^{-1}; The hourly *ETo* (ETo_h) was calculated using the ASCE-PM equation, according to recommendations

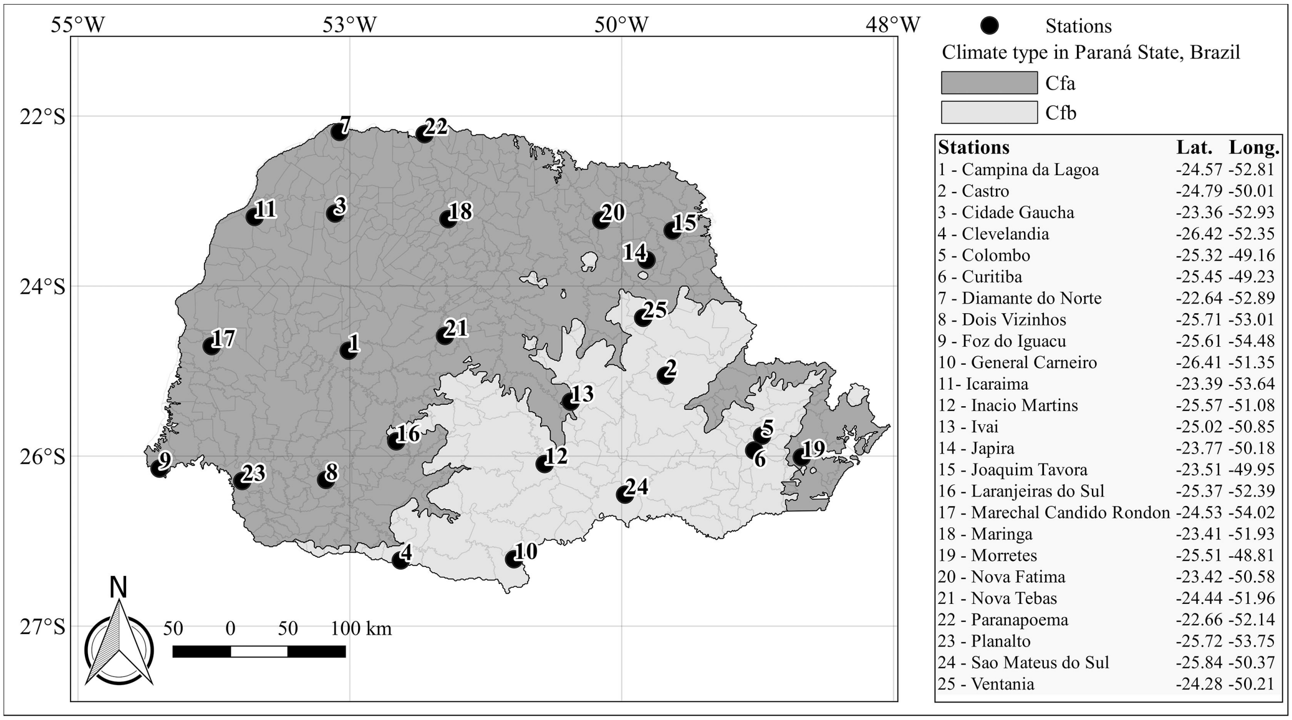

Figure 1 - Predominant climate classification in Paraná State and location of meteorological stations.

and coefficients of the ASCE Manual of Practice N° 70 (ASCE-EWRI, 2005; p.09-26), for soil cover with short grass: Cn_{hourly} = 37 K mm s^3 Mg^{-1} h^{-1}; and, Cd_{daytime} = 0.24 s m^{-1} for daytime period, or $Cd_{\text{nighttime}}$ = 0.96 s m^{-1} for nighttime period.

The 24 hourly ETo_h values of one day were added, for statistical comparison with the ETo_d of the respective day (Eq. (2)):

$$ETo_{24h} = \sum_{h=1}^{n=24} ETo_h \tag{2}$$

where ETo_{24h} is the reference evapotranspiration resulting from the sum of each h-values of hourly reference evapotranspiration of the same day (mm day^{-1}); ETo_h is the reference evapotranspiration of each h-hour (mm h^{-1}); n is the number of hours in a day (dimensionless; n = 24).

The hourly and daily reference evapotranspiration were calculated on an electronic spreadsheet developed especially for this purpose, at the Modeling and Agricultural Systems Laboratory - DSEA/SCA - Federal University of Paraná.

We were used data series from 25 automatic meteorological stations (Fig. 1), obtained from the National Meteorological Institute (INMET), between December 1, 2016 to November 8, 2018.

To estimate ETo with the ASCE-PM model, the variables required were: maximum and minimum relative humidity (RH; %); maximum and minimum air temperatures (T; °C); incident solar radiation (Rs; MJ m^{-2} day^{-1}); and wind speed at 2 meters height (u_2; m s^{-1}). The data in meteorological stations are measured in intervals from minute to minute, and after completing one hour, with the average of the measures, the hourly value is generated. Further details about the Automatic Meteorological Station System from National Meteorological Institute (INMET) used in the present study can be verified in INMET (2011), as well as measuring devices, how to install and execute the reading data.

A total of 424,800 hours were analyzed for 25 stations in Paraná State. However, when data failure was detected for some input variable to estimate hourly evapotranspiration (ETo_h), it was decided to exclude the time in question. Thus, 63,720 h (15% of the total) was eliminated. Considering the six input parameters, a total of 2,166,480 data were used.

The results obtained for ETo estimative equations with hourly (ETo_h, which added resulted in ETo_{24h} values) and daily (ETo_d) ASCE-PM model were compared and statistically validated using regression analyzes, and the main indexes and coefficients recommended in the literature (Eq. (3); Eq. (4) and Eq. (5)) (Jacovides & Kontoyiannis, 1995; Nolz & Rodný, 2019).

$$RMSE = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} \left(ETo_{24hi} - ETo_{di}\right)^2} \tag{3}$$

$$r = \frac{\sum_{i=1}^{n}\left[\left(ETo_{di} - \overline{ET}o_{d}\right)\cdot\left(ETo_{24hi} - \overline{ET}o_{24h}\right)\right]}{\sqrt{\sum_{i=1}^{n}\left(ETo_{di} - \overline{ET}o_{d}\right)^{2}\cdot\ \sum_{i=1}^{n}\left(ETo_{24hi} - \overline{ET}o_{24h}\right)^{2}}} \tag{4}$$

$$d = 1 - \frac{\sum_{i=1}^{n}\left(ETo_{24hi} - ETo_{di}\right)^{2}}{\sqrt{\sum_{i=1}^{n}\left(\left|ETo_{24hi} - \overline{ET}o_{d}\right|\left|ETo_{di} - \overline{ET}o_{d}\right|\right)^{2}}} \tag{5}$$

where *RMSE* is the root mean square error (mm day^{-1}); r is the Pearson correlation coefficient (dimensionless); d is the agreement index of Willmott (1982) (dimensionless); n is the number of hours analyzed (dimensionless); ETo_{24hi} is the each i-value of daily *ETo* resulting from the sum of each h-value of hourly reference evapotranspiration for the same day (mm day^{-1}); ETo_{di} is the reference evapotranspiration estimated with the standard Penman-Monteith method at each i-day (mm day^{-1}); $\overline{ET}o_{d}$ is the average of *ETo* values estimated with the standard method for all days analyzed in the period (mm day^{-1}); $\overline{ET}o_{24h}$ is the average of each i-daily *ETo* values of the period, resulting from the sum of each h-hourly reference evapotranspiration value of the same day (mm day^{-1}).

Table 1 - Seasonal average in the year[(1)] for air temperature (T; ºC), relative humidity (RH; %), incident solar radiation (Rs; MJ m^{-2} day^{-1}) and wind speed at 2 meters height (u_2; m s^{-1}) in 25 meteorological stations in Paraná State, between December 1, 2016 to November 8, 2018.

Climate	Meteorological stations	Spring				Summer				Autumn				Winter			
		RH	T	Rs	u_2	RH	T	Rs	u_2	RH	T	Rs	u_2	RH	T	Rs	u_2
	Campina da Lagoa	81.1	21.0	0.84	1.44	83.8	23.3	0.93	1.81	79.4	20.6	0.62	2.13	74.6	17.8	0.62	1.63
	Cidade Gaúcha	47.2	16.5	0.82	1.01	75.7	25.5	0.93	1.20	75.4	21.3	0.62	1.33	56.4	18.7	0.62	1.37
	Diamante do Norte	72.0	21.2	0.85	1.45	77.7	24.9	1.01	1.50	77.5	21.5	0.72	1.82	70.9	17.7	0.64	1.33
	Dois Vizinhos	59.7	19.3	0.83	1.73	81.2	24.2	1.01	1.67	80.9	18.2	0.55	1.71	63.5	19.3	0.69	2.14
	Foz do Iguaçu	79.2	20.8	0.85	1.30	80.1	24.5	1.01	0.37	25.6	7.2	0.34	0.08	63.7	14.3	0.59	1.08
	Icaraíma	65.6	18.9	0.61	1.17	71.2	23.6	0.95	1.68	69.3	19.4	0.61	2.25	66.6	17.1	0.61	1.65
	Japirá	77.3	20.2	0.80	1.39	64.7	19.2	0.82	0.40	60.6	14.0	0.47	1.45	74.0	16.1	0.56	1.29
Cfa	Joaquim Távora	76.6	20.8	0.78	1.03	78.7	23.7	0.91	1.16	76.8	19.9	0.71	1.79	75.0	16.5	0.65	0.85
	Marechal Cândido Rondon	69.3	19.0	0.82	1.35	78.0	24.3	0.97	1.37	82.8	19.8	0.62	1.53	70.5	17.0	0.63	1.70
	Maringá	72.6	21.6	0.86	1.24	74.4	24.3	0.95	1.23	71.6	21.1	0.71	1.58	67.7	17.8	0.64	1.17
	Morretes	87.0	19.9	0.76	0.58	87.5	24.0	0.80	0.60	91.5	20.6	1.00	0.53	86.9	14.7	0.61	0.42
	Nova Fátima	79.2	20.8	0.85	1.30	80.1	24.5	1.01	0.37	25.6	7.2	0.34	0.08	63.7	14.3	0.59	1.08
	Nova Tebas	69.3	21.3	1.06	1.99	79.8	23.1	1.02	1.49	80.0	19.1	0.69	1.66	60.8	18.1	0.84	1.75
	Paranapoema	71.6	21.1	0.84	1.65	77.0	24.9	0.98	1.53	68.1	20.4	0.71	2.14	54.3	12.3	0.55	0.95
	Planalto	70.0	23.5	0.97	2.42	77.7	25.4	0.98	1.73	72.7	18.1	0.53	1.67	49.0	16.6	0.61	1.76
Average *Cfa* climate		71.8	20.4	0.84	1.40	77.8	24.0	0.95	1.21	69.2	17.9	0.62	1.45	66.5	16.6	0.63	1.34
Standard deviation		9.6	1.6	0.10	0.43	5.3	1.5	0.07	0.52	19.1	4.7	0.16	0.69	9.5	1.9	0.07	0.44
Coefficient of variation (%)		13.3	7.7	11.64	30.89	6.8	6.2	6.96	42.96	27.6	26.4	26.46	47.39	14.3	11.6	10.90	32.56
	Castro	81.0	18.5	0.71	1.08	82.2	21.3	0.84	1.09	83.9	16.4	0.47	1.20	80.4	14.5	0.49	0.79
	Clevelândia	76.9	18.8	0.65	1.81	31.6	7.7	0.09	0.23	59.9	10.9	0.46	2.05	76.0	15.0	0.47	1.73
	Colombo	83.4	18.0	0.72	0.93	85.5	21.0	0.88	0.92	88.0	16.0	0.54	0.99	82.9	14.3	0.56	0.75
	Curitiba	74.5	19.4	0.92	1.36	73.2	22.7	1.10	1.46	70.9	17.8	0.73	1.64	72.8	15.5	0.70	0.99
	General Carneiro	83.3	17.8	0.76	0.64	85.1	20.9	0.85	0.70	88.1	15.1	0.52	0.57	76.0	12.8	0.52	0.47
Cfb	Inácio Martins	52.4	11.8	0.51	0.25	86.1	20.1	0.93	1.47	89.5	14.8	0.57	1.99	56.8	9.1	0.36	0.55
	Ivaí	71.2	17.9	0.75	0.92	80.6	22.1	0.89	0.99	80.8	17.3	0.62	1.06	74.0	14.9	0.61	0.86
	Laranjeiras do Sul	80.4	19.2	0.80	0.96	83.1	21.8	0.96	1.08	83.0	17.1	0.63	1.24	78.2	15.1	0.63	0.87
	São Mateus do Sul	81.9	18.5	0.87	0.57	84.7	21.5	1.81	0.33	85.8	15.8	0.88	0.35	83.3	14.1	0.56	0.46
	Ventania	80.3	18.7	0.81	1.85	57.2	15.9	1.01	1.24	83.0	16.5	0.78	2.51	75.2	15.3	0.63	1.63
Average *Cfb* climate		76.5	17.9	0.75	1.04	74.9	19.5	0.94	0.95	81.3	15.8	0.62	1.36	75.5	14.1	0.55	0.91
Standard deviation		9.3	2.2	0.12	0.52	17.6	4.5	0.41	0.42	9.2	2.0	0.14	0.68	7.5	1.9	0.10	0.44
Coefficient of variation (%)		12.2	12.3	15.54	49.63	23.5	23.3	44.05	44.63	11.3	12.4	22.28	50.19	9.9	13.5	17.74	48.70

[(1)]Seasons are considered to occur in the following periods: Summer between December 21 to March 20; Autumn between March 21 to June 20; Winter between June 21 to September 22; and Spring between September 23 to December 20.

3. Results and Discussion

3.1. Characterization of the input variables in the ASCE-PM model on daily and hourly periodicity

Table 1 shows the seasonal average values of air temperature (*T*; °C), relative humidity (*RH*; %), incident solar radiation (*Rs*; MJ m^{-2} day^{-1}) and wind speed at 2 meters height (u_2; m s^{-1}), of the 25 meteorological stations analyzed in Paraná State, in the period between December 1, 2016 to November 8, 2018. Of the total weather stations analyzed, 15 are in *Cfa* and 10 in *Cfb* climate type. Fig. 2 shows the average seasonal trend of the variables (*T*, *RH*, *Rs* and u_2), according to *Cfa* and *Cfb* climate types.

In general, the variables *T*, *RH*, *Rs* and u_2 showed very similar trends among the predominant climates in Paraná (Table 1 and Fig. 2). It was observed that: *i*) The *T* was higher in the summer (average of approximately 24 °C for *Cfa* climate and 19 °C for *Cfb* climate) and spring (average of approximately 20 °C for *Cfa* and 18 °C for *Cfb*); *ii*) The *RH* showed low seasonal variations for both climates, being between 66% to 80% throughout the year, with winter being

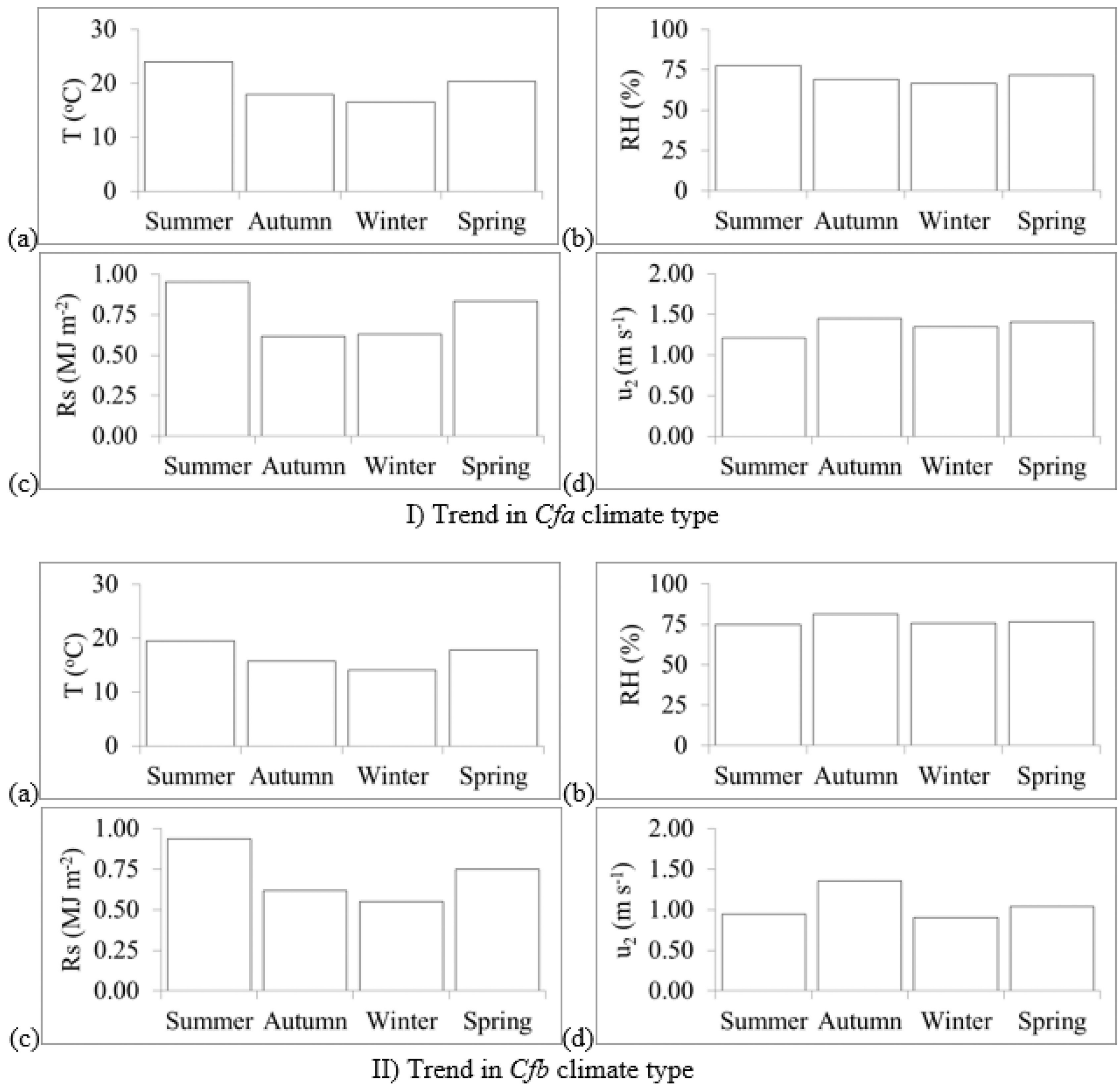

Figure 2 - Seasonal average trend of the climatic variables in Paraná State, between December 1, 2016 to November 8, 2018, for 15 stations in Cfa climate and 10 stations in Cfb climate: a) Air temperature (*T*; °C), b) Relative humidity (*RH*; %), c) Incident solar radiation (*Rs*; MJ m^{-2} day^{-1}), and, d) Wind speed at 2 meters height (u_2; m s^{-1}).

the period of lowest *RH* for *Cfa* (66%) and summer for *Cfb* (74.9%); *iii*) *Rs* showed a similar trend to *T*, with periods of higher *Rs* in the summer seasons (0.95 MJ m^{-2} day^{-1} for *Cfa* and 0.94 MJ m^{-2} day^{-1} for *Cfb*) and spring (0.84 MJ m^{-2} day^{-1} for *Cfa* and 0.75 MJ m^{-2} day^{-1} for *Cfb*); and, *iv*) The u_2 showed a similar trend to *RH*, with low seasonal variation, being between 0.95 to 1.45 m s^{-1}, with highest values observed during autumn (1.45 m s^{-1} for *Cfa* and 1.36 m s^{-1} for *Cfb*).

The tendency and dispersion of the climatic input variables used to calculate *ETo* in hourly periodicity (ETo_h) differ considerably throughout the day. *Rs* and u_2 provided the largest variations observed in the prevailing climates of Paraná State. The *Cfa* and *Cfb* climates showed a very similar hourly average trend for *T*, *RH*, *Rs* and u_2 (Fig. 3). For both climatic types it was found that the air temperature showed higher values between 2:00 p. m. and 4:00 p.m. and the *RH* had an inverse trend, presenting its lowest values between 2:00 p.m. and 4:00 p.m. The *Rs* showed a peak of solar energy between 12:00 p.m. and 2:00 p.m. In the same way as *Rs*, the wind speed tended towards the highest values between 2:00 p.m. and 4:00 p.m.

3.2. Trend of hourly reference evapotranspiration (*ETo*h) throughout the day

On average, for each weather station analyzed, the maximum values of ETo_h achieved over the 24 h of the day occurred between 12:00 p.m. and 2:00 p.m. Mean maximum ETo_h of 0.44 mm h^{-1} was observed for *Cfa* cli-

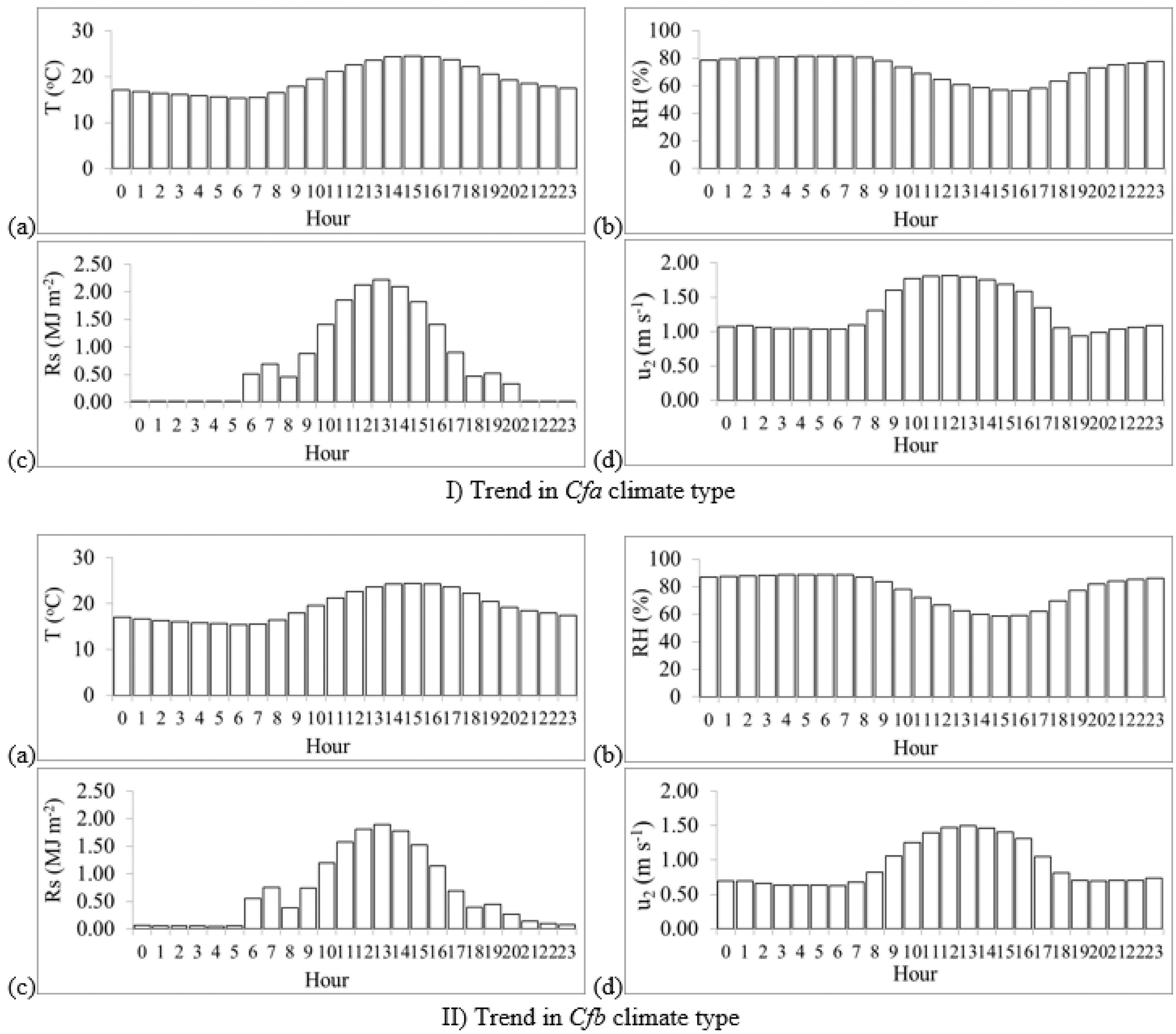

Figure 3 - Hourly average trend of the climatic variables in Paraná State, between December 1, 2016 to November 8, 2018, for 15 stations in the *Cfa* climate and 10 stations in *Cfb* climate: a) Air temperature (*T*; °C), b) Relative humidity (*RH*; %), c) Incident solar radiation (*Rs*; MJ m^{-2} day^{-1}), and, d) Wind speed at 2 meters height (u_2; m s^{-1}).

mate and 0.35 mm h^{-1} for *Cfb* (Fig. 4). During the peak ETo_h periods, the highest values of *T*, *Rs*, u_2 and lowest values of *RH* had occurred (Fig. 3). The trends observed for ETo_h are quite evident, due to the dependence of evapotranspiration on the variables *T*, *Rs*, u_2 and *RH*.

Ismael Filho *et al.* (2015) consider that *RH* has an inverse relationship to *ETo*. Thus, as higher the *RH*, lower the ETo_h. The authors statement also confirms the results obtained with ETo_h for the analyzed stations (Fig. 3 and 4).

An interesting aspect when working with the ASCE-PM method in the hourly periodicity refers to the occurrence of positive and negative values in the ETo_h estimates at night. In the analyzes carried out in the present study, ETo_h values close to zero or negative occurred, on average, between 9:00 p.m. and 4:00 a.m. for *Cfa* climate, and between 9:00 p.m. and 5:00 a.m. for *Cfb* climate (Fig. 3 and 4).

Caird *et al.* (2007) considered that some species of plants C3 and C4 do not present complete stomatal closure during the night period due to the recovery of daytime water losses. The amount of water lost by the leaf at night depends on the vapor pressure deficit between air and leaves, resulting in nighttime transpiration up to 30% of the daytime, since the nighttime vapor pressure is lower than the daytime. These aspects show the importance of considering positive nighttime water losses (Fig. 4) to compose accurate *ETo* analyzes.

Regarding the ETo_h negative values Guimarães *et al.* (2013) report that *Rs* sensors can have small errors, due to gradual changes in the atmosphere and radiation. In addition, however good the instrument used to measure a physical quantity can be, naturally the measured value will not be equal to the real value, since every measurement process introduces an error. In the present study, 37% of the 351.809 ETo_h values were negative. Therefore, it is believed that the estimation of negative ETo_h values may result from an error in the sensors measurement. As the values are very small, in the present study they were considered equal to zero. Yildirim *et al.* (2004) comparing ETo_h and ETo_d in Harran Plain, region of Turkey, also found ETo_h values close to or equal to zero in the nighttime hours, with accelerated increase between 6:00 a.m. and 12:00 p.m. Although the climates of Paraná and Harran are different, in the present study ETo_h trend was very similar to that observed by the authors (Fig. 4).

In general, the seasonal trend of hourly reference evapotranspiration (ETo_h) indicated that the highest values occurred in summer and spring, and the lowest in winter and autumn (Figure 5). A similar trend was observed for *T* and *Rs* (Fig. 3).

Pereira *et al*. (2016) note that *T* and *RH* are very active in *ETo* values. As higher the temperature is, higher will be the atmospheric demand for water, indicating the associations between Fig. 3 and 5, and the reasons why the spring and summer seasons have the highest ETo_h values.

3.3. ETo_d trend and association between ETo_d and ETo_{24h} throughout the year, in Paraná State

There was a tendency of the highest ETo_d amplitudes during the summer, with the mildest values between spring and autumn and the lowest amplitudes in the winter period (Table 2 and Fig. 6).

The daily *ETo* obtained with the standard ASCE-PM method (ETo_d) or with the sum of ETo_h (ETo_{24h}) did not show high variations. However, a trend towards higher ETo_{24h} values was observed in *Cfa* climate, mainly during spring and summer (Table 2 and Fig 7).

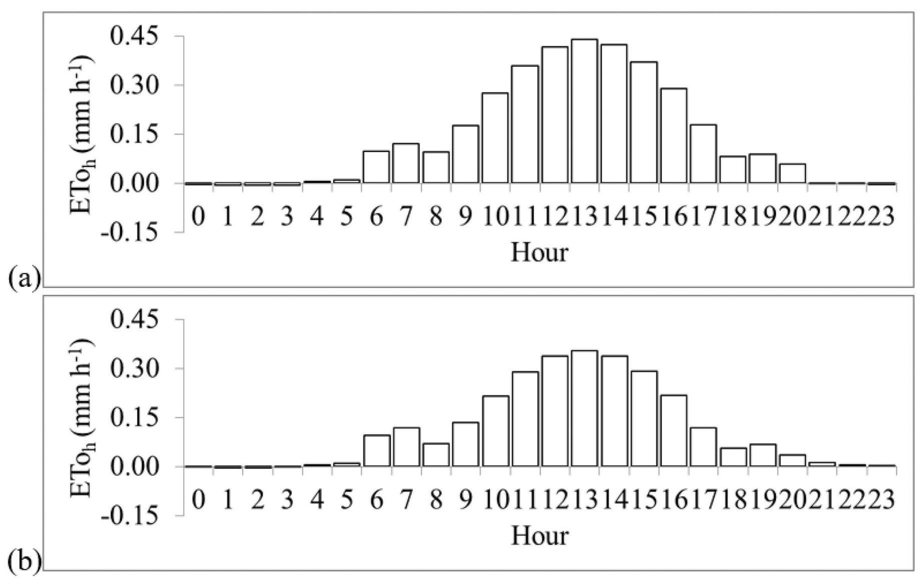

Figure 4 - Average trend of the hourly reference evapotranspiration (ETo_h), in 25 meteorological stations in Paraná State, between December 1, 2016 to November 8, 2018 according to: a) Average ETo_h of the 15 stations in *Cfa* climate type, and, b) Average ETo_h of the 10 stations in *Cfb* climate type.

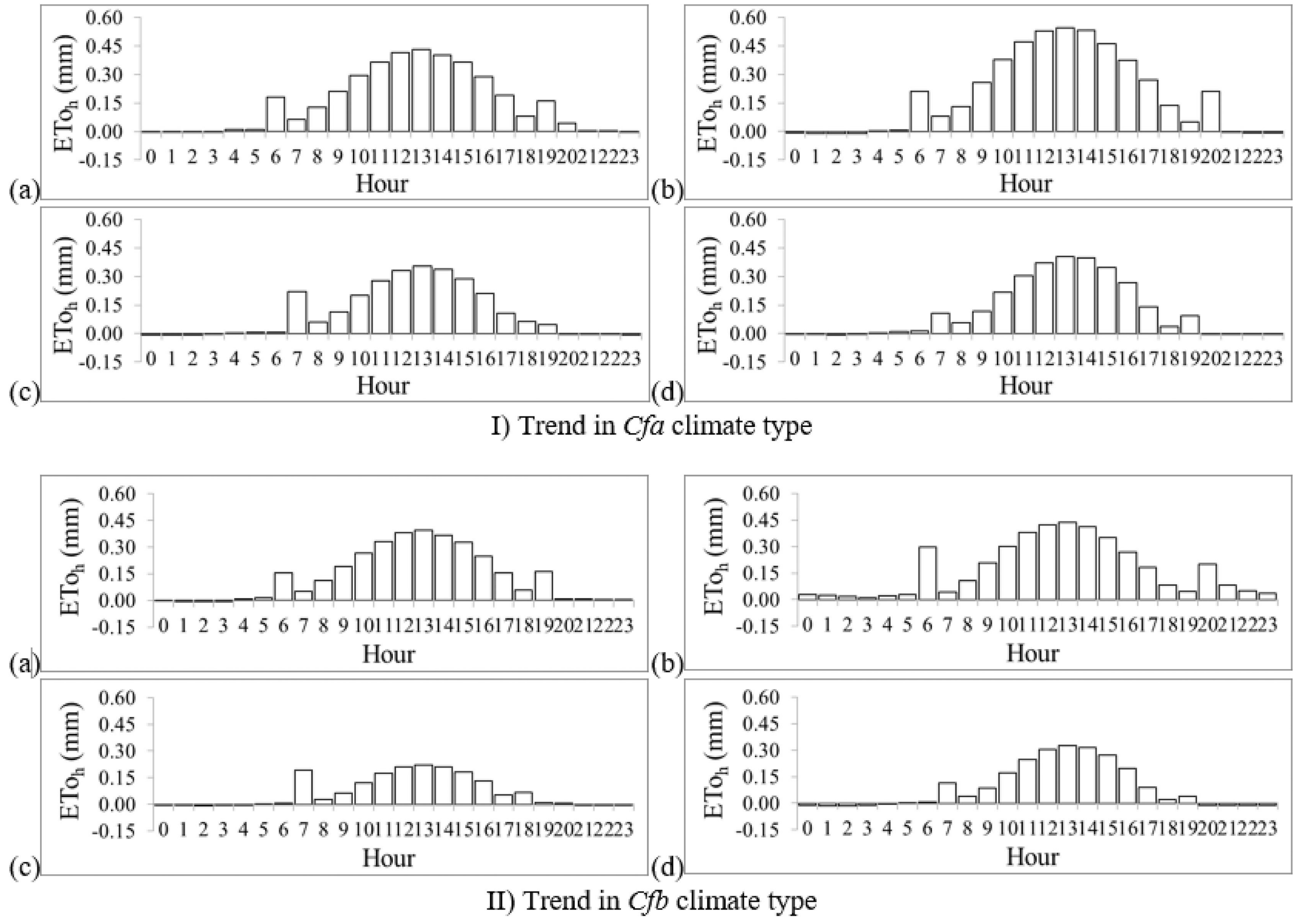

Figure 5 - Average trend of the hourly reference evapotranspiration (ETo_h), in 25 meteorological stations in Paraná State, for *Cfa* and *Cfb* climate type, between December 1, 2016 to November 1, 2018, considering: a) Spring, b) Summer, c) Autumn, and, d) Winter.

Table 2 - Seasonal average in the year[(1)] for ETo_d and ETo_{24h} (mm day^{-1}) in 25 meteorological stations in Paraná State, between December 1, 2016 to November 8, 2018.

Meteorological stations	Spring		Summer		Autumn		Winter		Annual average	
	ETo_{24h}	ETo_d	ETo_{24h}	ETo_d	ETo_{24h}	ETo_d	ETo_{24h}	ETo_d	ETo_{24h}	ETo_d
					Cfa climate					
Campina da Lagoa	2.56	2.38	5.08	4.77	4.64	4.48	1.67	1.28	3.49	3.23
Cidade Gaúcha.	4.88	5.20	4.70	4.88	2.90	2.62	2.22	1.99	3.68	3.67
Diamante do Norte	4.31	4.27	5.22	5.20	3.57	3.28	1.67	1.41	3.69	3.54
Dois Vizinhos	5.36	5.33	4.68	4.64	2.61	2.46	3.04	2.64	3.92	3.77
Foz do Iguaçu	4.00	4.02	5.38	5.44	0.91	1.80	1.68	1.31	2.99	3.14
Icaraíma	4.32	4.28	5.52	5.41	3.77	3.40	1.68	1.39	3.82	3.62
Japirá	3.67	3.73	4.07	4.30	3.04	2.82	1.67	1.41	3.11	3.06
Joaquim Távora	3.74	3.78	4.17	4.32	2.95	2.89	1.66	1.40	3.13	3.10
Marechal C. R.	3.90	3.89	4.84	4.83	2.83	2.63	1.68	1.36	3.31	3.18
Maringá	4.10	3.82	5.22	4.90	3.04	2.70	1.67	1.35	3.51	3.19
Morretes	3.42	3.25	3.50	3.58	2.48	2.34	1.63	1.25	2.75	2.61
Nova Fátima	4.02	3.87	5.43	5.25	0.92	1.68	1.67	1.36	3.01	3.04
Nova Tebas	5.16	4.65	5.49	5.16	3.35	2.95	2.25	1.80	4.06	3.64

(*continued*)

Table 2 - continued

Meteorological stations	Spring		Summer		Autumn		Winter		Annual average	
	ETo_{24h}	ETo_d	ETo_{24h}	ETo_d	ETo_{24h}	ETo_d	ETo_{24h}	ETo_d	ETo_{24h}	ETo_d
Paranapoema	4.21	3.91	5.36	4.95	3.83	3.26	1.63	1.35	3.76	3.37
Planalto	5.64	5.04	5.21	4.86	2.96	2.51	3.37	2.39	4.30	3.70
Average *Cfa* climate	4.22	4.09	4.92	4.83	2.92	2.79	1.95	1.58	3.50	3.32
Cfb climate										
Castro	3.05	2.97	3.91	3.93	2.24	1.53	1.91	1.66	2.78	2.52
Clevelândia	1.40	1.30	1.26	1.17	3.61	2.59	0.58	0.46	1.71	1.38
Colombo	3.03	3.09	3.90	4.07	2.06	1.69	1.91	1.73	2.73	2.64
Curitiba	3.05	3.10	3.90	4.07	2.10	2.10	1.92	1.73	2.74	2.75
General Carneiro	2.98	2.97	3.82	3.92	2.33	1.49	1.87	1.62	2.75	2.50
Inácio Martins	2.97	2.97	3.81	3.92	2.25	1.69	1.87	1.64	2.73	2.56
Ivaí	3.05	3.09	3.90	4.05	2.56	2.16	1.92	1.73	2.86	2.76
Laranjeiras do Sul	3.06	3.09	3.92	4.05	2.87	2.01	1.93	1.72	2.94	2.72
São Mateus do Sul	3.04	2.93	3.97	3.90	2.01	1.58	1.93	1.62	2.74	2.51
Ventania	3.00	2.85	3.88	3.76	2.90	2.06	1.89	1.58	2.92	2.56
Average *Cfb* climate	2.86	2.84	3.63	3.68	2.49	1.89	1.77	1.55	2.69	2.49

(1)Seasons are considered to occur in the following periods: Summer between December 21 to March 20; Autumn between March 21 to June 20; Winter between June 21 to September 22; and Spring between September 23 to December 20.

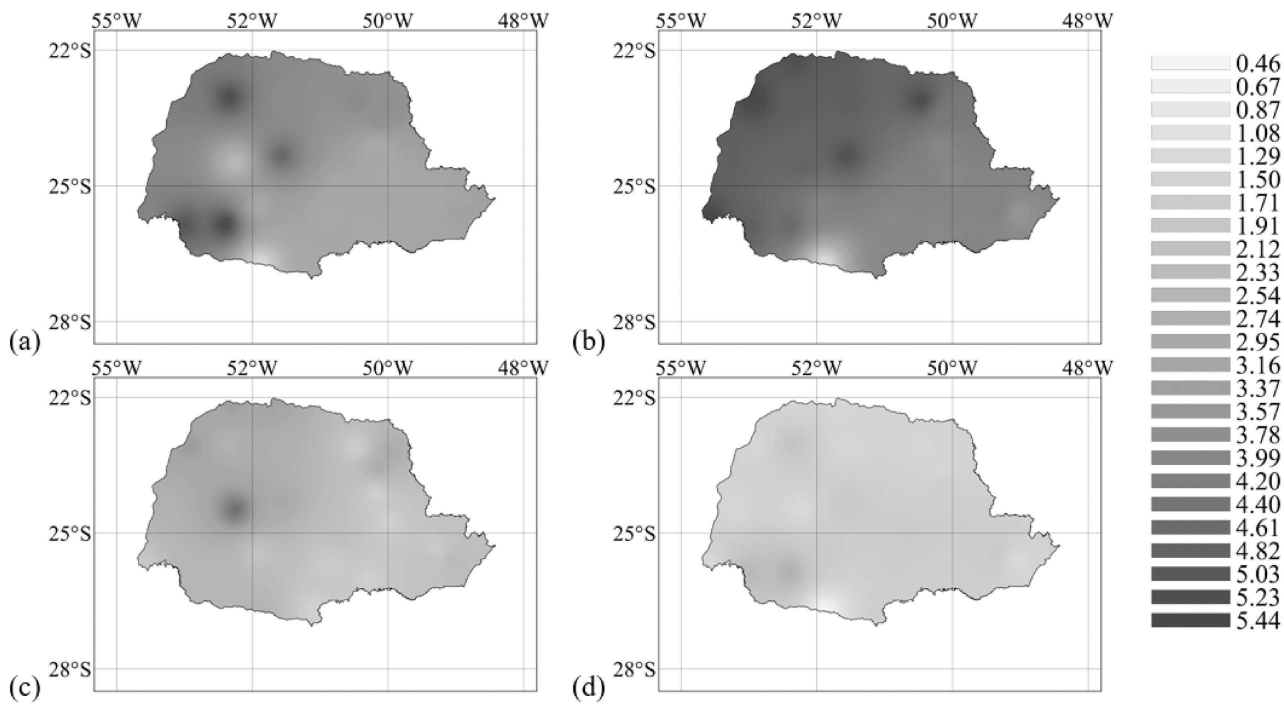

Figure 6 - Daily trend of the reference evapotranspiration (ETo_d; mm day^{-1}) over the analyzed period for Paraná State, being: a) Spring, b) Summer, c) Autumn, and, d) Winter.

As for the magnitude, the analyzes of the present study for *Cfa* climate indicated ETo_{24h} average values of 3.50 mm day^{-1} and ETo_d average of 3.32 mm day^{-1}, resulting in a difference of only 0.18 mm day^{-1} (5.1%). For *Cfb* climate, a ETo_{24h} average of 2.69 mm day^{-1} and ETo_d average of 2.49 mm day^{-1} were obtained, resulting in a difference of 0.20 mm day^{-1} (7.4%) (Table 2 and Fig. 7). The Clevelândia weather station was the one with the lowest *ETo* values and amplitudes. However, this season presented many data

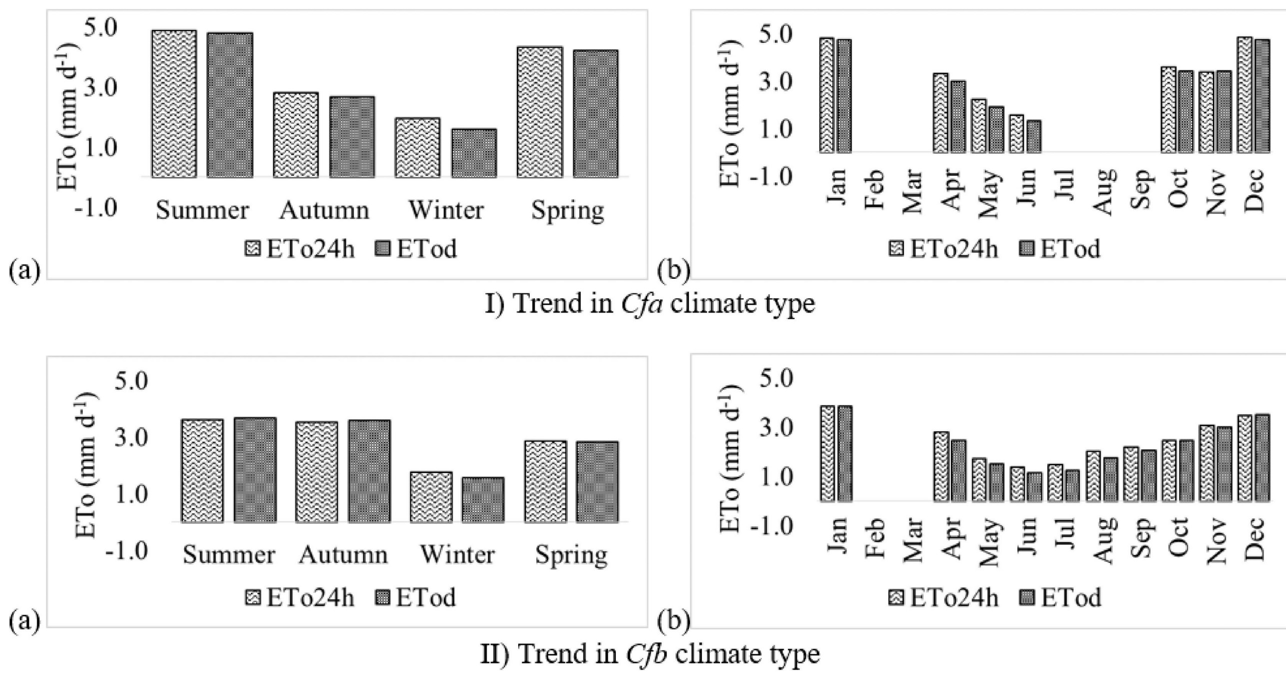

Figure 7 - Average values of ETod and ETo24h, in 25 meteorological stations in Paraná State, according to Cfa and Cfb climate types, between December 21, 2016 to November 8, 2018: a) Seasonal trend, and, b) Monthly trend.

failures, mainly in autumn and winter period for the *Rs* variable.

Nolz and Rodneý (2019) evaluating the ASCE-PM model to estimate hourly and daily *ETo* in sub-humid climate in northeastern Australia, obtained values between 0 and 8 mm day^{-1}. The magnitude differs from the highest values achieved in Parana State (Table 2 and Fig. 7). Allen *et al*. (1998) also considers that the presence of clouds in regions with humid climate provides lower *ETo* values. Dhungel *et al.* (2019) studying evapotranspiration in a BSh (dry semi-arid) climate obtained mean ETo_d values in a lysimeter ranging from 0 to 12 mm day^{-1}.

Lopes & Leal (2016) observed that the ETo_d and ETo_{24h} methodologies have different results when taking months or seasons into consideration. When working with a reduced number of data, such as a few months, there is no possibility to analyze *ETo* considering the changes in meteorological variables throughout the year. The reduced period for analysis can also provide closer correlations, but which do not correspond to the reality of the environment. Long periods, on the other hand, can provide higher variations, since the results will be analyzed through extreme weather changes over the seasons. However, even in a longer period, it was found in the present study that the variations between ETo_d and ETo_{24h} were small (Table 2), resulting in good correlations, errors and "*d*" index (Table 3). Similarly, Noia *et al.* (2014) in a study carried out in Dourados city, Mato Grosso do Sul State, Brazil, found that there is a small difference between the two methods of *ETo* estimation (ETo_d or ETo_{24h}), obtaining low deviations or errors.

In general, the results showed a monthly ETo_{24h} trend very similar to ETo_d (Fig. 7). This aspect can also be confirmed with the average values (mm day^{-1}) of the "*d*" indexes achieved in the 25 locations in Paraná State (Table 3; "*d*" ≥ 0.77 for *Cfa* climate and "*d*" ≥ 0.82 for *Cfb* climate). The average seasonal trend for ETo_{24h} and ETo_d in Paraná State were also similar and close, with the *Cfa* "*d*" index equal to 0.97 for spring and summer; and *Cfb* "*d*" index equal to 0.99 in the spring and 0.98 in the summer. Lopes & Leal (2016) associating ETo_d vs ETo_{24h} for semiarid climate obtained an agreement "*d*" index ranging from 0.98 to 0.99. In the present study, lower "*d*" indexes were observed in the autumn and winter periods for *Cfa* climate. The large number of failures in the input data to estimate *ETo* in the period may have influenced the differences in the results obtained in both methodologies. In stations with *Cfb* climate, in which there was a possibility of using more data in the winter period, "*d*" index ≥ 0.91 was obtained; and for the autumn period, when there were more failures, lower "*d*" indexes 0.34 ≤ "*d*" ≤ 0.96 were found (Table 3).

The correlation coefficients of the associations between ETo_d vs ETo_{24h} were very promising. The lowest average value was found for *Cfa* climate, at Cidade Gaúcha station (*r* = 0.64), with correlations between 0.80 and 0.99 for other locations with *Cfa* climate and between 0.85 and 0.97 for *Cfb* climate. The lowest mean correlation

Table 3 - Seasonal and annual values of the correlation coefficient (*r*; dimensionless), "*d*" index (dimensionless) and root mean square error (*RMSE*; mm day^{-1}) of the associations between ETo_d vs ETo_{24h}, for 25 meteorological stations in Paraná State, between December 1, 2016 to November 8, 2018.

Meteorological stations	Spring			Summer			Autumn			Winter			Annual average		
	RMSE	"*d*"	*r*	*RMSE*	"*d*"	*r*	*RMSE*	"*d*"	*r*	*RMSE*	"*d*"	*r*	*RMSE*	"*d*"	*r*
Cfa climate															
Campina da L.	0.36	0.97	0.96	0.51	0.97	1.00	0.26	0.95	0.97	0.44	0.86	0.71	0.39	0.94	0.91
Cidade Gaúcha	1.39	0.83	0.70	0.97	0.84	0.72	0.65	0.84	0.76	0.49	0.57	0.38	0.88	0.77	0.64
Diamante do N.	0.23	1.00	0.99	0.21	1.00	1.00	0.45	0.97	0.98	0.34	0.72	0.96	0.31	0.92	0.98
Dois Vizinhos	0.27	1.00	0.99	0.21	0.99	0.99	0.28	0.95	0.96	0.41	0.81	0.96	0.29	0.94	0.98
Foz do Iguaçu	0.25	0.99	0.99	0.16	1.00	1.00	1.35	0.54	0.26	0.44	0.58	0.95	0.55	0.78	0.80
Icaraíma	0.26	1.00	0.99	0.28	0.99	0.99	0.52	0.74	0.97	0.36	0.69	0.96	0.36	0.86	0.98
Japirá	0.24	0.99	0.98	0.32	0.99	0.99	0.39	0.94	0.96	0.35	0.71	0.96	0.33	0.91	0.97
Joaquim Távora	0.24	0.99	0.99	0.24	0.99	1.00	0.32	0.98	0.98	0.35	0.71	0.96	0.29	0.92	0.98
Marechal C. R.	0.23	0.99	0.99	0.19	0.99	0.99	0.40	0.81	0.84	0.40	0.64	0.95	0.31	0.86	0.94
Maringá	0.49	0.97	0.99	0.45	0.97	0.99	0.57	0.95	0.99	0.40	0.61	0.94	0.48	0.88	0.98
Morretes	0.44	0.97	0.99	0.27	0.98	0.99	0.39	0.94	0.95	0.47	0.51	0.92	0.39	0.85	0.96
Nova Fátima	0.38	0.99	0.99	0.27	0.98	0.99	1.19	0.57	0.32	0.39	0.63	0.94	0.56	0.79	0.81
Nova Tebas	0.68	0.95	0.99	0.48	0.98	0.99	0.59	0.94	0.98	0.54	0.67	0.98	0.57	0.89	0.99
Paranapoema	0.52	0.97	0.99	0.53	0.96	0.99	0.72	0.94	0.99	0.37	0.65	0.93	0.54	0.88	0.98
Planalto	0.76	0.95	0.99	0.47	0.95	0.99	0.60	0.81	0.91	1.02	0.58	0.90	0.71	0.82	0.95
Average *Cfa*	0.45	0.97	0.97	0.37	0.97	0.97	0.58	0.86	0.85	0.45	0.66	0.89	0.46	0.87	0.92
Cfb climate															
Castro	0.35	0.98	0.99	0.37	0.97	1.00	0.43	0.55	1.00	0.43	0.93	0.96	0.50	0.91	0.99
Clevelândia	0.32	0.99	0.99	0.16	1.00	1.00	1.03	0.73	1.00	0.18	0.99	0.99	0.42	0.93	1.00
Colombo	0.25	0.99	0.99	0.32	0.98	1.00	0.51	0.34	1.00	0.35	0.95	0.97	0.36	0.82	0.99
Curitiba	0.25	0.99	0.99	0.32	0.98	1.00	0.05	0.96	1.00	0.36	0.95	0.97	0.25	0.97	0.99
General C.	0.28	0.99	0.99	0.30	0.98	1.00	0.85	0.54	1.00	0.40	0.94	0.96	0.46	0.86	0.99
Inácio Martins	0.24	0.99	0.99	0.30	0.98	1.00	0.59	0.41	1.00	0.39	0.94	0.96	0.38	0.83	0.99
Ivaí	0.24	0.99	0.99	0.31	0.98	1.00	0.44	0.41	1.00	0.36	0.95	0.97	0.34	0.83	0.99
Laranj. do S.	0.27	0.99	0.99	0.30	0.98	1.00	0.86	0.64	1.00	0.36	0.95	0.97	0.45	0.89	0.99
São M. do Sul	0.34	0.98	0.99	0.37	0.97	0.99	0.43	0.77	1.00	0.46	0.92	0.96	0.40	0.91	0.99
Ventania	0.38	0.97	0.99	0.38	0.97	0.99	0.84	0.44	1.00	0.46	0.91	0.96	0.52	0.82	0.99
Average *Cfb*	0.29	0.99	0.99	0.31	0.98	1.00	0.64	0.60	1.00	0.38	0.94	0.97	0.41	0.88	0.99

(1)Seasons are considered to occur in the following periods: Summer between December 21 to March 20; Autumn between March 21 to June 20; Winter between June 21 to September 22; and Spring between September 23 to December 20.

values occurred in autumn and winter, reflected of the low number of data in the periods. Cidade Gaúcha showed considerable failures in the *Rs* sensor (it showed the same *Rs* values for day and night in about three months). It is believed that the lowest correlation obtained at the site was due to this reason. The *Cfb* climate presented excellent average correlations ($r \geq 0.99$) for the annual period, and between $0.97 \leq r \leq 1.0$ in the summer, autumn, winter and spring seasons (Table 3). The readings failures verified in autumn did not compromise the correlations between ETo_d vs ETo_{24h}. Treder & Klamkowski (2017) associating ETo_d vs ETo_{24h} with the ASCE-PM model, also obtained a correlation coefficient $r = 0.99$, in humid continental climate, in Poland, in the period of May and September, 2016. In a similar study, Nolz & Rodný (2019) also obtained a correction coefficient $r = 0.98$ in the association between ETo_d vs ETo_{24h} for sub-humid climate.

Nolz & Rodný (2019) obtained $RMSE = 0.27$ mm day^{-1} in the associations between ETo_d vs ETo_{24h} in sub-humid climate. In the present study the *RMSE* values were higher. With the exception of Cidade Gaúcha, due to its lower correlations, the values were between: $0.29 \leq RMSE \leq 0.71$ mm day^{-1} for the annual period; $0.23 \leq RMSE \leq 0.76$ mm day^{-1} in spring; $0.16 \leq RMSE \leq 0.53$ mm day^{-1} in summer; $0.26 \leq RMSE \leq 1.35$ mm day^{-1} in autumn; and, $0.35 \leq RMSE \leq 1.02$ mm day^{-1} in winter (Table 3).

Many studies have pointed out better estimates with ETo_{24h}, in relation to ETo_d with the ASCE-PM method, when compared to *ETo* measured by lysimeters (Nolz & Rodný, 2019; Dhungel *et al.* 2019). The analyzes carried out in the present study (Tables 2 and 3 and Fig. 7) showed that the ETo_d and ETo_{24h} values had the same trend, were close and well associated in the 25 locations analyzed in the Paraná State. The results obtained are very interesting, as they make possible the development of studies for the planning, design and management of water in Paraná agriculture, considering alternatives for water loss from the soil-plant-system over the hours of the day.

4. Conclusions

The ETo_h trend resembles the Gaussian distribution shape, corresponding inversely to relative humidity and directly to temperature, incident solar radiation and wind speed.

The highest ETo_h values throughout the 24 h of the day in Paraná State occur between 12:00 p.m. and 2:00 p. m. The maximum ETo_h average of the stations over the hours of the day is equal to 0.44 mm h^{-1} for *Cfa* climate and 0.35 mm h^{-1} for *Cfb* climate.

The two methodologies tested to obtain daily evapotranspiration in Paraná State resulted in average values of ETo_{24h} = 3.50 mm day^{-1} and ETo_d = 3.32 mm day^{-1} (difference of 5.1%) for *Cfa* climate. For *Cfb* climate, ETo_{24h} = 2.69 mm day^{-1} and ETo_d = 2.49 mm day^{-1} (difference of 7.4%) were obtained.

The ETo_{24h} was very well associated with ETo_d obtained with the standard ASCE-PM method, with the advantage of allowing better understanding and monitoring of water loss in hourly periodicity, as long as climatic data are available in quantity and quality for hourly periodicity.

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