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# REFERENCE CROP EVAPOTRANSPIRATION IN DISTINCT AGRICULTURAL REGIONS OF SOUTHERN BRAZIL: A COMPARISON OF IMPROVED EMPIRICAL MODELS

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## ABSTRACT

The FAO56 Penman-Monteith model is globally accepted for the accurate determination of reference evapotranspiration (ETo). However, a lack of appropriate data encouraged the improved model's approach to estimate ETo. This study compared the performance of 10 empirical models of ETo estimation (Penman, Priestley & Taylor, Tanner & Pelton, Makkink, Jensen & Haise, Hargreaves & Samani, Camargo, Benevides & Lopes, Turc, and Linacre) contrasted with the FAO56 model in two regions in Southern Brazil. Data were collected from automatic stations of the Brazilian National Institute of Meteorology (INMET) from December 21, 2019, to February 28, 2021. The determination coefficient ($R^2$), mean square error (*n*RMSE), mean bias error (MBE), Willmott index (d), and Pearson's correlation coefficient (r), clustering, and Principal Component Analysis (PCA) were performed. For the different regions, the radiation-based model proposed by Penman was the best alternative for estimating ETo. The model showed the most appropriated values for $R^2$ (0.9015) and r (0.9494). The clustering and PCA analyses indicated the interrelations of the meteorological data and the combination of the models according to the parameters used for the determination of ETo.

**Palavras-chave:**
FAO-56
Multi modelos climáticos
Balanço de água no sistema solo-planta-atmosfera
Modelos espaço-temporais

## EVAPOTRANSPIRAÇÃO DE REFERÊNCIA DA CULTURA EM DISTINTAS REGIÕES AGRÍCOLAS DO SUL DO BRASIL: UMA COMPARAÇÃO DE MODELOS EMPÍRICOS APRIMORADOS

## RESUMO

O modelo FAO56 Penman-Monteith é globalmente aceito para uma determinação precisa da evapotranspiração de referência (ETo). No entanto, a falta de dados apropriados encorajou a abordagem de modelos aprimorados para estimar a ETo. Este estudo comparou o desempenho de 10 modelos empíricos de estimativa de ETo (Penman, Priestley & Taylor, Tanner & Pelton, Makkink, Jensen & Haise, Hargreaves & Samani, Camargo, Benevides & Lopes, Turc e Linacre) contrastados com o modelo FAO56 em duas regiões do Sul do Brasil. Os dados foram coletados nas estações automáticas do Instituto Nacional de Meteorologia (INMET) de 21 de dezembro de 2019 a 28 de fevereiro de 2021. O coeficiente de determinação ($R^2$), raiz quadrada média do erro (*n*RMSE), tendência do erro médio (MBE), índice de Willmott (d), e coeficiente de correlação de Pearson (r), agrupamento e Análise de Componentes Principais (PCA). Para as diferentes regiões, o modelo baseado em radiação proposto por Penman foi a melhor alternativa para estimar a ETo. O modelo apresentou os valores mais adequados para $R^2$ (0,9015), e r (0,9494). As análises de agrupamento e PCA indicaram as inter-relações dos dados meteorológicos e a combinação dos modelos de acordo com os parâmetros utilizados para a determinação da ETo.



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## INTRODUCTION

Evapotranspiration (ETp) is characterized as a complex dynamic process that involves the passage of water from a liquid to a gaseous state towards the atmosphere (SALAM *et al*., 2020; MIRALLES *et al*., 2020). The reference evapotranspiration (ETo) is a term created according to the requisites to reconsider the measurement of ETp under a more precise and accurate arrangement (LIU *et al*., 2020). ETo is widely applied to measure the water demand of crops, acting directly on the scheduling of irrigations and production management practices (MUHAMMAD *et al*., 2019; OCHOA-SÁNCHEZ *et al*., 2019).

The FAO56 Penman-Monteith standard model, suggested by Allen *et al*. (1998), is globally accepted as a method of estimating ETo and widely used, due to the detailed variables considered for its determination (PENG *et al*., 2017). Alternatively, the requirement for a range of meteorological components and an insufficient arrangement of locations to obtain data compromise the computation of ETo by the FAO56 standard model, as well as resulting in gaps (ČADRO *et al*., 2017; CELESTIN *et al*., 2020).

The literature recommends the application of several models, such as temperature-based (LINACRE, 1977), radiation-based (MAKKINK, 1957; TURC, 1961; PRIESTLEY; TAYLOR, 1972), and integration-based (PENMAN, 1948) models. The performance of a particular model is directly influenced by the availability of local data, considering the particularities of a distinct region. Consequently, ETo estimates reveal incompatible results from a spatiotemporal perspective. To overcome this obstacle, the validation of empirical models has been widely considered globally in different environments and edaphoclimatic attributions (SALAM *et al*., 2020).

The validation of different empirical models for estimating ETo has been applied in several regions with high agriculture potential (MERAZ-MALDONADO; FLORES-MAGDALENO, 2019; CELESTIN *et al*., 2020). With an area of approximately 8,516,000 km², Brazil is the fifth largest country in extension and considered one of the most biodiverse, with geo and edaphoclimatic differences indicating a significative variability in ETo estimates. The Rio Grande do Sul state exhibits an elevated geo-climatic variability and, due to being in the subtropical zone, it presents an observable definition of the seasons, situating the state one of the main contributors of agricultural production to the national and world economies.

Correspondingly, the purpose of this study was: (i) provide a comprehension into the performance of improved empirical models of ETo estimation with the standard FAO56 Penman-Monteith model for different agricultural zones in Southern Brazil; (ii) prospect the implications and spatiotemporal variations of climatological parameters in ETo estimates; and (iii) select the empirical model with the best performance for each location, considering the particular edaphoclimatic dynamism of the contrasting agricultural areas.

## MATERIAL AND METHODS

*Study areas description*

Daily meteorological data obtained from automatic meteorological stations belonging to the Brazilian National Institute of Meteorology (INMET), located in the municipalities of Alegrete and Tupanciretã, Rio Grande do Sul State, were used. For Alegrete, the geo-climatic characteristics considered for this study were: latitude (º): -29.4659, longitude (º): -55.4731, altitude (m): 102, climatic classification according to Köppen-Geiger categorization (Cfa, humid subtropical climate). Finally, regarding Tupanciretã, the geo-climatic characteristics were latitude (º): -29.0824, longitude (º): -55.8369, altitude (m): 465, climatic classification according to Köppen-Geiger categorization (Cfa, humid subtropical climate).

From the variables Tmax (daily maximum temperature, ºC), Tmin (daily minimum temperature, ºC), Ws (wind speed at 2 meters high, m $s^{-1}$), atmospheric pressure (hPa), RHmax (daily maximum relative humidity, %), RHmin (daily minimum relative humidity, %), and K↓ (incident global radiation, MJ $m^{-2}$ $day^{-1}$), the values of es-e (partial pressure saturation deficit, hPa), K0↓ (solar radiation in the absence of the atmosphere, MJ $m^{-2}$ $day^{-1}$), and Q* (radiation balance, MJ $m^{-2}$ $day^{-1}$) were calculated.

*Meteorological data*

The collected data correspond to the period from December 21, 2019, to February 28, 2021. For the determination of ETo, the following meteorological data were required: Tmax (ºC), Tmin (ºC), Td (ºC), Ws (m s$^{-1}$), atmospheric pressure (hPa), RHmax (%), RHmin (%), and K↓ (MJ m$^{-2}$ day$^{-1}$). Correspondingly, Figure 1 reports the steps applied to the development of this study. Meteorological data were assessed for quality before use with any ETo equation. In case of missing data, they were used from the nearest station. For Alegrete, the Quaraí automatic station was used. In the case of Tupanciretã, it was not necessary to use data from nearby stations.

*FAO56 Penman-Monteith model*

The FAO56 Penman-Monteith standard model was employed for estimating daily ETo in Alegrete and Tupanciretã, Rio Grande do Sul, Brazil. Proposed by Allen *et al.* (1998), the Penman-Monteith determination is expressed by the Eq. 1:

$$ETo = 0{,}408\Delta(Q^* - G) + \frac{\left[(\gamma \times 900 \times Ws)\frac{(e_s - e)}{(T_{med} + 273)}\right]}{\Delta + \gamma(1 + (0.34 \times Ws))} \quad (1)$$

Where:

ET$_o$ = reference evapotranspiration (mm day$^{-1}$);
Δ = slope of the saturation curve at the daily temperature (kPa ºC$^{-1}$);
γ = psychrometric constant (0.066 kPa ºC$^{-1}$);
Q$^*$ = radiation balance (MJ m$^{-2}$ dia$^{-1}$);
G = daily soil heat flux (MJ m$^{-2}$ dia$^{-1}$);
T$_{med}$ = average daily air temperature at 2 m height (°C);
Ws = wind speed at 2 m height (m s$^{-1}$); and
($e_s$-$e$) = d: saturation deficit (kPa). For this study, G=0, as recommended by Allen *et al.* (1998).

The Q$^*$ is determined by the Eqs. 2-11:

$$Q^* = Q^*_{ns} - Q^*_{nl} \quad (2)$$

$$Q^*_{ns} = (1 - \alpha)Q^*_s \quad (3)$$

$$Q^*_s = \left[a_s + b_s \frac{N}{n}\right] Q^*_a \quad (4)$$

$$Q^*_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s sin(\varphi) sin(\delta) + cos(\varphi) cos(\delta) sin(\omega_s)] \quad (5)$$

$$d_r = 10.033 \cos\left(\frac{2\pi}{365} \mathrm{J}\right) \quad (6)$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} \mathrm{J} - 1.39\right) \quad (7)$$

$$\omega_s = arccos[-tan(\varphi)\ tan(\delta)] \quad (8)$$

$$Radians = {}^{\pi}/_{180}\ \text{(decimal degrees)} \quad (9)$$

$$Q^*_{nl} = \sigma \left[\frac{(T_{max})^4 + (T_{min})^4}{2}\right] \left(0.34 - (0.14\sqrt{e})\right) \left[1.35 \frac{Q^*_s}{Q^*_{so}} - 0.35\right] (10)$$

$$Q^*_{so} = \left(0.75 + (2 \times 10^{-5} Z)\right) Q^*_a \quad (11)$$

Where:

Q$^*_{ns}$ = net solar or shortwave radiation (MJ m$^{-2}$ day$^{-1}$);

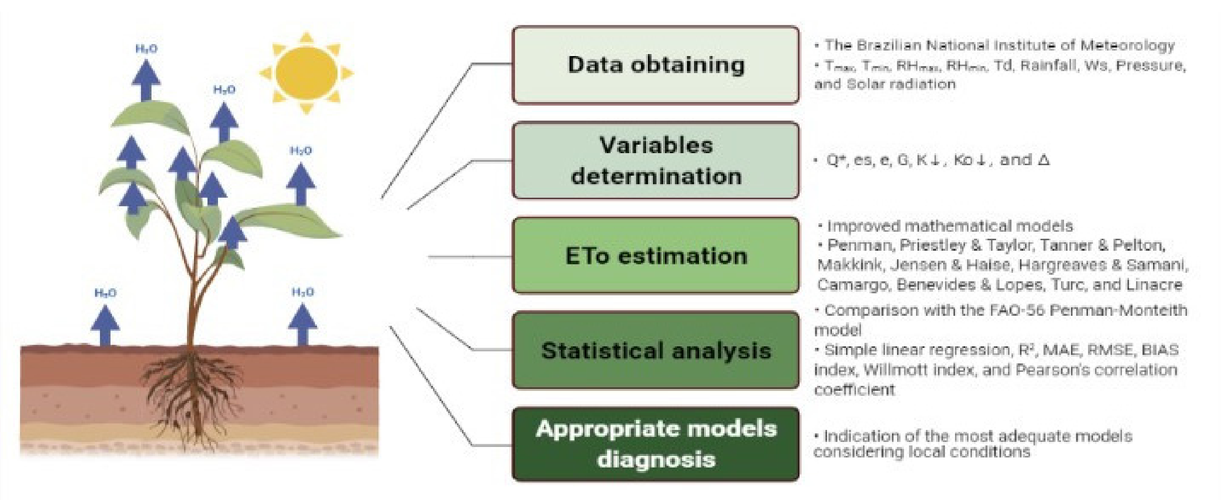


**Figure 1.** Representation of the steps adopted for ETo estimates by the FAO56 Penman-Monteith standard model and the empirical models applied for this study

$Q^*_{nl}$ = net outgoing longwave radiation (MJ $m^{-2}$ $day^{-1}$);
$Q^*_s$ = global solar radiation (MJ $m^{-2}$ $day^{-1}$);
N = maximum sunshine duration (hours $day^{-1}$);
n = actual sunshine duration (hours $day^{-1}$);
$Q^*_a$ = extraterrestrial radiation (MJ $m^{-2}$ $d^{-1}$);
$G_{sc}$ = solar constant (0.0820 MJ $m^{-2}$ $min^{-1}$);
$d_r$ = inverse relative distance Earth-Sun;
$\omega_s$ = sunset hour angle (rad);
$\varphi$ = latitude (rad);
$\delta$ = solar declination (rad);
J = Julian date;
$\sigma$ = Stefan-Boltzmann constant ($4.903 \times 10^{-9}$ MJ $K^{-4}$ $m^{-2}$ $day^{-1}$)
$\alpha$ = albedo;
$T_{max}$ = maximum absolute temperature (ºC);
$T_{min}$ = minimum absolute temperature (ºC);
$Q^*_{so}$ = direct sky solar radiation (MJ $m^{-2}$ $day^{-1}$), and;
Z = station elevation above sea level (m).

*ETo empirical models*

For higher accuracy in ETo determination, different mathematical models were widely addressed in the literature. The models were selected according different edaphoclimatic classes of study, such as (i) water balance or mass transfer, (ii) temperature, (iii) radiation, and (iv) the integration based. Furthermore, the validation of empirical models in opposition to the FAO56 Penman-Monteith standard model has been widely considered globally in different environments and edaphoclimatic attributions. The selected models, their mathematical equations, and other details are presented in Table 1.

**Table 1.** Description of the methods used to determine ETo, the variables necessary for mathematical calculations and their respective references

| Equation | Empirical models (ETo) | | Variables | Reference |
|---|---|---|---|---|
| Penman | $\frac{\left[\left(\frac{s}{\gamma}\right)\left(\frac{Q^*}{2.45}\right)+E_a\right]}{\frac{s}{\gamma}+1}$ | (12) | $s^1$, $\gamma^2$, $e^3$, $es^4$, $Q^{*5}$, $E_a^{\ 6}$ | Penman (1948) |
| Priestley & Taylor | $1.26\left(\frac{\Delta}{\Delta+\gamma}\right)\left(\frac{Q^*-G}{2.45}\right)$ | (13) | $\Delta^7$, $\gamma$, $Q^*$, $G^8$ | Pristley & Taylor (1972) |
| Tanner & Pelton | $\frac{(1.12\times Q^*)}{(2.45-0.11)}$ | (14) | $Q^*$ | Tanner & Pelton (1960) |
| Makkink | $0.61\left(\frac{\Delta}{\Delta+\gamma}\right)\left(\frac{K\downarrow}{2.45}\right)-0.12$ | (15) | $\Delta$, $\gamma$, $K\downarrow^9$ | Makkink (1957) |
| Jensen & Haise | $\left(\frac{K\downarrow}{2.45}\right)\left((0.0252\times T_{med})+0.078\right)$ | (16) | $K\downarrow$, $T_{med}^{\ 10}$ | Jensen & Haise (1963) |
| Hargreaves & Samani | $\left(\frac{0.023\times K0\downarrow}{2.45}\right)\left[(T_{max}-T_{min})^{0.5}\,(T_{med}+17.8)\right]$ | (17) | $K0\downarrow^{11}$, $T_{max}^{\ 12}$, $T_{min}^{\ 13}$, $T_{med}$ | Hargreaves & Samani (1985) |
| Camargo | $0.01\left(\frac{K0\downarrow}{2.45}\right)T_{med}$ | (18) | $K0\downarrow$, $T_{med}$ | Camargo (1971) |
| Benevides & Lopes | $\left[\left(1.21\times 10^{\left[\frac{7.5\times T_{med}}{237.5+T_{med}}\right]}\right)\left(1-(0.01\times RH_{med})\right)+0.21(T_{med}-2.3)\right]$ | (19) | $T_{med}$, $RH_{med}^{\ 14}$ | Benevides & Lopes (1970) |
| Turc | $0.013\left[\frac{T_{max}}{(T_{max}+15)(50+(23.88\times K\downarrow))}\right]$ | (20) | $T_{max}$, $K\downarrow$ | Turc (1961) |
| Linacre | $\frac{\left[\left(\frac{500\times T_H}{100-\theta}\right)+(15\times(T_{med}-Td))\right]}{(80-T_{med})}$ | (21) | $T_H^{\ 15}$, $\theta^{16}$, $T_{med}$, $Td^{17}$ | Linacre (1977) |

[1]s: Δ: slope of the saturation curve at the daily temperature (kPa $ºC^{-1}$); [2]psychrometric constant (0.066 kPa $ºC^{-1}$); [3]partial pressure water vapor (hPa); [4]saturation vapor pressure (hPa); [5]radiation balance (MJ $m^{-2}$ $day^{-1}$); [6]evapotranspiration aerodynamic factor (mm); [7]slope of the saturation curve at the daily temperature (kPa $ºC^{-1}$); [8]daily soil heat flux (MJ $m^{-2}$ $day^{-1}$); [9]incident solar radiation (MJ $m^{-2}$ $day^{-1}$); [10]average daily air temperature at 2 m height (°C); [11]solar radiation in the absence of the atmosphere (MJ $m^{-2}$ $day^{-1}$); [12]daily maximum air temperature at 2 m height (°C); [13]daily minimum air temperature at 2 m height (°C); [14]average daily relative humidity (%); [15]air temperature at sea level (ºC); [16]local latitude (º); and [17]daily dew point temperature (°C)

*Performance of ETo empirical models*

The definition for the ranking criteria used to select the most appropriated method for each location was performed out using different statistical criteria. Additionally to a simple linear regression, the determination coefficient ($R^2$), mean square error ($n$RMSE), mean bias error (MBE), Willmott index (d) (WILLMOTT *et al.*, 2012), and Pearson's correlation coefficient (r) were executed, expressed by Equations. (22-26):

$$R^2 = \frac{\sum_{i=1}^{n}(ETo_{obs} - ETo_{sim})^2}{\sum_{i=1}^{n}(ETo_{obs} - \overline{ETo_{sim}})^2} \quad (22)$$

$$nRMSE = \sqrt{\frac{1}{2}\sum_{i=1}^{n}(ETo_{obs} - ETo_{sim})^2} \quad (23)$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n} ETo_{sim} - ETo_{obs} \quad (24)$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(ETo_{obs} - ETo_{sim})^2}{\sum_{i=1}^{n}([ETo_{obs} - \overline{ETo_{sim}}] + [ETo_{sim} - \overline{ETo_{sim}}])^2}\right] \quad (25)$$

$$r = \frac{cov(ETo_{sim}, ETo_{obs})}{\sigma_{ETo_{sim}}\sigma_{ETo_{obs}}} \quad (26)$$

where:

$ETo_{obs}$ = ETo estimated by FAO56 Penman-Monteith model (mm day$^{-1}$);

$ETo_{sim}$ = ETo estimated the empirical models (mm day$^{-1}$), and;

n = total number of daily ETo values.

*Cluster and PCA analyses*

To provide a comprehensive perception into groups and subgroups of the meteorological variables and empirical models of ETo estimation, multivariate analyses of clustering and Principal Component Analysis (PCA) analyses were performed. For the statistical multivariate analyses, the software RStudio® (RSTUDIO, 2015) integrated for R language (R CORE TEAM®, 2019) version 4.0.5 was applied. For the analyzes carried out in R language, the following packages were used, all included in the CRAN repository (The Comprehensive R Archive Network): FactoMineR (LE *et al.*, 2008), factoextra (KASSAMBARA; MUNDT, 2017), cluster (MAECHLER *et al.*, 2017) and corrgram (WRIGHT, 2018). For Principal Component Analysis (PCA) a multivariate correlation analysis was performed, where the variables used for the analysis were then represented in a graph with the two components that best explain the variability of the data. With this, a correlation, and its p-value in relation to the originating variable were obtained, thus forming the principal component analysis. The authors of the analyzed mathematical models were grouped by the multivariate statistical test of Cluster Analysis (Cluster Analysis), which determined the formation of 5 homogeneous groups.

## RESULTS AND DISCUSSION

*ETo empirical models estimates*

The temporal performance of the daily ETo during the study period showed notable differences between the estimates of the different empirical models (Figure 2). For Alegrete, the cumulative precipitation in the period was 1785.6 mm, while the ETo estimated by the FAO56 standard model was 1300.4 mm. The tendency of each model to underestimate or overestimate ETo can be clearly observed in Figure 3. Generally, the Hargreaves & Samani (736.4 mm) and Linacre (1262.6 mm) models were those ones that most underestimated ETo. The Benevides & Lopes (2309.5 mm) and Makkink (1947.8 mm) models overestimated the ETo estimate. The linear coefficient (a) varied from 0.2682 to 1.3388 for the models proposed by Hargreaves & Samani and Jensen & Haise, respectively (Figure 2). The slope coefficient (b) varied from 0.0275 (Turc) to 1.7081 (Hargreaves & Samani). Finally, the determination coefficient ($R^2$) varied from 0.2683 (Hargreaves & Samani) to 0.8811 (Penman).

According to the parameterization of ETo when compared to the standard FAO56 method, studies show that methods such as Benevides & Lopes tend to overestimate the ETo values, making it an inefficient alternative for safe ETo estimates (COSTA *et al.*, 2020). Nevertheless, studies showed that the Benevides & Lopes model can be an alternative to the FAO56 model when compared to other models that use $T_{air}$. Considering this study, the $RH_{med}$ parameter, used in the model, may have been a limiting factor for accurate model estimates. This scenario is clearly noted from Figure 3, which shows that in the event of rain, the ETo estimate is significantly overestimated. In contrast, studies have shown that the model proposed by Makkink is the most accurate for determining ETo in Rio

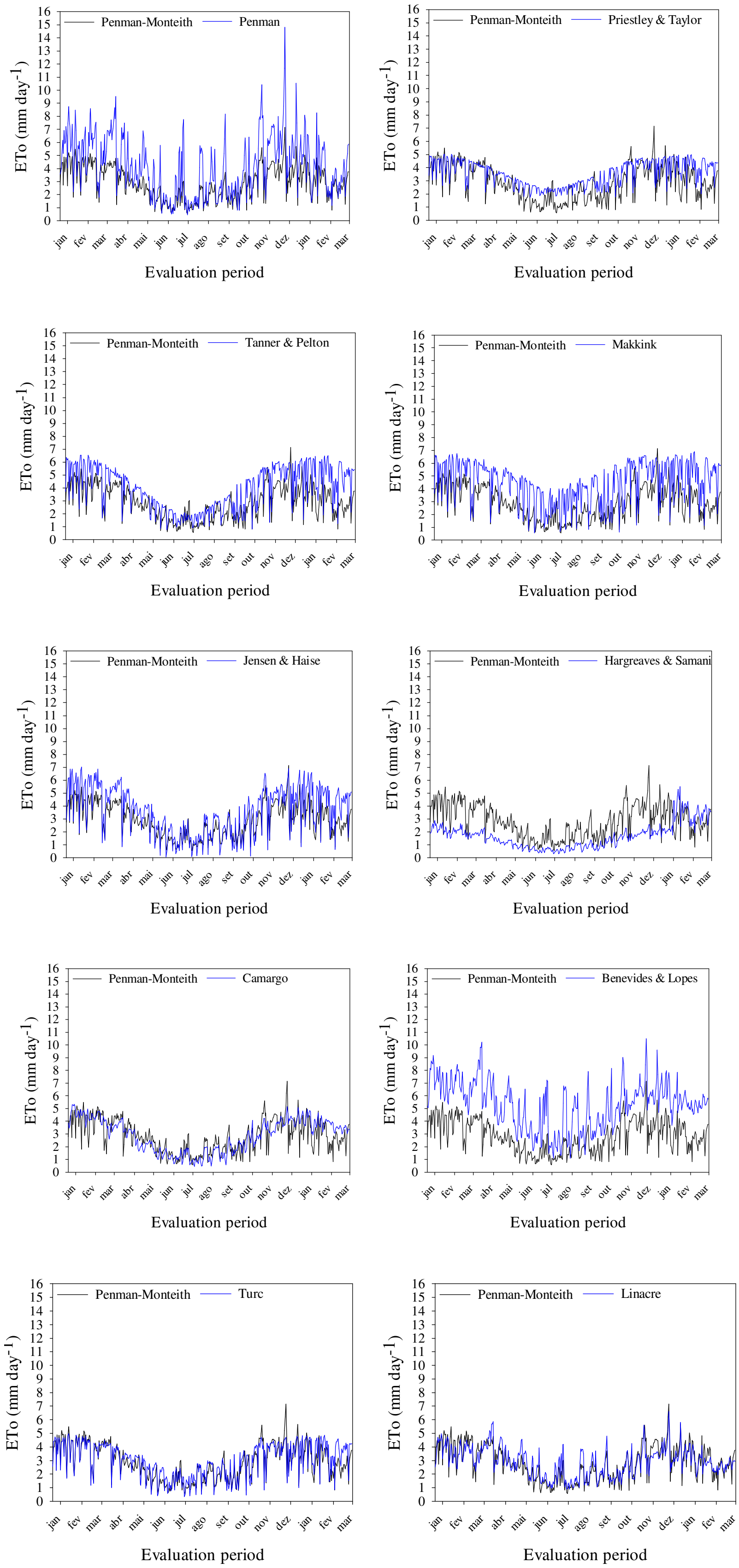


**Figure 2.** ETo estimates by the FAO56 Penman-Monteith standard model and empirical models, from December 21, 2019, to February 28, 2021, in Alegrete, Rio Grande do Sul, Brazil

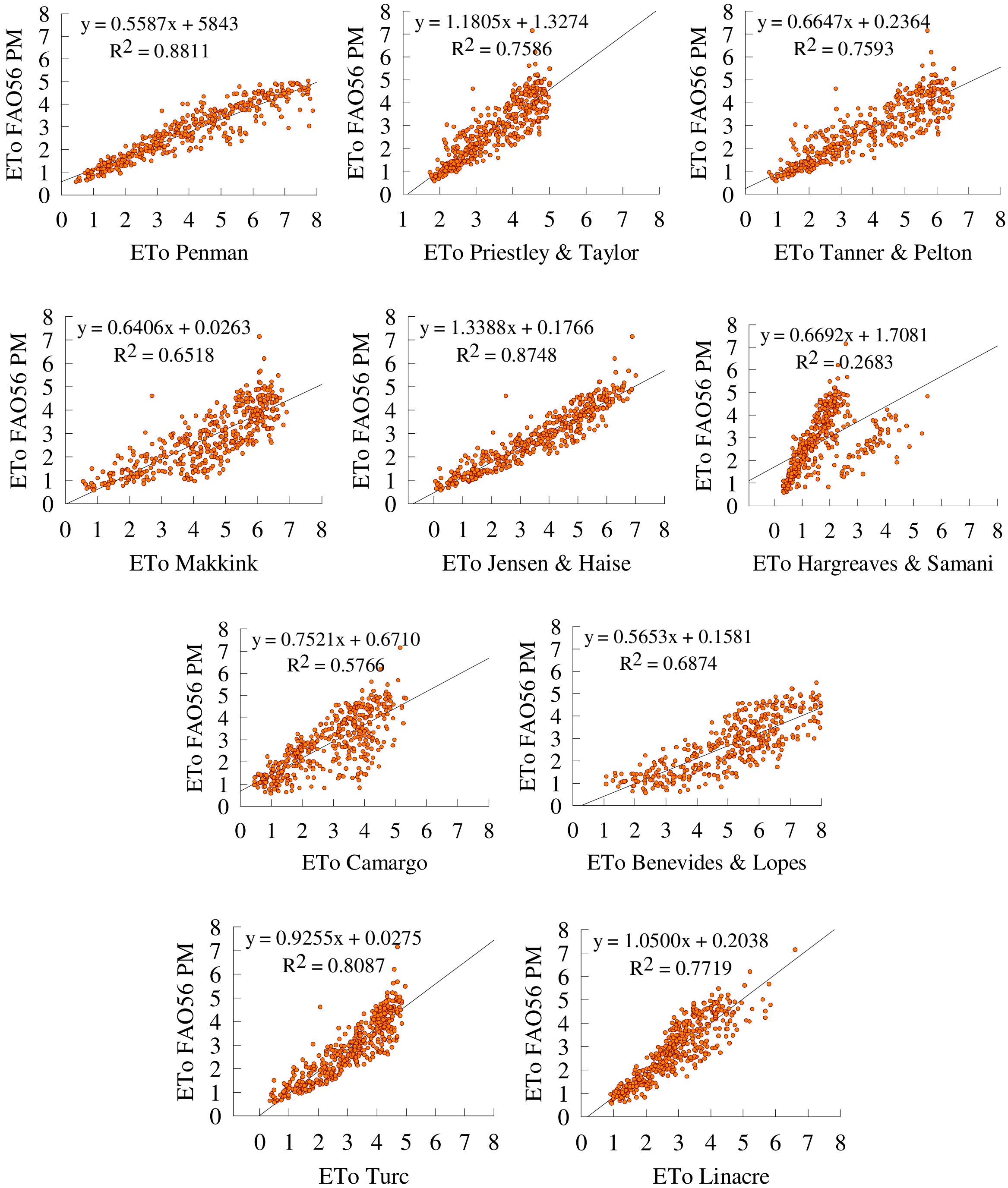


**Figure 3.** Linear regression of the empirical models against the FAO56 Penman-Monteith standard model for Alegrete, Rio Grande do Sul, Brazil

Grande do Sul, especially in drought conditions (BRIXNER *et al.*, 2014; PILAU *et al.*, 2012). In Iran, the overestimation of ETo by the Makkink model was up to 66% higher than the values found when compared to the FAO56 model (SABZIPARVAR; TABARI, 2010). In African Sahel, the Makkink model underestimated ETo, even though it is one of the best alternatives compared to the FAO56 standard model (DJAMAN *et al.*, 2015).

As observed for Tupanciretã, the temporal performance of the daily ETo indicated notable differences between the estimates of the different empirical models (Figure 4). Regarding to Tupanciretã, the cumulative precipitation in the period was 1779.2 mm, while the ETo estimated by the FAO56 Penman-Monteith standard

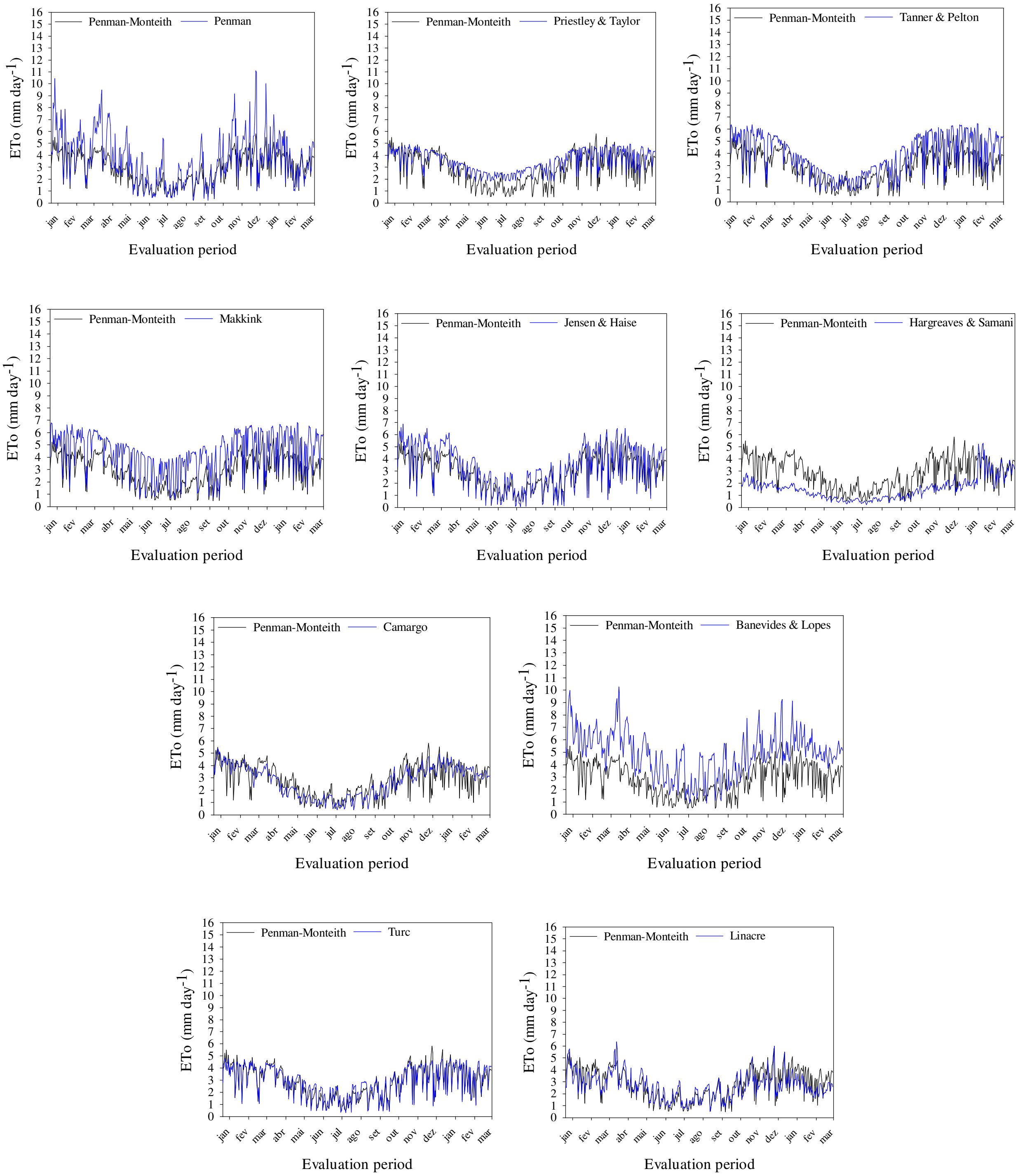


**Figure 4.** ETo estimates by the FAO56 Penman-Monteith standard models and empirical models, from December 21, 2019, to February 28, 2021, in Tupanciretã, Rio Grande do Sul, Brazil

model was 1162.0 mm. As presented by Figure 4, the Hargreaves & Samani (680.3 mm) most underestimated the ETo value compared to the FAO56 model. The model proposed by Benevides & Lopes (2126.3 mm) and Makkink (1904.3 mm) overestimated the ETo compared to the FAO56 model. The determination coefficient ($R^2$) varied from 0.3130 (Hargreaves & Samani) to 0.9015 (Penman). From this scenario, the high performance of the Penman model can be closely related to the application of *e* (partial pressure water vapor) and *es* (saturation vapor pressure) in the ETo estimates. Similar results were indicated for the Southeast Brazil (northern Espírito Santo), where the $R^2$ for the Hargreaves & Samani model ranged from 0.53 to 0.58, making it impossible to encourage its use for this region (VENANCIO *et al*., 2019). In this case, studies have shown that the application of the Hargreaves & Samani model in arid and semi-arid regions promotes greater precision and further applicability (RAZIEI; PEREIRA, 2013).

Like the Alegrete scenario, the linear coefficient (a) varied from 0.5591 to 1.3139 for the models proposed by Penman and Jensen & Haise, respectively (Figure 5). The slope coefficient (b) varied from 0.0826 (Tanner & Pelton) to 1.5015 (Priestley & Taylor). Finally, the determination coefficient ($R^2$) varied from 0.3130 (Hargreaves & Samani) to 0.9015 (Penman).

Furthermore, regardless the under and overestimation of ETo, studies developed in Australian territory have shown that methods that use only temperature variables tend to overestimate ETo values without following a pattern (DONOHUE *et al*., 2010). The same point was verified for the region of Minas Gerais, in central Brazil (SILVA *et al*., 2018). Penman, Priestley & Taylor, and Hargreaves & Samani were better adjusted ($R^2$) in these conditions than in the Brazilian Cerrado (GOTARDO *et al*., 2016). Different results were obtained in Baixada Cuiabana, MT, where Hargreaves & Samani and Linacre models presented the best performances and the Penmann model showed lower performance (SOUZA; JUNIOR, 2017). The Hargreaves & Samani model contributes to overestimate ETo (TRAJKOVIC; KOLAKOVIC, 2009). In studies conducted in Mainland China the Turc method is inclined to underestimate ETo (SONG *et al*., 2019). In well-defined season locations, as is the case in this study, the Makkink model significantly underestimates ETo (VESCOVE; TURCO, 2005).

*Performance of ETo empirical models*

Table 2 shows the statistical criteria applied to verify the performance of 10 empirical models against the FAO56 Penman-Monteith standard model, selected for Alegrete. According to $R^2$, the highest values were obtained for the Penman (0.8811) and Jensen & Haise (0.8748). The models that generated the lowest values were Hargreaves & Samani (0.2683) and Camargo (0.5766).

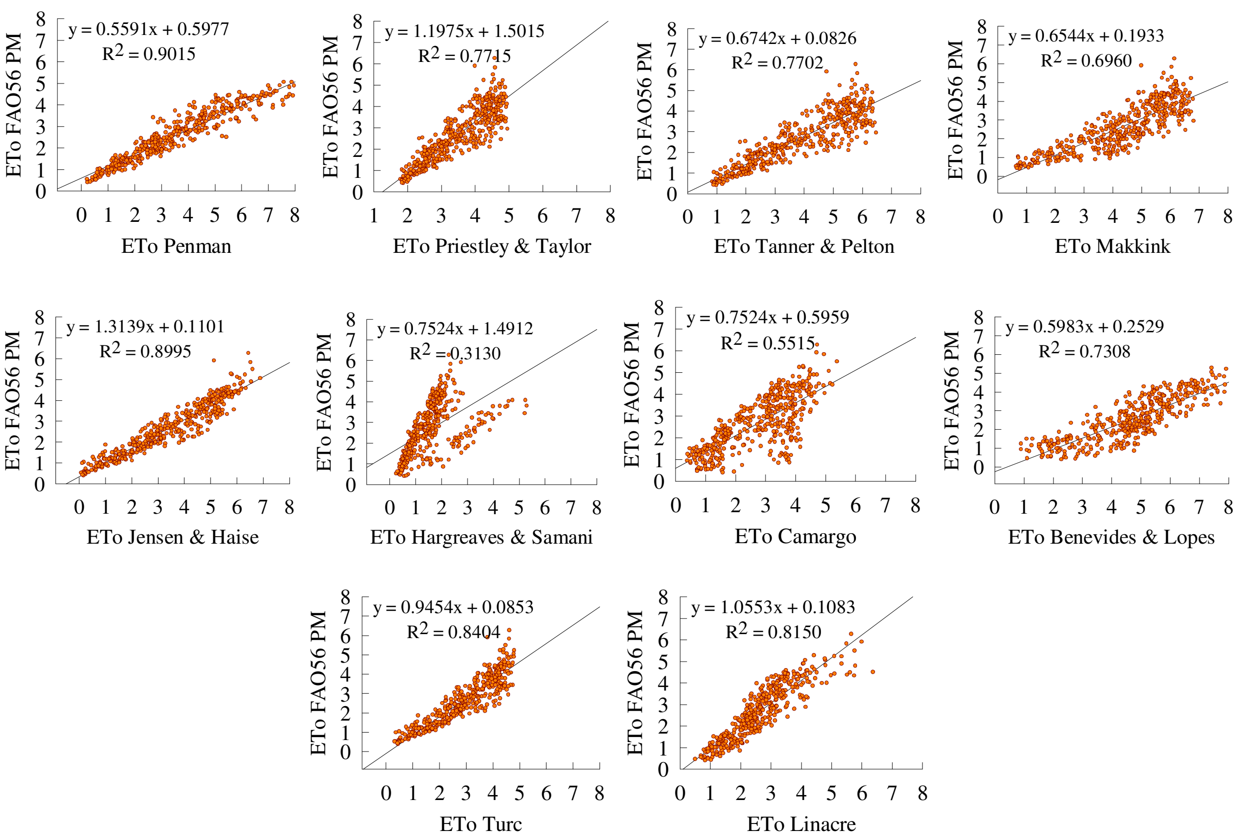


**Figure 5.** Linear regression of the empirical models against the FAO56 Penman-Monteith standard model for Tupanciretã, Rio Grande do Sul, Brazil

**Table 2.** Statistical criteria for the performance evaluation of the empirical models in opposition to the FAO56 Penman-Monteith standard model for Alegrete, Rio Grande do Sul, Brazil

| Empirical model | Statistical criteria | | | | |
|---|---|---|---|---|---|
| | $R^2$ [1] | *n*RMSE[2] | MBE[3] | d[4] | r[5] |
| Penman | 0.8811 | 2.381 | 1.2716 | 0.7867 | 0.9386 |
| Priestley & Taylor | 0.7586 | 1.350 | 0.6880 | 0.8212 | 0.8709 |
| Tanner & Pelton | 0.7593 | 1.951 | 1.0765 | 0.7962 | 0.8713 |
| Makkink | 0.6518 | 2.704 | 1.6332 | 0.6444 | 0.8073 |
| Jensen & Haise | 0.8748 | 1.576 | 0.7850 | 0.8753 | 0.9353 |
| Hargreaves & Samani | 0.2683 | 2.302 | 1.1441 | 0.4963 | 0.5180 |
| Camargo | 0.5766 | 1.260 | 0.0452 | 0.8628 | 0.7593 |
| Benevides & Lopes | 0.6874 | 3.854 | 2.4606 | 0.5161 | 0.8291 |
| Turc | 0.8087 | 0.8490 | 0.1986 | 0.9403 | 0.8993 |
| Linacre | 0.7719 | 0.8690 | 0.0584 | 0.9268 | 0.8785 |

[1]determination coefficient, [2]mean square error, [3]mean bias error, [4]Willmott index, and [5]Pearson's correlation coefficient

The *n*RMSE values were acceptable (*n*RMSE <1) for the Turc (0.8490 mm) and Linacre (0.8690 mm) models. Considering the MBE values, the highest values were found in the Benevides & Lopes (2.4606 mm) and Makkink (1.6332 mm). Surprisingly, the lowest MBE value and, consequently, the most suitable was the Camargo model (0.0452 mm).

For the Willmott index (d), most of the methods presented satisfactory results. The highest values were obtained by Turc (0.9403) and Linacre (0.9268) models. The lowest values were found by the Hargreaves & Samani (0.4963), Benevides & Lopes (0.5161), and Makkink (0.6444) models. Table 3 indicates the Pearson's linear correlation indices. For the temperature variable ($T_{max}$, $T_{med}$, and $T_{min}$), a positive linear correlation was observed for all models, since it is one of the main parameters for determining ETo by the different methodologies employed. The highest correlations were obtained for the Benevides & Lopes model in $T_{med}$ (0.9689), $T_{max}$ (0.9456), and $T_{min}$ (0.9418).

The variables related to the RH showed a negative linear correlation for all models, indicating an inverse effect of this variable for ETo determination. The highest values were obtained for the Linacre model ($RH_{med}$, -0.8398; $RH_{max}$, -0.8203; and $RH_{min}$, -0.8147).

According to this study, the variables *e*, *es*, and *es-e* showed the highest correlations. For *e*, the Tanner & Pelton and Priestley & Taylor models exhibited the most positive correlations (1.0000 and 0.9999, respectively). Considering *es*, most of the models presented expressive positive correlations, which shows the importance of this variable in the ETo estimates. As observed for *e*, the highest correlations were observed for the Tanner & Pelton (1.0000) and Priestley & Taylor (1.0000) models.

Generally, the importance of the radiation balance and its components in the ETo estimates by the different models is emphasized, which significantly influences the underestimation or overestimation of ETo. The influence of solar radiation on ETo is significant, showing positive linear performance in the empirical models of ETo estimates (MCVICAR *et al*., 2012). The precision in the results of models that adopt the radiation balance as a variable for the ETo calculation in Rio Grande do Sul ensures that these models can replace the FAO56 Penman-Monteith model in the study region (PILAU *et al*., 2012). The Penman, Penman-Monteith, Prestley & Taylor, and Makkink models were the most suitable for estimating ETo in conditions of low humidity and intense incident

**Table 3.** Pearson's linear correlation for meteorological variables to determine ETo in different empirical estimation models for Alegrete, Rio Grande do Sul

| Empirical models | Meteorological variables | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $T_{max}$ | $T_{min}$ | $T_{med}$ | $RH_{max}$ | $RH_{min}$ | $RH_{med}$ | Td | Ws | K0↓ | K↓ | $Q^*$ | *es* | *e* | *es-e* |
| Penman-Monteih | 0.7098 | 0.6925 | 0.7839 | -0.7536 | -0.7464 | -0.7408 | 0.3666 | 0.2010 | 0.6691 | 0.6745 | 0.8104 | 0.8714 | 0.8714 | -0.2757 |
| Penman | 0.7190 | 0.7175 | 0.8170 | -0.8093 | -0.7846 | -0.8066 | 0.3679 | 0.3105 | 0.5265 | 0.5306 | 0.6357 | 0.6864 | 0.6864 | -0.2101 |
| Priestley & Taylor | 0.5855 | 0.4892 | 0.6420 | -0.5683 | -0.5912 | -0.6375 | 0.2957 | 0.0056 | 0.7787 | 0.7854 | 0.9335 | 0.9999 | 0.9999 | -0.2779 |
| Tanner & Pelton | 0.5908 | 0.4943 | 0.6462 | -0.5660 | -0.5892 | -0.6361 | 0.2988 | 0.0039 | 0.7820 | 0.7886 | 0.9314 | 1.0000 | 1.0000 | -0.2794 |
| Makkink | 0.3966 | 0.3030 | 0.4210 | -0.6733 | -0.6971 | -0.7283 | 0.0788 | -0.0859 | 0.5449 | 0.5516 | 0.9999 | 0.9286 | 0.9286 | -0.1605 |
| Jensen & Haise | 0.7191 | 0.6530 | 0.7417 | -0.6543 | -0.6685 | -0.7228 | 0.3015 | -0.0169 | 0.6901 | 0.6964 | 0.9062 | 0.9498 | 0.9498 | -0.2325 |
| Hargreaves & Samani | 0.6698 | 0.4265 | 0.8375 | -0.2623 | -0.3035 | -0.5883 | 0.2800 | -0.1215 | 0.7596 | 0.7639 | 0.5323 | 0.6862 | 0.6862 | -0.2978 |
| Camargo | 0.8967 | 0.8547 | 0.9044 | -0.3249 | -0.3432 | -0.4552 | 0.5610 | 0.0413 | 0.9154 | 0.9167 | 0.5063 | 0.7370 | 0.7370 | -0.3526 |
| Benevides & Lopes | 0.9456 | 0.9418 | 0.9689 | -0.6064 | -0.6038 | -0.6765 | 0.5085 | 0.0363 | 0.6118 | 0.6180 | 0.4923 | 0.6213 | 0.6213 | -0.2001 |
| Turc | 0.6370 | 0.5433 | 0.6620 | -0.6650 | -0.6843 | -0.7453 | 0.2432 | -0.0435 | 0.6674 | 0.6749 | 0.9565 | 0.9678 | 0.9678 | -0.2039 |
| Linacre | 0.8069 | 0.8062 | 0.8750 | -0.8203 | -0.8147 | -0.8398 | 0.3828 | 0.0309 | 0.5222 | 0.5279 | 0.5933 | 0.6421 | 0.6421 | -0.1378 |

$T_{max}$ (daily maximum temperature, ºC), $T_{min}$ (daily minimum temperature, ºC), $T_{med}$ (daily average temperature, ºC), $RH_{max}$ (daily maximum relative humidity, %), $RH_{min}$ (daily minimum relative humidity, %), $RH_{max}$ (daily average relative humidity, %), Td (daily dew point temperature, ºC), Ws (wind speed at 2 meters high, m $s^{-1}$), K↓ (incident global radiation, MJ $m^{-2}$ $day^{-1}$), K0↓ (solar radiation in the absence of the atmosphere, MJ $m^{-2}$ $day^{-1}$), $Q^*$ ($R_n$) (radiation balance, MJ $m^{-2}$ $day^{-1}$), *es* (saturation vapor pressure, hPa), *e* (partial pressure water vapor, hPa), and *es-e* (partial pressure saturation deficit, hPa)

solar radiation in an arid region in Iranian territory (AHMADIPOUR *et al.*, 2019). Correlation indexes found for such variables causally related to the incident radiation balance agree with those identified by Tabari *et al.* (2013).

Table 4 presents the statistical criteria applied to verify the performance of 10 empirical models against the FAO56 Penman-Monteith standard model, selected for Tupanciretã. According to $R^2$, the highest values were obtained for the Penman (0.9015), Jensen & Haise (0.8995), Turc (0.8404), and Linacre (0.8150) models. The models that generated the lowest values were Hargreaves & Samani (0.3130) and Camargo (0.5515).

As observed for Alegrete, the *n*RMSE values were acceptable (*n*RMSE <1) for the Turc (0.8404 mm) and Linacre (0.8150 mm) models. According to the MBE values, the highest values were found in the Benevides & Lopes (2.2066 mm), Makkink (1.6987 mm), and Tanner & Pelton (1.1686 mm) models. Considering the Willmott index (d), most of the methods presented satisfactory results, except for the Hargreaves & Samani (0.5215), Benevides & Lopes (0.5607), and Makkink (0.6382) models. Finally, for r, the highest values attained were from the Penman (0.9494), Jensen & Haise (0.9484), Turc (0.9167), and Linacre (0.9027) models. The Hargreaves & Samani model (0.5594) indicated an unsatisfactory value.

Accordingly, Table 5 presents the influence of the meteorological parameters for each model adopted. For the temperature variable ($T_{max}$, $T_{med}$, and $T_{min}$), a positive linear correlation was observed for all models. The highest correlations were obtained for the Benevides & Lopes in $T_{med}$ (0.9432), $T_{max}$ (0.9372), and $T_{min}$ (0.9247).

According to the relative humidity of the air ($RH_{max}$, $RH_{med}$, and $RH_{min}$), a negative linear correlation for all models showed the ineffective influence of this variable for ETo determination. As

**Table 4.** Statistical criteria for the performance evaluation of the empirical models in opposition to the FAO56 Penman-Monteith standard model for Tupanciretã, Rio Grande do Sul, Brazil

| Empirical model | Statistical criteria | | | | |
|---|---|---|---|---|---|
| | $R^2$ [1] | *n*RMSE[2] | MBE[3] | d[4] | r[5] |
| Penman | 0.9015 | 2.0610 | 1.0301 | 0.8255 | 0.9494 |
| Priestley & Taylor | 0.7715 | 1.4630 | 0.8124 | 0.7895 | 0.8783 |
| Tanner & Pelton | 0.7702 | 2.0170 | 1.1686 | 0.7777 | 0.8776 |
| Makkink | 0.6960 | 2.7410 | 1.6987 | 0.6382 | 0.8342 |
| Jensen & Haise | 0.8995 | 1.4120 | 0.7247 | 0.8914 | 0.9484 |
| Hargreaves & Samani | 0.3130 | 2.1810 | 1.1022 | 0.5215 | 0.5594 |
| Camargo | 0.5515 | 1.2640 | 0.0847 | 0.8510 | 0.7425 |
| Benevides & Lopes | 0.7308 | 3.4530 | 2.2066 | 0.5607 | 0.8548 |
| Turc | 0.8404 | 0.7930 | 0.2437 | 0.9463 | 0.9167 |
| Linacre | 0.8150 | 0.7660 | 0.0370 | 0.9425 | 0.9027 |

[1]determination coefficient, [2]mean square error, [3]mean bias error, [4]Willmott index, and [5]Pearson's correlation coefficient

**Table 5.** Pearson's linear correlation for meteorological variables to determine ETo in different empirical estimation models for Tupanciretã, Rio Grande do Sul

| Empirical models | Meteorological variables | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $T_{max}$ | $T_{min}$ | $T_{med}$ | $RH_{max}$ | $RH_{min}$ | $RH_{med}$ | Td | Ws | K0↓ | K↓ | $Q^*$ | *es* | *e* | *es-e* |
| Penman-Monteih | 0.7233 | 0.6813 | 0.7119 | -0.8000 | -0.7941 | -0.7982 | 0.3112 | 0.0929 | 0.6373 | 0.6445 | 0.8332 | 0.8776 | 0.8776 | 0.8940 |
| Penman | 0.7207 | 0.6862 | 0.7130 | -0.8604 | -0.8418 | -0.8521 | 0.2702 | 0.1561 | 0.5185 | 0.5241 | 0.7013 | 0.7258 | 0.7258 | 0.9651 |
| Priestley & Taylor | 0.6092 | 0.5071 | 0.5666 | -0.6061 | -0.6232 | -0.6160 | 0.2616 | -0.0072 | 0.7588 | 0.7668 | 0.9292 | 0.9999 | 0.9999 | 0.6502 |
| Tanner & Pelton | 0.6097 | 0.5062 | 0.5664 | -0.6064 | -0.6235 | -0.6163 | 0.2610 | -0.0080 | 0.7584 | 0.7664 | 0.9296 | 1.0000 | 1.0000 | 0.6498 |
| Makkink | 0.4328 | 0.3325 | 0.3888 | -0.7227 | -0.7426 | -0.7342 | 0.0166 | -0.0888 | 0.5182 | 0.5265 | 0.9999 | 0.9299 | 0.9299 | 0.6463 |
| Jensen & Haise | 0.7362 | 0.6650 | 0.7106 | -0.7062 | -0.7119 | -0.7103 | 0.3421 | -0.0380 | 0.6576 | 0.6654 | 0.9085 | 0.9439 | 0.9439 | 0.8106 |
| Hargreaves & Samani | 0.6772 | 0.4320 | 0.5648 | -0.3286 | -0.3519 | -0.3413 | 0.4350 | -0.0343 | 0.7516 | 0.7547 | 0.5408 | 0.6935 | 0.6935 | 0.4538 |
| Camargo | 0.9032 | 0.8630 | 0.8950 | -0.3437 | -0.3529 | -0.3490 | 0.7035 | 0.0275 | 0.9160 | 0.9175 | 0.4943 | 0.7249 | 0.7249 | 0.6373 |
| Benevides & Lopes | 0.9372 | 0.9247 | 0.9432 | -0.6471 | -0.6365 | -0.6426 | 0.5997 | -0.0122 | 0.6143 | 0.6216 | 0.5410 | 0.6513 | 0.6513 | 0.9026 |
| Turc | 0.6645 | 0.5640 | 0.6234 | -0.7142 | -0.7252 | -0.7211 | 0.2629 | -0.0510 | 0.6365 | 0.6455 | 0.9550 | 0.9626 | 0.9626 | 0.7523 |
| Linacre | 0.7830 | 0.7641 | 0.7838 | -0.8546 | -0.8434 | -0.8501 | 0.3280 | -0.0416 | 0.5063 | 0.5136 | 0.6450 | 0.6690 | 0.6690 | 0.9881 |

$T_{max}$ (daily maximum temperature, ºC), $T_{min}$ (daily minimum temperature, ºC), $T_{med}$ (daily average temperature, ºC), $RH_{max}$ (daily maximum relative humidity, %), $RH_{min}$ (daily minimum relative humidity, %), $RH_{max}$ (daily average relative humidity, %), Td (daily dew point temperature, ºC), Ws (wind speed at 2 meters high, m $s^{-1}$), K↓ (incident global radiation, MJ $m^{-2}$ $day^{-1}$), K0↓ (solar radiation in the absence of the atmosphere, MJ $m^{-2}$ $day^{-1}$), $Q^*$ ($R_n$) (radiation balance, MJ $m^{-2}$ $day^{-1}$), *es* (saturation vapor pressure, hPa), *e* (partial pressure water vapor, hPa), and *es-e* (partial pressure saturation deficit, hPa) observed for Alegrete, K↓, and $Q^*$ showed positive correlations. For K↓, most of the models presented expressive positive correlations, which shows the importance of this variable in the ETo estimates. The highest correlations were observed for the Camargo model (0.9175). According to the $Q^*$ values, the Makkink (0.9999) and Tanner & Pelton (0.9296) models showed the highest correlations. Finally, for K0↓, the Camargo (0.9160) and the Priestley & Taylor (0.7588) models obtained the most positive correlations.

Ultimately, *es, e,* and *es-e*, in general, showed positive linear correlations. For *es*, the Tanner & Pelton (1.0000) and Priestley & Taylor (0.9999) models showed the highest correlation. Similarly, *e* indicated the same behavior. Regarding to the *es-e* parameter, all methods showed positive correlation values. The most expressive values were obtained by the Linacre (0.9881), Penman (0.9651), and Benevides & Lopes (0.9026) models.

*Clustering and PCA analyses*

The clustering analysis was used based on the daily ETo data (mm day$^{-1}$) of the FAO56 Penman-Monteith standard and empirical models. For the hierarchic clustering analysis in Alegrete, five main clusters were generated: Hargreaves & Samani; Camargo, Linacre, Penman-Monteith, and Turc; Makkink, Priestley & Taylor, Tanner & Pelton, and Jensen & Haise; Penman; and Benevides & Lopes (Figure 6).

In this study, the hierarchical structure allows as the main objective the association of models that serve as complementary tools in the absence of meteorological data that make the application of other models infeasible. Particularly, it serves as a parameter for the adequacy of other models in the study area.

This scenario is observed if parameters such as the $ETo_{med}$ or the accumulated $ETo_{accumulated}$ value for each empirical model in the period are considered. The $ETo_{med}$ and the $ETo_{accumulated}$ for the FAO56 model were 2.98 mm day$^{-1}$ and 1303.4 mm in the study period, respectively. The empirical models of Camargo (2.89 mm day$^{-1}$ and 1256.4 mm), Linacre (2.90 mm day$^{-1}$ and 1262.6 mm), and Turc (3.04 mm day$^{-1}$ and 1322.5 mm), in addition to the FAO56 model, were lower than the Benevides & Lopes (5.31 mm day$^{-1}$ and 2309.5 mm). Comparing these empirical models with the FAO56 model, they are represented at the same group. Contrastingly, the models proposed by Makkink (4.48 mm day$^{-1}$ and 1947.8 mm), Priestley & Taylor (3.53 mm day$^{-1}$ and 1536.2 mm), Tanner & Pelton (3.92 mm day$^{-1}$ and 1705.0 mm), and Jensen & Haise (3.63 mm day$^{-1}$ and 1577.9 mm) super estimated the estimates of $ETo_{med}$ and $ETo_{accumulated}$ and are represented in group 3.

For the hierarchic clustering analysis in Tupanciretã, five main clusters were generated: Hargreaves & Samani, Camargo, Penman-Monteith, and Linacre; Penman; Benevides & Lopes, Makkink; Priestley & Taylor, Turc, Tanner & Pelton, and Jensen & Haise (Figure 7).

In comparison with Alegrete, the performance of the clustering analysis for Tupanciretã was extremely different, considering the composition

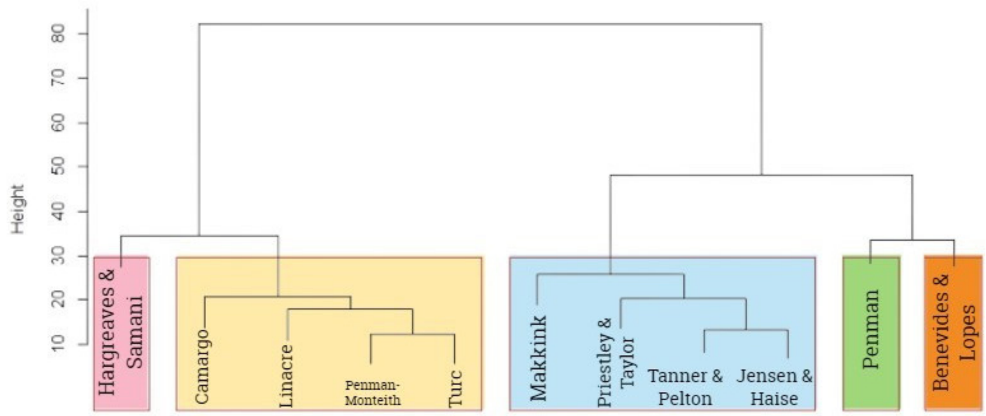


**Figure 6.** Dendrogram from clustering analysis based on ETo estimates by the FAO56 Penman-Monteith standard and empirical models for Alegrete, Rio Grande do Sul, Brazil

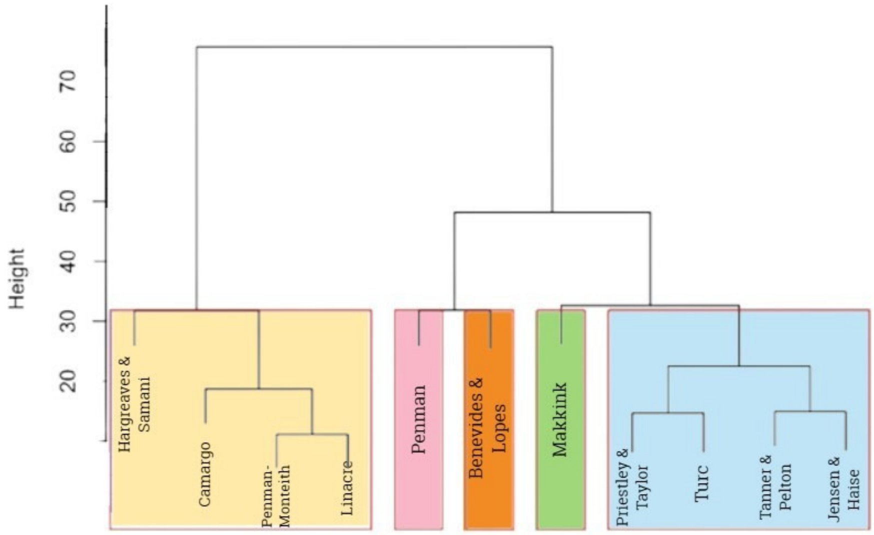


**Figure 7.** A dendrogram from clustering analysis based on ETo estimates by the FAO56 Penman-Monteith standard and empirical models for Tupanciretã, Rio Grande do Sul, Brazil

of the hierarchical structure. The $ETo_{med}$ and the $ETo_{accumulated}$ for the FAO56 model were 2.67 mm day$^{-1}$ and 1162.0 mm in the period, respectively. The Hargreaves & Samani model (1.56 mm day$^{-1}$ and 680.3 mm), Camargo (2.75 mm day$^{-1}$ and 1199.0 mm) belongs to the same group as the Linacre (2.63 mm day$^{-1}$ and 1145.8 mm) model. These methods represent means and values similar or lower than those verified by the standard model. The empirical models of Penman (3.70 mm day$^{-1}$ and 1612.1 mm), Benevides & Lopes (4.88 mm day$^{-1}$ and 2126.3 mm), and Makkink (4.37 mm day$^{-1}$ and 1904.3 mm) are represented in separated groups. These models show high values for $ETo_{med}$ and the $ETo_{accumulated}$ compared to the FAO56 model.

The representation of the PCA provides an assertive comprehension of the influence of meteorological variables on ETo estimates by the different empirical models. For Alegrete, the first and second main components explain the data variability by 52.22% and 33.21%, respectively (Figure 8). In this context, it was observed that the meteorological variables that most influenced the ETo determination by the empirical models were *e*, *es*, K↓, Q$^*$, Td, and temperature ($T_{max}$, $T_{min}$, and $T_{med}$). Parameters such as RH and K0↓ did not contribute significantly to the variability of ETo estimates. These results agree with the information presented in Table 3, where *e* and *es* obtained values of up to 1 (Tanner & Pelton) and up to 0.999 (Priestley & Taylor), K↓ up to 0.9167 (Camargo), and K0↓ up to 0.9154 (Camargo). For $T_{med}$ values of up to 0.9689 (Benevides & Lopes) and $RH_{med}$ up to -0.8398 (Linacre) were obtained. Furthermore, the disparity between the empirical models was observed, with the models proposed by Jensen & Haise, Turc, Priestley & Taylor, and Tanner & Pelton awfully close to the FAO56 model. Oppositely, the distance between the models of Makkink, Linacre, Penman, Benevides & Lopes, and Camargo is clearly noticed.

Considering the PCA for Tupanciretã, the first and second main components explain the data variability by 57.95% and 34.52%, respectively (Figure 9). The meteorological variables that most influenced the ETo determination by the empirical models were *es-e*, K↓, Td, e, Q$^*$, $T_{max}$, and $e_s$. Parameters such as RH and Ws did not contribute significantly to the variability of ETo estimates. In comparison to the Alegrete scenario, the meteorological variables K↓ and Q$^*$ were determinants for the ETo variability in Tupanciretã as well as for Alegrete. These results agree with the information presented in Table 4, where Q$^*$ obtained values of up to 0.9999 (Makkink) and K↓ up to 0.9175 (Camargo). A similar observation is presented according to *e* (up to 1.000, Tanner & Pelton) and *es* (up to 1.000, Tanner & Pelton). According to the disparity between the empirical models, the models proposed by Penman, Jensen & Haise, Linacre, and Turc were close to the FAO56 model. However, the distance between the models of Makkink, Hargreaves & Samani, Benevides & Lopes, and Camargo is verified, like Alegrete.

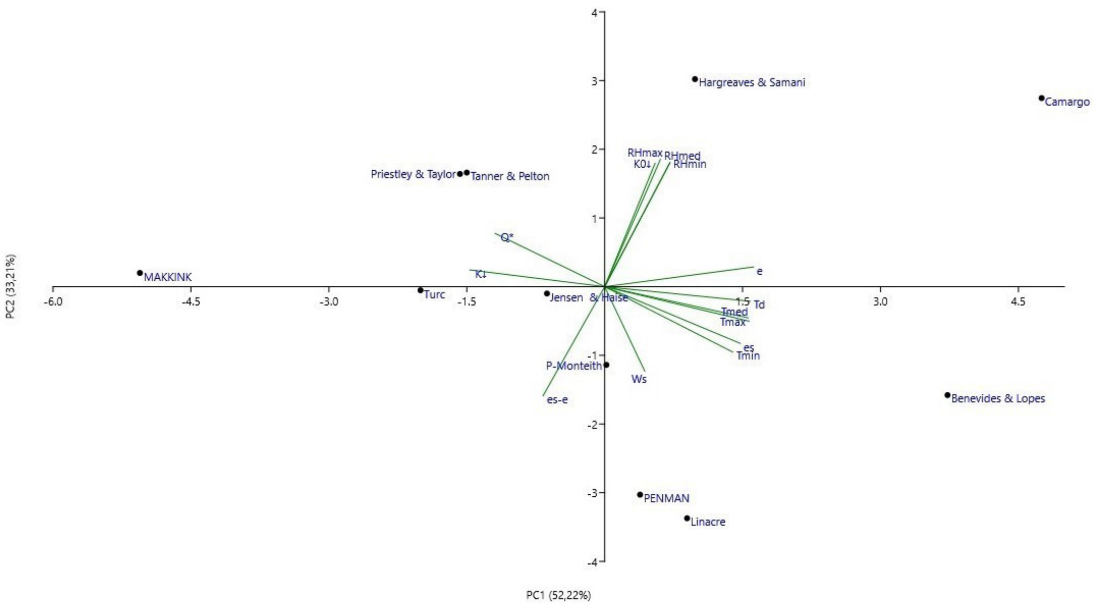


**Figure 8.** Principal Component Analysis (PCA) of the meteorological parameters and ETo estimates empirical models for Alegrete, Rio Grande do Sul, Brazil

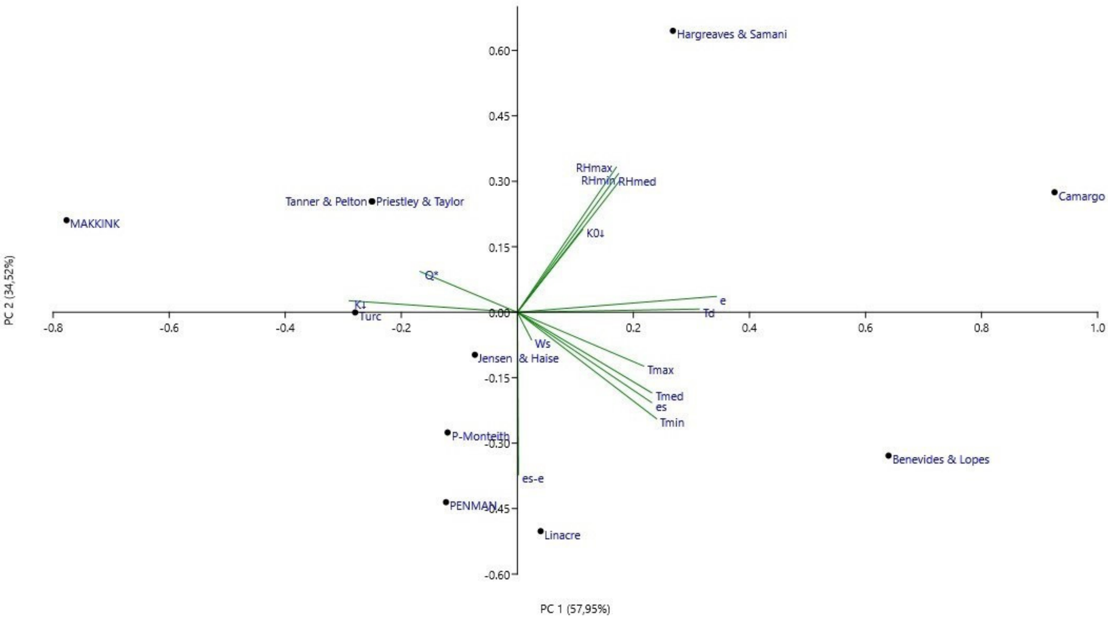


**Figure 9.** Principal Component Analysis (PCA) of the meteorological parameters and ETo estimates empirical models for Tupanciretã, Rio Grande do Sul, Brazil

## CONCLUSIONS

For this study, a detailed comparison of the model FAO56 Penman-Monteith standard with 10 empirical models of ETo estimation established:

- Predominantly, the radiation-based model proposed by Penman was the best alternative to estimate ETo in comparison with the other models during the period ($R^2$ – 0.9015 and r – 0.9494).
- This scientific study contributes significantly to the parameterization of ETo with precision to 2020/21 harvest in regions essential for agricultural production in Southern Brazil.

- Encouraging accurate ETo estimates is essential for effective irrigation schedules and a better comprehension of the water requirement and cycle in the soil-plant-atmosphere complex.

## AUTHORSHIP CONTRIBUTION STATEMENT

**SANTOS, M.S.N.:** Conceptualization, Data curation, Investigation, Methodology, Writing – original draft; **CASTRO, I.A.:** Data curation, Formal Analysis, Software, Visualization; **ORO, C.E.D.:** Data curation, Formal Analysis, Visualization, Writing – review & editing; **ZABOT, G.L.:** Supervision, Visualization, Writing – review & editing; **TRES, M.V.:** Resources, Visualization, Writing – review & editing.

## DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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