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# CALIBRATION AND EVALUATION OF ESTIMATION MODELS OF GLOBAL SOLAR RADIATION FOR THE STATE OF GOIÁS, BRAZIL

## CALIBRAÇÃO E AVALIAÇÃO DE MODELOS DE ESTIMATIVA DA RADIAÇÃO SOLAR GLOBAL PARA O ESTADO DE GOIÁS, BRASIL

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**ABSTRACT:** Despite the importance of global solar radiation (Rs), data of this variable are not available for many regions of Brazil due to low density of surface weather stations, mainly in the North and Central-West regions. The estimation of this variable for regions with no Rs data are based on mathematical models, which has shown to be a viable alternative. The objective of this work was to contribute to these studies through the calibration and evaluation of three traditional models: Angstrom-Prescott (AP), Hargreaves (HAR), and Bristow-Campbell (BC), and, in addition, propose a new model (PMo) for estimation of Rs from multiple regression. The models were adjusted and evaluated for six locations in the state of Goiás (Central-West of Brazil), using meteorological data from 2008 to 2016. The local adjustment process improved the predictive capacity of the models AP ($r^2$ = 0.74 and MAE = 1.68), BC ($r^2$ = 0.62 and MAE = 2.34) and HAR ($r^2$ = 0.55 and MAE = 2.32). However, according to the Nash index, unsatisfactory performances were found for the HAR model for the municipalities of Mineiros and Rio Verde, and for the BC model for Rio Verde. Despite requiring more meteorological variables, the PMo model estimated Rs adequately for the evaluated regions ($r^2$ = 0.70 and MAE = 1.98), with superior performance to BC and HAR methods.

**Keywords:** *Brazilian Cerrado, Estimation Methods, Solar Irradiance.*

**RESUMO**: Apesar da importância dos dados da radiação solar global (Rs), os dados dessa variável não estão disponíveis para muitas regiões do Brasil devido à baixa densidade de estações meteorológicas de superfície, principalmente nas regiões Norte e Centro-Oeste. Normalmente, a estimativa dessa variável para regiões sem dados de Rs é baseada em modelos matemáticos, o que se mostrou uma alternativa viável. O objetivo deste trabalho foi contribuir para esses estudos através da calibração e avaliação de três modelos tradicionais: Angstrom-Prescott (AP), Hargreaves (HAR) e Bristow-Campbell (BC), além de propor um novo modelo (PMo) para estimativa de Rs a partir de regressão múltipla. Os modelos foram ajustados e avaliados para seis localidades no estado de Goiás (Centro-Oeste do Brasil), utilizando dados meteorológicos de 2008 a 2016. O processo de ajuste local melhorou a capacidade preditiva dos modelos AP ($r^2$ = 0,74 e MAE = 1,68), BC ($r^2$ = 0,62 e MAE = 2,34) e HAR ($r^2$ = 0,55 e MAE = 2,32). No entanto, de acordo com o índice de Nash, foram encontrados desempenhos insatisfatórios para o modelo HAR para os municípios de Mineiros e Rio Verde e para o modelo BC para Rio Verde. Apesar de exigir mais variáveis meteorológicas, o modelo PMo estimou a Rs adequadamente para as regiões avaliadas ($r^2$ = 0,70 e MAE = 1,98), com desempenho superior aos métodos BC e HAR.

**Palavras-chave:** *Cerrado Brasileiro, Irradiância Solar,Métodos de Estimativa*

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## INTRODUCTION

The solar radiation that reaches the Earth's surface is important for the energy balance of many physical, chemical, and biological processes; it is an important meteorological variable for studies on water requirements of crops, modeling of plant growth and production, and climate changes (BORGES et al., 2010;QIN et al., 2011; SANTOS et al., 2011; PATRIOTA et al., 2017; ELBELTAGI et al., 2020).

However, observed solar radiation data are not always available due to the high cost and need for calibration and maintenance of the measuring equipment (HASSAN et al., 2016).

An alternative to the direct measurements, when these data are not available, is the estimation of solar radiation through mechanistic models, based on different mechanisms of direct and diffuse radiation generation (MAXWELL, 1998); or empirical models, through mathematical relationships from observed data, considering meteorological and geographical data (MOHAMMADI et al., 2015).

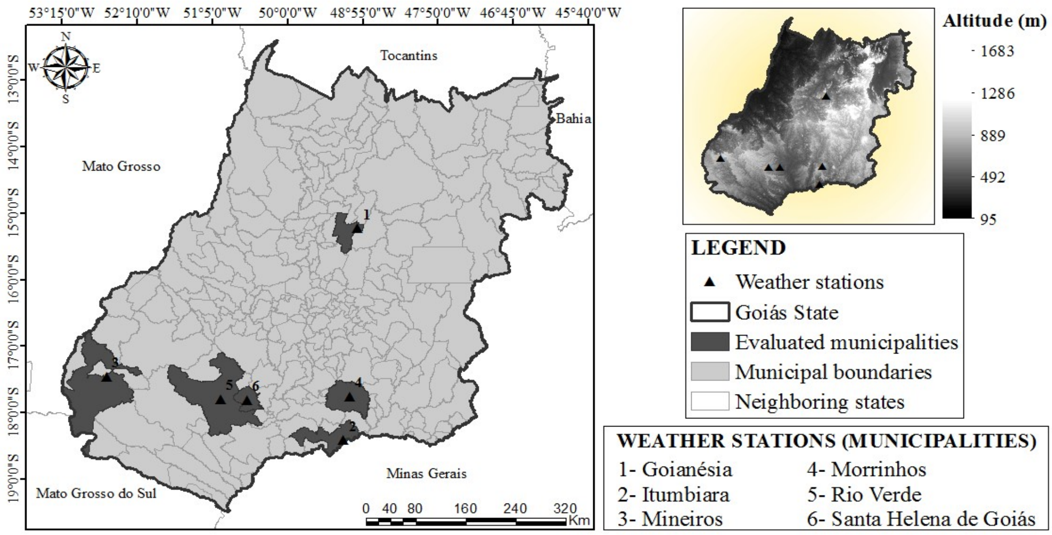
Among empirical models, there are several classic models, such as those developed by Angstrom (1924) and Prescott (1940), Bristow; Campbell (1984), and Hargreaves (1981). Although these models present satisfactory estimates for the proposed locations, their results vary from one location to another, limiting their generalization and leading to great uncertainty of their predictions (QIN et al., 2015). Considering the difficulties for direct measurements, the objective of this work was to calibrate and evaluate the Angstrom-Prescott, Bristow-Campbell, and Hargreaves models traditionally used to estimate global solar radiation and, in addition, to propose a new estimation model that correlates solar radiation with several meteorological variables by, using multiple regression, for different locations of the state of Goiás, Central-West region of Brazil.

## MATERIAL AND METHODS

The state of Goiás is in the Central-West region of Brazil (12°00'S to 20°00'S, 45°30' to 53°30'W). According to the Köppen classification, there are four climate types in the state, namely Aw (predominantly), Am (northern region), Cwa (southwestern region), and Cwb (central-east region).

The state of Goiás has an average annual temperature of 23.4 °C, with 20.5 °C in the southwest and 26.5 °C in the northwest region. The annual average rainfall depth is 1500 mm, with variation of 35% throughout the state (CARDOSO; MARCUZZO; BARROS, 2014).

The municipalities of Goianésia, Rio Verde, Mineiros, Itumbiara, Santa Helena de Goiás, and Morrinhos (Figure 1) were considered in the study for proposition, calibration, and validation of global solar radiation estimation models.




| Weather stations | Latitude (deg) | Longitude (deg) | Altitude (m) | Period | Number of data |
|---|---|---|---|---|---|
| 1 | -15.22 | -48.99 | 667 | | 2954 |
| 2 | -18.41 | -49.19 | 491 | | 1494 |
| 3 | -17.45 | -52.60 | 862 | 2008-2016 | 2952 |
| 4 | -17.75 | -49.10 | 751 | | 1906 |
| 5 | -17.79 | -50.96 | 780 | | 2881 |
| 6 | -17.80 | -50.58 | 570 | | 2128 |

**Figure 1.** Geographic location of the weather stations (municipalities) and number of data in the period of meteorological observations used in the study of global solar radiation estimates for the state of Goiás, Central-West region of Brazil. Source: Author (2019)

## Meteorological data

Meteorological data from 2008 to 2016 were obtained from meteorological stations of the System of Meteorology and Hydrology of the State of Goiás (SIMEHGO) and the National Institute of Meteorology (INMET). The variables used were: maximum (Tx), minimum (Tn), and mean (Tmean) air temperatures; air relative humidity (RH) (Figure 2); global solar radiation (Rs); and sunshine (n)—which was measured only in the municipalities of Itumbiara and Rio Verde.

Extraterrestrial solar radiation (Ra) and day length (photoperiod)(N) data were also considered for the estimation of Rs (OMETTO, 1981); they were determined using Equations 1 and 2, respectively.

$$Ra = 37.6 \left(\frac{d}{D}\right)^2 \left[\left(\frac{\pi}{180}\right) hn\ sen\phi\ sen\ \delta + cos\phi\ cos\ \delta\ sen\ hn\right] \quad (1)$$

$$N = \frac{2\ h_n}{15} \quad (2)$$

where Ra is the extraterrestrial solar radiation in MJ $m^{-2}$ $d^{-1}$; $(d/D)^2$is the adjustment coefficient for the relative distance from the Sun to Earth; $h_n$ is the half-day length ($h_n$ = $\arccos(-tg\delta \cdot tg\phi)$); $\phi$ is the local latitude, and $\delta$ is the solar declination; $h_n$, $\delta$ and $\phi$ are expressed in degrees, and N in hours.

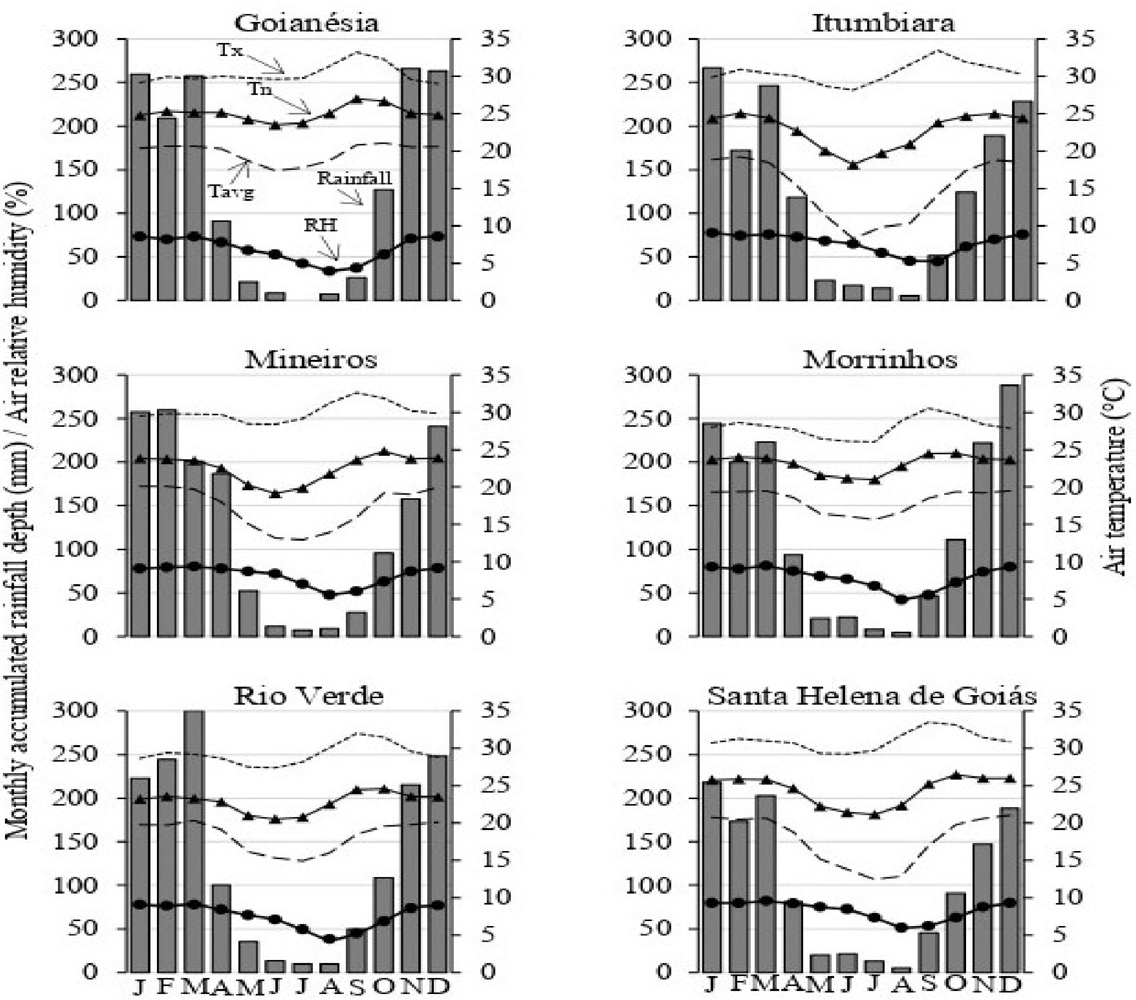



**Figure 2.** Mean maximum (Tx), minimum (Tn), and mean (Tmean) air temperatures (°C), air relative humidity (RH; %), and monthly accumulated rainfall depth (mm) in Goianésia (a), Itumbiara (b), Mineiros (c), Morrinhos (d), Rio Verde I, and Santa Helena de Goiás (f), in the state of Goiás, Central-West region of Brazil, from 2008 to 2016. Source: Author (2019)

Before the data analysis, the data were evaluated and processed according to the criteria described by Tymvios et al. (2005), Liu et al. (2009), and Moradi (2009): the data of the day are not considered i) when data on sunshine and global solar radiation is missing, ii) if the clearness index (Rs / Ra) or the sunshine ratio (n/N) is greater than 1, and iii) if Rs is less than 0.03 × Ra; and the data of the month is not considered iv) if 10 or more days in the same month have missing data. The data were subjected to consistency analysis; and flaws in air temperature and relative humidity data were filled using the grid database developed by Xavier; King; Scanlon (2015), with a high correlation coefficient ($r^2$>0.95) for the study data, as shown by Bender and Sentelhas (2018), which is reasonable to fill gaps in daily weather series in Brazil.

**Description of the models**

The global solar radiation was estimate by the Angstrom-Prescott (AP), Hargreaves (HAR), and Bristow-Campbell (BC) models and by a fourth model (Proposed Model - PMo) that uses multiple regression of meteorological variables, as described in Table 1.

**Table 1.** Estimation models of global solar radiation used in the study.

| Model | Equation | Coefficients | Source |
|---|---|---|---|
| Angstrom-Prescott | $R_s = Ra \cdot (a + b\frac{n}{N})$ | *a, b* | Angstrom (1924) and Prescott (1940) |
| Hargreaves | $R_s = a \cdot \sqrt{\Delta T} \cdot Ra$ | *a* | Hargreaves (1981) |
| Bristow-Campbel | $R_s = a \cdot [1 - exp\,(-b \cdot \Delta T_2^c)] \cdot Ra$ | *a, b, c* | Bristow and Campbell (1984) |
| Proposed model | $R_s = a + bx_1 + cx_2 + dx_3 \ldots zx_n$ | *a, b, c, d...z* | Multiple regression |

Rs = global solar radiation (MJ $m^{-2}$ $d^{-1}$); Ra = extraterrestrial solar radiation (MJ $m^{-2}$ $d^{-1}$); ΔT = difference between the maximum and minimum daily air temperatures (°C); ΔT1 = difference between maximum temperature and mean of the minimum air temperature of two consecutive days; a, b, and c = empirical coefficients of the models (dimensionless).

The HAR model is widely used because of its simplicity and is recommended to be used when radiation data are absent or of questionable quality (ALLEN et al., 1998). Regarding the BC model, the values frequently found for coefficients *a*, *b* and *c*are 0.7 for *a*; the range from 0.004 to 0.010 for *b*; and 2.4 for *c* (MEZA; VARAS, 2000).

The PMo was obtained by multiple regression, using the variables Tx, Tn, Tmean, ΔT, RH, Ra, n, N, and n / N, according to the following general model (Equation 3):

$$R_s = a_0 + a_1T_x + a_2T_n + a_3T_{mean} + a_4\Delta T + a_5RH + a_6R_a + a_7n + a_8N + a_9\, {}^{n}/_{N} \qquad (3)$$

where the coefficients $a_0$ to $a_9$ are the constants of adjustment of the multiple regression equation, and the other terms are as described in the weather data section.

The significance of the coefficients of the multiple regression model was evaluated by the t-test, and the configuration of the equation that best explains the Rs estimates for the studied locations was evaluated using the stepwise technique.

In addition, the predictive capacity of the proposed model was evaluated from four versions, namely: PMo (full version with all available weather variables of the study areas), and three other versions without the variables air RH (PMo1), n (PMo2), and both (PMo3).

**Calibration and validation of the models**

The coefficients of the AP, HAR, and BC models were calibrated and evaluated using independent sets of 70 and 30% of the observed data, through the cross-validation technic (holdout method).

The coefficients of the AP method were calibrated by simple regression, using the clarity index (Rs/Ra) and the sunshine ratio (n/N); and for the BC and HAR models, the Ordinary Lest Square (OLS) method was used.

**Evaluation of the Rs estimates of the models**

The performance of the models was quantitatively evaluated by comparing estimated and observed Rs, using the following statistical indicators: coefficient of determination ($r^2$; Eq. 4), Nash index or modeling efficiency index (E; NASH; SUTCLIFFE (1970); Eq 5), concordance or accuracy index (d; WILLMOTT et al. (1985); Eq. 6), mean bias error (MBE; Eq. 7), root mean square error (RMSE; Eq. 8), and mean absolute percentage error (MAPE; Eq. 9). In addition, the models were classified according to the range of the E index, using the criteria suggested by Moriasi et al. (2007), as follows: very good (0.75 < E ≤ 1.00), good (0.65 < E

<0.75), satisfactory (0.50 < E <0.65), or unsatisfactory (E ≤ 0.50).

The best Rs estimation method in each study location was the one that presented the highest $r^2$, d, and E, and the lowest RMSE. Regarding the MBE, this indicator allows the evaluation of underestimation or overestimation of the models

$$r^2 = \left\{ \frac{\sum_{i=1}^{n}(x_i - \bar{x}) \cdot (y_i - \bar{y})}{\left|\left[\sum_{i=1}^{n}(x_i - \bar{x})^2\right]^{0.5}\right| \cdot \left|\left[\sum_{i=1}^{n}(y_i - \bar{y})^2\right]^{0.5}\right|} \right\}^2 \quad (4)$$

$$E = 1 - \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (5)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{\sum_{i=1}^{n}(|y_i - \bar{x}| + |x_i - \bar{x}|)^2} \quad (6)$$

$$MBE = \frac{1}{n}\sum (x_i - y_i) \quad (7)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{n}} \quad (8)$$

$$MAPE = \left[\frac{1}{n}\sum_{i=1}^{n}\frac{|y_i - x_i|}{x_i}\right] \times 100 \quad (9)$$

where*yi* is the Rs value estimated by the different Rs estimation methods (MJ $m^{-2}$ $d^{-1}$), *xi* is the observed Rs; $\bar{x}$ and $\bar{y}$ are the means of *yi* and *xi*; and *n* is the number of observed data.

## RESULTS AND DISCUSSION

### Adjustment and evaluation of the traditional models

The adjustment of the AP, HAR, and BC models for the local climatic conditions of Goianésia, Itumbiara, Mineiros, Morrinhos, Rio Verde, and Santa Helena de Goiás, presented an increase in the coefficient of determination of up to 16.4% (Table 2). The coefficient *a* of the BC model ranged from 0.522 to 0.699; the coefficient *b* from 0.014 to 0.050, and coefficient *c* from 1.517 to 2.043. These are similar values to those reported in other studies, such as those conducted by Silva et al. (2012) in Minas Gerais (Southeast of Brazil), Souza et al. (2017) in Mato Grosso (Central-West of Brazil), and Yildirim; Teke; Antonanzas-Torres (2018) in Turkey.

**Table 2.** Coefficients of adjustment for the Angstrom-Prescott (AP), Hargreaves (HAR), and Bristow-Campbell (BC) models calibrated for six locations in the state of Goiás, Brazil.

| Weather station | Models | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | AP | | | HAR | | BC | | | |
| | *a* | *b* | $r^2$ | *a* | $r^2$ | *a* | *b* | *c* | $r^2$ |
| GOI | # | # | # | 0.168 | 0.58 | 0.683 | 0.035 | 1.660 | 0.64 |
| ITU | 0.293 | 0.439 | 0.690 | 0.165 | 0.52 | 0.678 | 0.024 | 1.820 | 0.65 |
| MIN | # | # | # | 0.151 | 0.52 | 0.617 | 0.050 | 1.517 | 0.55 |
| MOR | # | # | # | 0.150 | 0.53 | 0.638 | 0.024 | 1.804 | 0.64 |
| RIO | 0.342 | 0.409 | 0.790 | 0.167 | 0.48 | 0.699 | 0.036 | 1.609 | 0.53 |
| STH | # | # | # | 0.124 | 0.69 | 0.522 | 0.014 | 2.043 | 0.71 |

ITU = Itumbiara; GOI = Goianésia; MIN = Mineiros; MOR = Morrinhos; RIO = Rio Verde; STH = Santa Helena de Goiás. # Locations with not available sunshine data.

In the BC model, its empirical coefficients are modeled as a function of the transmittance of the atmosphere (coefficient *a*) and the effect of thermal amplitude on the maximum value of this transmittance (coefficients *b* and *c*) (BRISTOW; CAMPBELL, 1984). Thus, the physical principle of these coefficients allows the study of the effect of climate on new coefficients obtained with local calibration.

The coefficients *a* and*c* presented low variability between the studied locations (~35%), which is in accordance with the recurrent recommendation to fix these two coefficients when local Rs data are not available for calibration.

However, the coefficient *b* showed high variability (~350%), which has also been found in other studies (LIU et al., 2009b; HEINEMANN et al., 2012), requiring caution when using fixed values for this coefficient. Bristow and Campbell (1984) recommended 0.010 for winter and 0.004 for summer; however, the values that presented the best results for the annual estimate of Rs ranged from 0.014 to 0.050 for the climatic conditions of the state of Goiás (Table 2), and the effect of seasonality on this coefficient was not evaluated.

Regarding the performance of the models after calibration, the locations that presented the highest thermal amplitude values throughout the year (Itumbiara and Santa Helena de Goiás) showed the best $r^2$ results. This was expected, since clear sky conditions allow greater atmospheric transmissivity, which is commonly found on days with high thermal amplitude (GRANT et al., 2004). Another factor that may affect the magnitude of the BC method coefficients (particularly *b* and *c*) is the thermal amplitude calculation (LIU et al., 2009a), which can be performed by simple arithmetic mean between maximum and minimum daily air temperatures and by the difference between the maximum air temperature and average of the minimum temperature of two consecutive days.

In the HAR model, the calibration of its coefficient showed significant improvement only for Goianésia, with an $r^2$ increase of 13% ($r^2$ = 0.45 to $r^2$ = 0.58). In the other locations, increases in $r^2$ ranged from 0 to 2.8% (Table 2), showing similarity to the coefficient of adjustment for the interior regions of the continent (*a* = 0.16), as recommended by Hargreaves (1981). However, the coefficient a for Santa Helena de Goiás was significantly lower (0.124) due to the minimization of the residual sum of squares (OLS method).

In the AP model, which was only adjusted to locations that had sunshine (n) data, the coefficients a and b were 0.293 and 0.342 (Itumbiara) and 0.439 and 0.409 (Rio Verde), respectively. These results improved the $r^2$ values in approximately 3% when compared to the Glover; McCulloch (1958) methodology for the AP coefficients (where a = 0.29 cosϕ and b = 0.52).

However, better estimates can be reached by adjusting monthly values to the coefficients, given that the transmissivity of the atmosphere presents seasonal variation (CARVALHO et al., 2011).

**Adjustment and evaluation of the proposed model and modifications**

The proposed model was developed using the multiple regression of the maximum number of available meteorological variables for the study regions (PMo). Then, restrictions were determined, disregarding RH (PMo1), n (PMo2), or both (PMo3). In addition, the square root was considered for ΔT to minimize the effect of the identified multicollinearity. The results showed that the estimation of Rs using air temperature and *n* data does not explain most of the Rs variation in all versions tested (Table 3). Particularly for the complete model (PMo), $r^2$ reached up to 83% when adjusted and validated for Rio Verde; similar performance was found for Itumbiara ($r^2$ = 0.76); sunshine data could be used for both locations. Locations with no sunshine data (PMo2 and PMo3) presented lower $r^2$, ranging from 0.51 to 0.64 in their different combinations.

The stepwise regression allowed the identification of the independent variables that contributed most for the final model. Thus, sunshinedata (when available) is the variable that the most impacts the model, followed by Tx, ΔT, and Tmean; Ra, RH, and P have secondary importance; and Tn contributes little to the regression model. This is shown by the correlation between Rs and the other variables and by the hierarchy (order of importance of the variables in the regression model) resulted from the stepwise regression (Figure 3).

**Table 3.**Coefficients of adjustment of the proposed model (PMo) and their modified versions (PMo1, PMo2, and PMo3) for estimation of global solar radiation (Rs) in six locations in the state of Goiás, Brazil.

| Station | Model | Coefficients | | | | | | | | | | $r^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ | $a_6$ | $a_7$ | $a_8$ | $a_9$ | |
| GOI | PMo | -38.988 | -1.529 | 1.915 | $0.096^{ns}$ | 16.079 | -0.024 | 0.282 | # | $-0.327^{ns}$ | # | 0.65 |
| | PMo1 | -42.685 | -1.372 | 1.696 | 0.269 | 15.305 | # | 0.223 | # | $0.512^{ns}$ | # | 0.62 |
| ITU | PMo | 3.202 | -1.663 | 1.391 | 0.204 | 27.423 | 0.003 | 0.755 | 3.324 | -3.183 | -27.135 | 0.76 |
| | PMo1 | 1.792 | -2.068 | 1.713 | 0.248 | 14.392 | # | 0.797 | 3.263 | -3.433 | -26.758 | 0.77 |
| | PMo2 | -32.320 | -4.532 | 3.637 | 0.854 | 32.548 | -0.044 | 0.893 | # | -3.095 | # | 0.64 |
| | PMo3 | -37.119 | -4.298 | 3.354 | 1.014 | 31.650 | # | 0.860 | # | 3.058 | # | 0.64 |
| MIN | PMo | -60.486 | -0.987 | 1.334 | $0.125^{ns}$ | 11.294 | -0.073 | -0.261 | # | 4.936 | # | 0.57 |
| | PMo1 | -67.048 | -0.653 | 0.868 | 0.482 | 9.388 | # | -0.353 | # | 4.936 | # | 0.53 |
| MOR | PMo | -26.508 | -0.871 | $0.854^{ns}$ | $0.168^{ns}$ | 10.646 | -0.060 | 0.219 | # | $0.962^{ns}$ | # | 0.65 |
| | PMo1 | -35.490 | -0.538 | 0.352 | 0.492 | 9.479 | # | $0.087^{ns}$ | # | 1.431 | # | 0.63 |
| RIO | PMo | -50.376 | 2.414 | 2.373 | $0.018^{ns}$ | 17.390 | -0.038 | $0.065^{ns}$ | 2.570 | 2.853 | -20.704 | 0.83 |
| | PMo1 | -56.472 | -2.103 | 1.912 | 0.273 | 15.681 | # | $-0.024^{ns}$ | 2.510 | 3.321 | -19.586 | 0.71 |
| | PMo2 | -61.189 | -3.743 | 3.399 | 0.384 | 27.423 | -0.075 | $0.180^{ns}$ | # | 2.261 | # | 0.56 |
| | PMo3 | -70.886 | -3.230 | 2.581 | 0.102 | 24.928 | # | $0.041^{ns}$ | # | 2.767 | # | 0.51 |
| STH | PMo | -25.161 | -2.865 | 2.654 | 0.184 | 24.115 | $-0.012^{ns}$ | 0.910 | # | -3.287 | # | 0.71 |
| | PMo1 | -25.451 | -2.822 | 2.570 | 0.234 | 23.921 | # | 0.927 | # | -3.421 | # | 0.71 |

GOI = Goianésia; ITU = Itumbiara; MIN = Mineiros; MOR = Morrinhos; RIO = Rio Verde; STH = Santa Helena de Goiás; PMo = Rs estimate with all available meteorological variables for the location (maximum, minimum, and average air temperatures, thermal amplitude, air relative humidity, extraterrestrial solar radiation, sunshine, day length (photoperiod), and sunshine ratio); PMo1 = Rs estimate without considering air relative humidity; PMo2 = Rs estimate without considering sunshine; PMo3 = Rs estimate without considering air relative humidity and sunshine; $^{ns}$ = not significant at 5% probability. Coefficients of the model: $a_0$ = linear coefficient; $a_1$ = maximum air temperature ($T_x$); $a_2$ = minimum air temperature ($T_n$); $a_3$ = mean air temperature ($T_{mean}$); $a_4$ = daily thermal amplitude (ΔT); $a_5$ = air relative humidity (RH); $a_6$ = extraterrestrial solar radiation (Ra); $a_7$ = sunshine (n); $a_8$ = day length (photoperiod) (N); $a_9$ = sunshine ratio (n/N).# Locations with not available sunshine data.

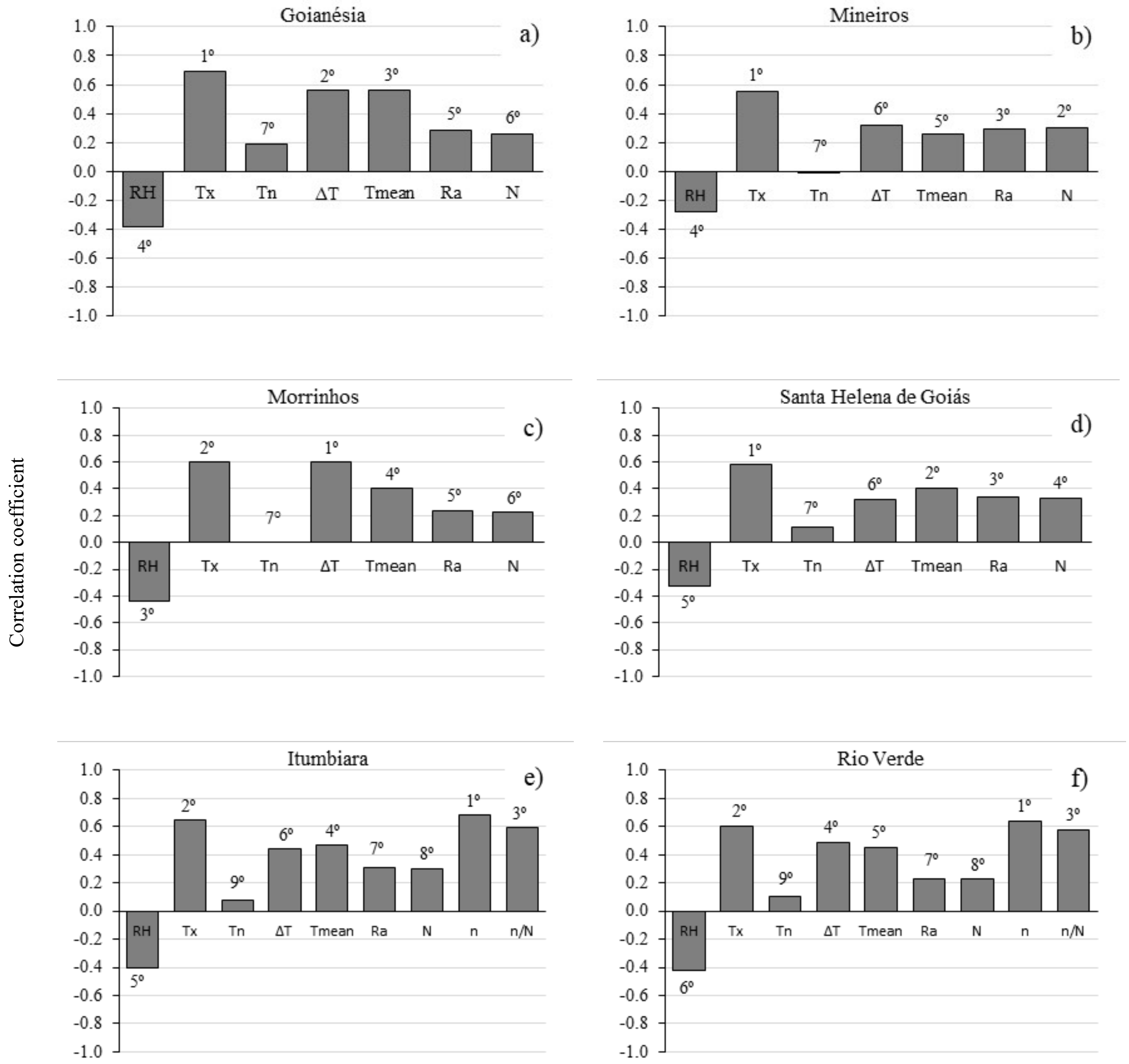



**Figure 3.** Correlation between solar radiation and other meteorological variables (air relative humidity, RH; maximum air temperature, Tx; minimum air temperature, Tn, thermal amplitude, ΔT; mean air temperature, Tmean; extraterrestrial solar radiation, Ra; day length (photoperiod), N; sunshine, n; and sunshine ratio, n / N) for Goianésia (a), Mineiros (b), Morrinhos (c), Santa Helena de Goiás (d), Itumbiara (e), and Rio Verde (f), in the state of Goiás, Central-West region of Brazil. Source: Author (2019)

According to Liu et al. (2009a), these evaluations can identify correlations between variables and evaluate the maintenance of certain meteorological variables in the composition of the model. The occurrence of higher correlations between the variables used in the regression model usually means that the simplification of the model by coefficient fixation can generate loss of predictive capacity, thus, becoming more unstable.

The correlations between variables were classified as moderate, except for Ra and Tn, which presented weak correlation according to the classification proposed by Dancey; Reidy (2006) and, therefore, should be kept in the model. Thus, it is important to know the correlation level between variables to include or remove variables from a regression model.

RH was the only variable that showed negative correlations for all evaluated locations, indicating that a high RH - high water vapor content in the atmosphere - may be associated with significant presence of clouds, which attenuates Rs on the earth's surface. Similar results, but with greater magnitude, was found by Ogolo (2014) in Nigeria, and by Ahmed Kutty; Masral; Rajendran (2015) in Malaysia, in which the inclusion of RH in Rs estimation models may have improved their accuracy.

**Comparative analysis of global solar radiation estimation models**

Table 4 shows the statistical indicators used for the comparative analysis between the evaluated estimation models of Rs in the six locations in the state of Goiás, Brazil.In this table, only the proposed model in its complete version was analyzed, as the modified versions presented similar or worse performance than the traditional methods.

The models adjusted to local conditions presented acceptable performance, with 60% of the tested conditions classified as satisfactory based on the Nash efficiency index (NASH; SUTCLIFFE, 1970). The remaining ranges were 15% (very good), 10% (good), and 15% (unsatisfactory).

The other statistical indicators presented variations of 0.48 to 0.83 for $r^2$, -0.37 to 1.29 MJ $m^{-2}$ $d^{-1}$ for MBE, 1.20 to 2.81 MJ $m^{-2}$ $d^{-1}$ for MAE, 9.75 to 22.62 % for MAPE, and 0.45 to 0.82 for the E index. Thus, the greater the number of variables and coefficients considered in the evaluated models, the better their performance.

**Table 4.** Statistical indicators for comparative analysis between the traditional Angstrom-Prescott (AP), Hargreaves (HAR), and Bristow-Campbell (BC) models and the proposed PMo model adjusted to local conditions for estimation of global solar radiation in six locations in the state of Goiás, Central-West region of Brazil.

| Weather Station | Model | $r^2$ | MBE | MAE | MAPE | E | Classification E |
|---|---|---|---|---|---|---|---|
| GOI | HAR | 0.58 | -0.09 | 2.48 | 16.48 | 0.58 | Satisfactory |
| | BC | 0.64 | -0.22 | 2.32 | 14.26 | 0.61 | Satisfactory |
| | PMo | 0.65 | -0.01 | 2.25 | 14.22 | 0.65 | Good |
| ITU | AP | 0.69 | -0.09 | 1.83 | 12.54 | 0.69 | Good |
| | HAR | 0.51 | -0.27 | 1.68 | 17.69 | 0.50 | Satisfactory |
| | BC | 0.65 | -0.37 | 2.25 | 13.26 | 0.65 | Satisfactory |
| | PMo | 0.76 | -0.08 | 1.29 | 10.98 | 0.76 | Very Good |
| MIN | HAR | 0.52 | -0.74 | 2.77 | 18.68 | 0.45 | Unsatisfactory |
| | BC | 0.55 | -0.82 | 2.78 | 15.69 | 0.52 | Satisfactory |
| | PMo | 0.57 | 0.01 | 2.41 | 16.70 | 0.58 | Satisfactory |
| MOR | HAR | 0.53 | 0.18 | 2.50 | 22.62 | 0.53 | Satisfactory |
| | BC | 0.64 | -0.07 | 2.19 | 17.91 | 0.62 | Satisfactory |
| | PMo | 0.65 | 0.06 | 2.11 | 18.18 | 0.64 | Satisfactory |
| RIO | AP | 0.79 | 0.35 | 1.52 | 11.32 | 0.78 | Very Good |
| | HAR | 0.48 | 0.70 | 1.66 | 19.02 | 0.45 | Unsatisfactory |
| | BC | 0.53 | 0.81 | 2.57 | 16.81 | 0.48 | Unsatisfactory |
| | PMo | 0.83 | 0.45 | 1.20 | 9.75 | 0.82 | Very Good |
| STH | HAR | 0.69 | 1.23 | 2.81 | 23.44 | 0.59 | Satisfactory |
| | BC | 0.71 | 1.29 | 2.09 | 20.53 | 0.63 | Satisfactory |
| | PMo | 0.71 | 1.19 | 2.64 | 20.15 | 0.64 | Satisfactory |

ITU = Itumbiara; GOI = Goianésia; MIN = Mineiros; MOR = Morrinhos; RIO = Rio Verde; STH = Santa Helena de Goiás; $r^2$ = coefficient of determination; MBE = Mean Bias Error; MAE = Mean Absolute Error; MAPE = Mean Absolute Percentage Error; E = Nash index (modeling efficiency index); Classification E = hierarchy according to E index; PMo = Rs estimate with all available meteorological variables for the location (maximum, minimum, and average air temperatures, thermal amplitude, air relative humidity, extraterrestrial solar radiation, sunshine, day length (photoperiod), and sunshine ratio).

The evaluation of the estimation models showed that the proposed model in its full version presented the best statistical performance indicators, with the highest $r^2$ and E, and the lowest MBE, MAE, and MAPE for the studied locations. However, despite the improved estimates compared to the traditional models, the proposed model has limitations regarding its applicability, requiring new calibrations for use in different climatic conditions.

In addition, the model requires more meteorological variables than the traditional models, which would discourage its adoption; and the low contribution of the predictive capacity of models to the estimation of Rs, considering the low magnitude of uncertainties found in the present study, little affects the applications where this variable is used, such as in crop growth models, as found by Heinemann et al. (2012) and Battisti; Bender; Sentelhas (2019).

After the adjustment of the AP model, the Rs estimates presented E index with very good (Itumbiara) and good (Rio Verde) performances; low MAE values (1.83 and 1.52 MJ $m^{-2}$ $d^{-1}$, respectively); satisfactory predictive capacity of the regression model ($r^2$>0.69); and high concordance to the observed data (d>0.90) (Figure 3).

This model is the result of the combined efforts of Angstrom (1924) and Prescott (1940); it has been one of the most worldwide used method for estimating Rs. According to Liu et al. (2009b), the robustness of this model is due to the variables contained in it, which aggregate the effects of the essential factors for Rs estimation; thus, the inclusion of new variables is little significant. The BC model presented a satisfactory performance for all studied locations, except for Rio Verde, for which this model was unsatisfactory and presented the highest mean absolute error (MAE = 2.57 MJ $m^{-2}$ $d^{-1}$). Similar results were found by Conceição; Marin (2007) for Piracicaba, state of São Paulo; and Bender; Sentelhas (2018) for several locations in Brazil.

This model has also been widely used due to its formulation, which contains only air temperature as the input variable (observed data). According to Liu et al. (2009a) and Li et al. (2014), models based on air temperature are suitable for locations with high thermal amplitude, as the Central-West region of Brazil (particularly in autumn and spring months), because Rs affects proportionally and directly the daily variation of sensible heat flux, which is the main component of the energy balance in dry seasons.

In addition, according to these authors, the importance of this models may increase in the context of climate change, in which intensification of extreme air temperatures is expected.The HAR model presented the worst statistical indexes among the evaluated models, with the highest MAPE and RMSE, and lowest $r^2$ and E.

Therefore, the use of this model is not recommended for the evaluated locations, since it requires the same input data as the BC model.

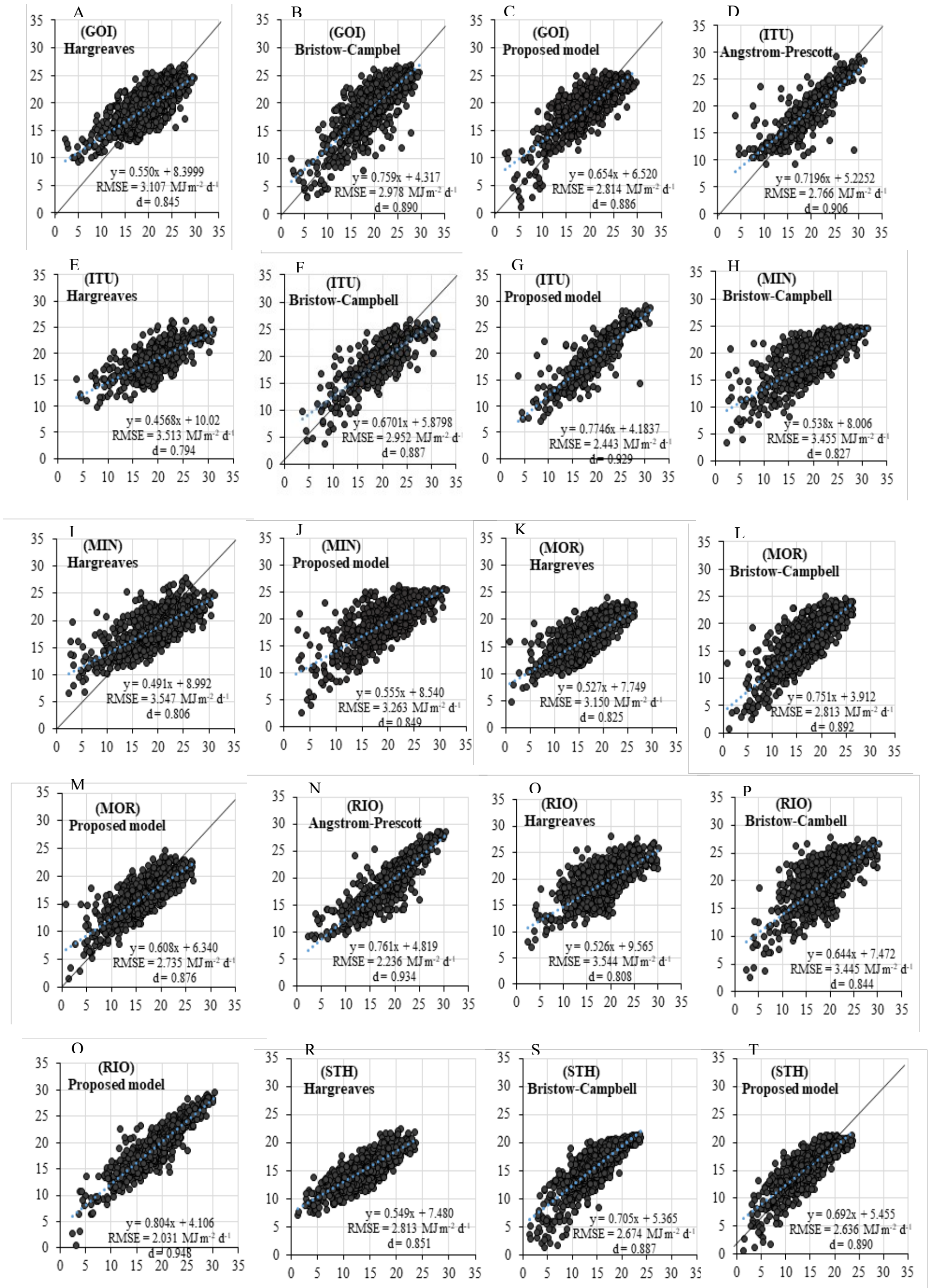



**Figure 3.** Comparison between the global solar radiation measured and estimated from the Angstrom-Prescott, Hargreaves, and Bristow-Campbell methods and from the method proposed in the present study for Goianésia, Itumbiara, Mineiros, Morrinhos, Rio Verde, and Santa Helena de Goiás (state of Goiás, Central-West of Brazil). RMSE = Root Mean Square Error (MJ $m^{-2}$ $d^{-1}$); *d* = concordance index; GOI = Goianésia; ITU = Itumbiara; MIN = Mineiros; MOR = Morrinhos; RIO = Rio Verde; STH = Santa Helena de Goiás. Source: Author (2019)

## CONCLUSIONS

Despite restricted to local use, the proposed model adequately estimated the global solar radiation in the studied locations.

The proposed model presented the best performance when compared to the evaluated traditional models (Angstrom-Prescott, Bristow-Campbell, and Hargreaves), and its use is recommended whenever climate data is available to implement it.

The Angstrom-Prescott and Bristow-Campbell traditional models showed significant improvement after adjustment to local conditions and can be used satisfactorily for the studied locations.

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