

Performance of solar radiation models for obtaining reference evapotranspiration to Santa Maria-RS, Brazil

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ABSTRACT: In the absence of observed data from Solar radiation (Sr), it is possible to estimate it using mathematical models. In general, the models vary in degree of complexity and the adjustment coefficients, and these must be calibrated to the place of interest to obtain the best performance. In this regard, the present work aims to evaluate the performance of simplified models of solar radiation in obtaining reference evapotranspiration. The data were obtained from the automatic meteorological station of the National Meteorological Institute (Inmet), located in Santa Maria – RS, Brazil. In the estimates of global solar radiation and its influence on reference evapotranspiration, ten models were evaluated, five models with the coefficients calibrated and five models, with the coefficients determined by the authors. It was observed that all the models studied presented performance index above 0.82, indicating "optimal" performance. Thus, both calibration and non-calibration models to obtain Sr do not interfere with ETo estimation. Therefore, given the impossibility of obtaining Sr data in meteorological stations, it is possible to use any of the models analyzed.

Key words: air temperature; evaporative demand; Penman-Monteith; water requirement

Desempenho de modelos de radiação solar para obtenção da evapotranspiração de referência para Santa Maria-RS, Brasil

RESUMO: Na ausência de dados observados de Radiação Solar (Rs) é possível estimá-la mediante a utilização de modelos matemáticos. Em geral, os modelos variam em grau de complexidade e nos coeficientes de ajuste, e esses devem ser calibrados para o local de interesse para obtenção do melhor desempenho. Neste sentido, o presente trabalho tem como finalidade avaliar o desempenho de modelos simplificados de radiação solar na obtenção da evapotranspiração de referência. Os dados foram adquiridos junto a estação meteorológica automática do Instituto Nacional de Meteorologia (Inmet), localizada na cidade de Santa Maria – RS. Nas estimativas de radiação solar global e sua influência na evapotranspiração de referência, foram avaliados dez modelos, sendo cinco modelos com os coeficientes calibrados e cinco modelos, com os coeficientes determinados pelos autores. Observou-se que, todos os modelos estudados, apresentaram índice de desempenho acima de 0,82, indicando "ótimo" desempenho. Dessa forma, tanto os modelos com calibração quanto os sem calibração para a obtenção da Rs, não interferem na estimativa da ETo. Sendo assim, dada a impossibilidade de se obter os dados de Rs nas estações meteorológicas, é possível utilizar qualquer um dos modelos analisados.

Palavras-chave: temperatura do ar; demanda evaporativa; Penman-Monteith; necessidade hídrica

Introduction

Solar radiation (Sr) is the main input variable in the estimation of the reference evapotranspiration (ETo) to later calculate the irrigation blade (Tabari et al., 2016). The use of this technique is of paramount importance in studies related to the modeling of crop growth, plant production and studies on the flow of water in the soil-plant-atmosphere system (Quej et al., 2016; Jamil & Akhtar, 2017). However, unlike other climatological variables such as air temperature, duration of sunlight and relative air humidity, solar radiation (Sr) measurements are relatively sparse in several places in the world, especially in developing countries (Jahani et al., 2017).

The quantification of solar radiation (Sr) is performed by measuring instruments such as pyranometers, radiometers, and actinographs (Besharat et al., 2013). However, the direct obtaining of the solar radiation data (Sr) is not always available, since few meteorological stations have records of solar radiation, due to the high costs of the instruments, maintenance, and calibration (Fan et al., 2018a).

As an alternative to places where there are no data records of solar radiation, estimated values can be obtained with the use of alternative mathematical models to quantify solar radiation (Mohammadi et al., 2016). These models differ from each other, by the degree of complexity and by input variables (Mostafa et al., 2014). However, it is important to emphasize that the models are generally restricted to the conditions for which they were developed, rendering them inefficient if they are not properly calibrated and tested for the climatic conditions of the new place (Benghanem & Mellit, 2014). As they are properly calibrated, they have the benefit of using meteorological elements registered at the place of study, thus representing the local meteorological conditions (Carvalho et al., 2011). In general, models estimating Sr based on insolation have better results when compared to models based on other meteorological elements, due to the high relationship between insolation and global solar radiation flux density (Mostafa et al., 2014; Hassan et al., 2016; Fan et al., 2018b). However, its application is often limited by the lack of records of insolation in meteorological stations (Hassan et al., 2016). In this context, the estimation models of *Sr* based on air temperature are more attractive and feasible options (Almorox et al., 2013).

In this context, the present work aims to evaluate the performance of simplified models of solar radiation in obtaining reference evapotranspiration, using the city of Santa Maria - RS as a case study.

Materials and Methods

To conduct the present study, daily meteorological data obtained from an automatic station of the National Institute of Meteorology (Inmet), located in the dependencies of the Federal University of Santa Maria (Figure 1), were used, which had a historical series of data available. Whose geographical coordinates are: latitude 29°42′25″S, longitude 53°48′42″W, and altitude of 95 meters. The climate of the city is characterized, according to Koppen, as being humid subtropical (Cfa), without dry season, with the warmest month average temperature over 22 °C and an annual average rainfall of 1.616 mm (Alvares et al., 2013).

Solar radiation (Sr) was estimated by ten simplified models (Table 1), five models with the calibration of their coefficients with the aid of TableCurve 2D v5.01 software (Systat, 2002). The data collection period ranged from 2002 to 2018, where 80% of the data were used to perform the coefficient calibration and 20% for validation.



Figure 1. Geographic location of the state of Rio Grande do Sul, highlighting the city of Santa Maria-RS, Brazil.

Table 1. Global solar radiation estimation models evaluated.
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Eq.	Abbreviation	Equation	Coefficients	Reference
1	BA	$R_S = \{a[(T_{max} - T_{min})^{0.5}]b\}$	a,b	Ball et al. (2004)
2	BC	$R_{S} = a. [exp(-b\Delta T^{c})]. R_{a}$ b = 0.036 exp. (-0.154. ΔT)	с	Bristow & Campbell (1984)
3	СН	$R_S = R_a \cdot [a \ (T_{max} - T_{min})^b]$	a,b	Chen et al. (2004)
4	На	$R_S = a. (T_{max} - T_{min})^{0.5}. R_a$	а	Hargreaves (1981)
5	MV	$R_S = 0.75. \left(1 - exp(-b\Delta T^2)\right). R_a$	b	Meza & Varas (2000)
6	Ann	$R_S = R_a K_{RS} (1 + 2.7 - 10^{-5} \overline{\Delta T}) (T_{max} - T_{min})^{0.5}$	-	Annandale et al. (2002)
7	DC	$R_{S} = R_{a} \{ 0.75 [1 - exp(-0.226(T_{max} - T_{min})^{2})] \}$	-	Donatelli & Campbell (1998)
8	GD	$R_{S} = R_{a} \{ 0.68 [1 - \exp(-0.03(T_{max} - T_{min})^{2.02})] \}$	-	Goodin et al. (1999)
9	HS	$R_S = K_{rs} \cdot \sqrt{(T_{max} - T_{min})} \cdot R_a$	-	Hargreaves & Samani (1982)
10	WS	$R_{S} = 0.75. \left(1 - exp\left(-b\frac{\Delta T^{2}}{R_{a}} \right) \right). R_{a}$	-	Weiss et al. (2001)

Sr - surface incident solar radiation (MJ m⁻² d⁻¹); Ra - extraterrestrial incident solar radiation (MJ m⁻² d⁻¹); a, b, c - calibration coefficients of empirical models (dimensionless) K_{rs} = empirical coefficient (0.16 for inland cities and 0.19 for coastal cities); ΔT - thermal amplitude; ΔT - average thermal amplitude; T_{min} - minimum air temperature; T_{max} - maximum temperature.

Thus, the coefficients for each equation were generated and used to estimate solar radiation according to each model. The estimated values were compared with the measured solar radiation values. For the other models, the coefficients proposed by the authors were used. The meteorological variables used in this study were: maximum and minimum temperature, relative air humidity, solar radiation, and wind speed.

Before conducting the Sr estimates, some data failures were identified in the historical series. Corrections to these failures were filled with the aid of the Clima software developed by the Paraná Agronomic Institute - IAPAR (Faria et al., 2002).

Performance comparisons of solar radiation estimation methods were performed using the Penman-Monteith equation (Equation 11) as a reference. The results of the estimation of the reference evapotranspiration with the data of Sr measured at the station were considered as standard, and they were compared with the results obtained from the estimate of the reference evapotranspiration using Sr data estimated by the abovementioned models (Table 1).

$$ET_{o} - PM = \frac{0.408\Delta(R_{n} - G) + \gamma\left(\frac{900}{T + 273}\right)v(e_{s} - e_{a})}{\Delta + \gamma(1 + 0.34v)}$$
(11)

where: ET_{o} - PM is the reference evapotranspiration, in lawn, mm d⁻¹; (R_n) is the net radiation, MJ.m⁻².d⁻¹; (G) is the heat flux in the soil, MJ.m⁻².d⁻¹; T is the average air temperature, ° C; v is the average wind speed at 2 m height, m.s⁻¹; (e_s - e_a) is the vapor pressure deficit, kPa; Δ - is the vapor pressure curve, kPa.°C⁻¹; γ is the psychometric constant, kPa °C⁻¹ and 900 is the conversion factor.

To evaluate the performance of each model and its influence on obtaining ETo, the following statistical indices were used: coefficient of determination (R²) of linear regressions between measured and estimated values, root-mean-square error (RMSE), absolute error (MBE), index (d) proposed by Willmott (1981), correlation coefficient (r) and

Camargo & Sentelhas index (Id) (1997), adapted by Pimenta et al. (2018), according to (Table 2). For the "RMSE" indicator, the lower its value, the better the model performance. For the "MBE" indicator, positive values overestimate and negative values underestimate the estimated values. On the other hand, the index (Id) qualifies the models according to their performance, being the best those that obtained values close to one, that is, greater linear statistical dependence among the variables (Table 3).

Table 2. Performance indicators, root-mean-square error (RMSE), mean bias error (MBE), Willmot index (d), correlation coefficient (r) and Camargo & Sentelhas index (Id) used to classify the models.

Eq.	Performance parameters	Equations
12	RMSE	$\sqrt{\left(N^{-1}\sum_{i=1}^{n}(P_i-O_i)^2\right)}$
13	MBE	$N^{-1} \sum_{i=1}^{n} P_i - O_i $
14	D	$1 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (P_i - O_i + O_i - O)^2}\right]$
15	R	$\frac{\sum_{i=1}^{n} (P_{i}-P)(O_{i}-O)}{\sqrt{\sum_{i=1}^{n} (P_{i}-P)^{2} \sum_{i=1}^{n} (O_{i}-O)^{2}}}$
16	Id	r.d

Pi are the estimated values, Oi the observed values, P the average of the estimated values, and O the average of the observed values; N = number of observations; r = correlation coefficient.

To verify if, in fact, the ETo values estimated by the models differ significantly between the ETo values measured, the t-test derived from RMSE and MBE (Togrul & Togrul, 2002) was used, according to Equation 17.

$$t = \left[\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}\right]^{0.5}$$
(17)

Values of Id	Classification
0.90 - 1.00	Excellent
0.80 - 0.90	Optimal
0.70 - 0.80	Very Good
0.60 - 0.70	Good
0.50 - 0.60	Moderately Good
0.40 - 0.50	Moderate
0.30 - 0.40	Moderately Bad
0.20 - 0.30	Poor
0.10-0.20	Very Poor
0.00 - 0.10	Terrible
0.30 - 0.40 $0.20 - 0.30$ $0.10 - 0.20$ $0.00 - 0.10$	Moderately Bad Poor Very Poor Terrible

Table 3.	Criteria to	classify	the	performance	of	global	solar
radiation	estimatio	n models	by t	he index Id.			

Source: Pimenta et al. (2018).

The critical value of t was obtained from the statistical table $(t_{tab}$ t-Student), with significance level (α), and (n-1) degrees of freedom. A model was considered statistically significant (accepting the null hypothesis, Ho: Pi = Oi) in the interval (1 - α), if the calculated value of t is less than the critical value. In the present study, the significance level chosen was 0.05, with n = 5.844 and t_{tab} = 1.96.

Results and Discussions

Based on the ten estimation models of the global solar radiation (Sr) studied, five of them were selected, according to (Table 4), for calibration of the coefficients. For the other models, we used the coefficients determined by the authors themselves (without calibration).

The coefficient "c" of Bristow & Campbell (BC) showed little variation for the studied years, with a mean value of 2.02, which could be used, showing that it was not necessary to calibrate this coefficient for Santa Maria - RS and other climatologically similar places.

For the Hargreaves model (Ha), the coefficient "a" obtained a mean value of 0.16. This value was 6.1% higher than those obtained by (Liu et al., 2009) and 5.7% to those obtained by (Almorox, 2011), although close to that recommended by Allen et al. (1998) to an inland location and uncalibrated, emphasizing the universality of this model.

The coefficient "b" obtained for the Meza & Varas (MV) model was 0.010, which is the same as those presented by the authors Meza & Varas (2000), who suggest that the value of "b" after its calibration is in the range of 0.004 to 0.010.

Table 4. Values of the calibration coefficients of global solar radiation estimation models of Ball et al. (2004) (BA), Bristow & Campbell (BC) (1984), Chen et al. (2004) (CH), Hargreaves (1981) (Ha) and Meza & Varas (2000) (MV), for Santa Maria - RS, Brazil.

Madals	Calibrated Coefficients			
Widdels	а	b	С	
Ball (BA)	0.10	1.33	-	
Bristow & Campbell (BC)	-	-	2.02	
Chen (CH)	0.10	0.67	-	
Hargreaves (Ha)	0.16	-	-	
Meza & Varas (MV)	-	0.010	-	

The models proposed by Ball (BA) and Chen (CH) presented mean results for the coefficient "a" of 0.10, values below those found by (Macêdo et al., 2016), in six cities of the state of Ceará, with a mean of 0.33 for the BA model and 0.35 for the CH model. The same occurred for the coefficient "b", where the values were below those found by (Macêdo et al., 2016), who found mean values of 0.58 for Ball and 0.28 for Chen.

In Figure 2 we represent the correlations between the reference evapotranspiration values estimated by Penman-Monteith using the solar radiation estimated by the abovementioned models and the values estimated by Penman-Monteith using the data measured at the weather station.

The dispersion of the points around the 1:1 trend line and the straight line presented similar behavior for most models. The Meza & Varas model (2000) presented the best fit with a coefficient of determination (R^2) of 0.89.

Although they presented a small trend to overestimate/ underestimate ETo, all the models had coefficients of determination (R^2) ranging from 0.73 to 0.89. These values are close to those found by Bandyopadhyay et al. (2008) and Conceição (2010) who obtained R^2 values higher than 0.70 for several locations on different continents. However, lower than the values obtained by Abraha & Savage (2008), who found R^2 of 0.95.

The performance of Sr estimation models in obtaining ETo can be explained by the fact that this is the main energy source for the evapotranspiration process, being the element that most interferes in this process (Tagliaferre et al., 2015). According to Minuzzi et al. (2018), Sr has a strong influence on this determination. Besides, it affects all other elements, as reported by Pereira et al. 2015). Studies by Lemos Filho et al. (2010) show that the meteorological elements have great spatial variability. Therefore, in the absence of Sr data, it is better to estimate it by calibrated empirical models than to have simpler models for calculating ETO.

In this study, we also used the t-test, where the ETo estimates for all models studied did not differ, at a 0.05 probability level, in relation to observed values, since all t values are less than $t_{0.05}$ =1.96.

(Table 5) shows the values of RMSE, MBE, and R², the results obtained showed a good performance of the models studied, indicating the models of Ball and Chen as the best, followed by Hargreaves, Bristow & Campbell, and Meza & Varas. Corroborating the results obtained by (El Nesr et al., 2011) in studies conducted in different locations. However, the estimates of ETo using solar radiation data estimated with the non-calibrated models presented a greater dispersion of the values in comparison to the calibrated coefficients. The model of Weiss presented the best value of RMSE 0.73, while the model of Donatelli & Campbell, presented the worst performance among all models studied with RMSE 1.72.

However, it is not known by RMSE alone whether the model underestimates or overestimates the values. In this respect, the Mean Bias Error refers to the underestimation and overestimation of reference evapotranspiration. Table 5 shows that for the estimation of ETo, the values of solar radiation used when the coefficients are calibrated for the study place, they presented positive values, overestimating the ETo values. The solar radiation models without local calibration, when applied to the Penman - Monteith model to estimate ETo, showed a greater dispersion of the values. The Ann, DC, GD, and HS models overestimated ETo values, the WS model being the only one that underestimated the values. This indicates that when there is local calibration of solar radiation estimation models, the estimation of ETo by Penman - Monteith tends to present behavior similar to Sr.

The performance parameters of the models can be observed in (Table 6), where the classifications of the ETo estimates are presented through the use of the Sr estimation using models with calibrated and non-calibrated coefficients.





Figure 2. Values of the reference evapotranspiration estimated by Penman-Monteith as a function of the reference evapotranspiration values estimated by different models of solar radiation for Santa Maria - RS, Brazil.

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for Santa Maria - RS, Brazil.		
estimate using solar radiation estimated by	different	models
(MBE), and Coefficient of Determination (R^2)	to obtain t	the ETo
Table 5. Root mean square error (RMSE), I	Mean Bia	s Error

Models with calibration	RMSE	MBE	R ²
Ball (BA)	0.72	0.24	0.88
Bristow & Campbell (BC)	0.79	0.31	0.85
Chen (CH)	0.72	0.27	0.88
Hargreaves (Ha)	0.74	0.30	0.87
Meza & Varas (MV)	0.80	0.31	0.89
Models without calibration			
Models without calibration Annandale (Ann)	0.75	0.31	0.87
Models without calibration Annandale (Ann) Donatelli & Campbell (DC)	0.75	0.31	0.87 0.73
Models without calibration Annandale (Ann) Donatelli & Campbell (DC) Goodim (GD)	0.75 1.72 1.11	0.31 1.20 0.66	0.87 0.73 0.84
Models without calibration Annandale (Ann) Donatelli & Campbell (DC) Goodim (GD) Hargreaves & Samani (HS)	0.75 1.72 1.11 0.74	0.31 1.20 0.66 0.30	0.87 0.73 0.84 0.87

It is observed that both the models with the calibration of their coefficients and the models without calibration showed little variability among themselves, with values from 0.96 to 1.0 for the index "d". These results corroborate those found by Conceição & Marin (2005), for studies conducted in two **Table 6.** Concordance Index (d), Correlation Coefficient (r), and Performance Index (Id) of the ETo estimate using estimates of Sr by different models for Santa Maria - RS, Brazil.

Models with calibration	d	r	Id	Classification
Ball (BA)	1.0	0.94	0.93	Excellent
Bristow & Campbell (BC)	0.98	0.92	0.91	Excellent
Chen (CH)	1.0	0.94	0.93	Excellent
Hargreaves (Ha)	1.0	0.93	0.92	Excellent
Meza & Varas (MV)	0.98	0.94	0.93	Excellent
Models without calibration				
Annandale (Ann)	1.0	0.93	0.92	Excellent
Donatelli & Campbell (DC)	0.96	0.86	0.82	Optimal
Goodim (GD)	0.98	0.92	0.90	Excellent
Hargreaves & Samani (HS)	1.0	0.93	0.92	Excellent
Weiss (WS)	0.98	0.93	0.92	Excellent

cities in the state of São Paulo, which verified values for "d" of 0.88 and 0.86, respectively, and (Lêdo et al., 2012) that found values of 0.61 to 0.64 for Barbalha - CE.

For the correlation coefficient "r", all the models presented a good ratio, above 0.92 for models with calibration and of 0.86 for models without calibration, being classified as excellent and optimal, showing a great linear statistical dependence among the variables.

For the performance index "Id", where values above 0.91 were obtained for models with calibration and 0.82 with Donatelli & Campbell, this being the lowest result found for the models without calibration. For the other uncalibrated models, the mean values were 0.91, which, according to (Pimenta et al., 2018), classifies as excellent. Conceição & Marin (2005) found performance classified as "Very Good" for the localities of Jales and Piracicaba-SP, with "Id" of 0.71 and 0.72, respectively. Massignam (2007) found performance classified as "Moderate" in Itajaí, Pedras Grandes, and Florianópolis-SC, with "Id" of 0.46, 0.47, and 0.48 respectively, and "Very Good" classification in the locality of Urussanga-SC, with an "Id" value of 0.76. (Rodrigues et al., 2008) obtained "Moderate" performance for conditions of Limoeiro do Norte-CE, with "Id" of 0.45.

Conclusions

Based on the results obtained, it can be concluded that there is no interference in the reference evapotranspiration estimate. Thus enabling the calculation of ETo, regardless of the calibration or not of the coefficients used in the study.

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