Original Article

SOLAR RADIATION ESTIMATED FROM EMPIRICAL MODELS FOR THE NORTH OF MINAS GERAIS, BRAZIL

RADIAÇÃO SOLAR ESTIMADA POR MODELOS EMPÍRICOS PARA O NORTE DE MINAS GERAIS, BRASIL

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ABSTRACT: Estimating daily solar radiation (R_s) provides an important alternative in situations where it cannot be measured by conventional pyranometers. This study used meteorological data from nine cities in the north of the Minas Gerais state, Brazil, for the period from 2008 to 2010 with the aim of evaluate the accuracy and applicability of some simple models to help regions where R_s is impossible to be measured. Five models were evaluated for their estimates of R_s based on simple available data. For each city studied, the equations were previously calibrated. Meteorologically based empirical models to estimate daily global solar radiation are an appropriate tool if the parameters can be calibrated for different locations. These models have the advantage of using meteorological data, which are commonly available. Based on the overall results, we conclude that the accuracy of estimation by available meteorological data is acceptable and comparable with the accuracy of classical models. Considering the greater availability of air temperature data and application in studies that do not require great accuracy in estimating R_s, all models were adequate for use. The accuracy of R_s was only slightly improved by adding rainfall records as input variable. Therefore, in the region studied, the choice of simpler models, having as input the daily maximum and minimum air temperature would not imply large error in the estimates. For most sites, Bristow and Campbell model had the best estimate of R_s with a *RMSE* of 2.69 MJ m^{-2} and R^2= 0.69, with the possibility to calibrate with available temperature data, becoming a practical and reliable model. Hargraves model should be avoided due to its lower performance compared to the other models applied.

KEYWORDS: Meteorological models. Air temperature. Model comparison. Center of Brazil.

INTRODUCTION

Local daily solar radiation data (R_s) is extremely important for studies involving the surface energy-balance, thermal load on buildings analysis, solar energy collecting systems, crop growth models and studies of the water requirement of irrigated crops (THORNTON; RUNNING, 1999; ROBBA, 2009).

However, R_s data are not available in some places, due to the absence of instruments for their measurement. Thereby, empirical equations were developed to estimate R_s from variables normally available at a majority of weather stations such as sunshine duration (Ångström, 1924), air temperature range (HARGREAVES, 1981; BRISTOW; CAMPBELL, 1984; CHEN et al., 2004), air temperature range and rainfall (DE JONG; STEWART, 1993; HUNT et al., 1998; LIU; SCOTT, 2001), air temperature and water vapor pressure (ALMOROX et al., 2011) or based on day of year (BULUT, 2003; LI et al., 2010). Those models vary with numbers of variables and complexity. It is generally recognized that sunshine duration based models yield best results (WU et al., 2007; BAKIRCI, 2009). However, sunshine duration is not commonly observed at all standard meteorological stations compared to air temperature and precipitation.

Although empirically derived and conceptually simple, the air temperature-based model is founded on theoretical concepts for energy exchange in the surface boundary layer (GOODIN et al., 1999). This model assumes radiation loading as the predominant forcing mechanism for diurnal air temperature variation. Bristow and Campbell (1984) found that the model provided accurate estimates and could account for 70-90% of R_s at three sites in the U.S.A.

In Brazil, despite the large increase in automatic weather stations network, R_s data are not commonly available at agricultural areas, where it is essential for the reference evapotranspiration used in irrigation management. Therefore, it is important to check simple R_s estimation models, especially in northern of Minas Gerais, which has 46.075ha in four irrigated perimeters (Gorutuba, Lagoa Grande, Pirapora and Jaíba) (CODEVASF, 2012). The aim of this study was to evaluate the accuracy and applicability of some simple models for estimating daily values of solar radiation to the north region of Minas Gerais State, Brazil, to determinate which

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models are more reliable to be used in sites where R_s cannot be measured.

MATERIAL AND METHODS

Meteorological data

The hourly meteorological data were obtained from nine automatic weather stations located in the cities listed in Table 1 and are shown in Figure 1. These cities are in the north of the Minas Gerais state. The stations are part of National Meteorology Institute (Instituto Nacional de Meteorologia - INMET). The INMET represents Brazil in the World Meteorological Organization. These weather stations were acquired in 2006 but the data were only available in 2008. It was used a CM6B pyranometer (Kipp & Zonen, Netherlands, 5% of accuracy) for measurements of daily R_s. For air temperature, QMH102 probe (Vaisala, Finland, 0.1ºC of accuracy) and for daily rainfall a QMR102 tipping-bucket rain gauge (Vaisala, Finland, 0.2 mm of accuracy) was used. All data were available at the INMET official web site (INMET, 2011).

Table 1. Geographic location of meteorological stations used in the study and the mean and range of daily solar radiation (R_s), period and percentage of omission data records for each station.

Site	City	Latitude South (°)	Longitude West (°)	Altitude (m)	Period	Omission (%)	R_s range ---------(MJ m^{-2})	R_s mean --------
1	Águas Vermelhas	-15.75	-41.45	750	2009-2010	0.96	3.19 - 30.70 4.85 - 29.95	18.10 18.55
2	Chapada Gaúcha	-15.30	-45.61	880	2008-2009	0.96	4.24 - 31.79 7.12 - 31.44	20.29 20.04
3	Espinosa	-14.91	-42.80	570	2009-2010	2.05	5.76 - 30.55 7.20 - 30.86	20.75 21.14
4	Mocambinho	-15.08	-44.01	460	2009-2010	0.95	5.30 - 30.40 5.88 - 30.49	20.87 21.04
5	Montalvânia	-14.40	-44.40	512	2009-2010	1.10	4.36 - 31.13 7.60 - 31.60	20.85 21.71
6	Pirapora	-17.25	-44.83	503	2008-2009	0.96	5.44 - 32.67 4.62 - 31.50	20.42 20.49
7	Rio Pardo de Minas	-15.72	-42.43	853	2009-2010	1.92	3.78 - 30.74 3.72 - 30.36	18.08 18.90
8	Salinas	-16.16	-42.30	495	2008-2009	0.55	5.16 - 30.62 3.61 - 30.99	18.70 18.88
9	São Romão	-16.36	-45.12	460	2008-2009	0.96	5.40 - 31.90 4.33 - 31.28	20.76 20.78

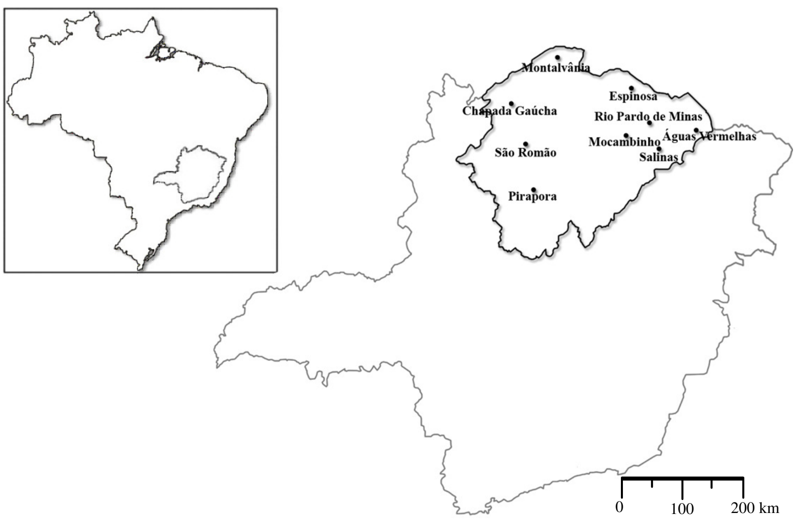

Figure 1. Distribution of stations in the north of Minas Gerais state.

Data sets were collected from 2008 to 2010. The limited series of data was due to the automatic weather stations from National Institute of Meteorology in Brazil were acquired in 2006 but the data were available only from 2008. For each site, a series of two years data were used in the study: the first to calibrate and the last to validate the models. Firstly, data reported at hourly intervals were reduced to daily values, obtaining the values of maximum and minimum temperatures (T_{max}, T_{min}) and daily solar radiation (R_s) and total rainfall (P). Data were subjected to a screening to verify their integrity and consistency. Criterions for the elimination of data, proposed by Liu et al. (2009) were used. Data were discarded in the case of: a) missing data for any of the elements T_{max}, T_{min} or R_s; b) $T_{max}<T_{min}$; c) $R_s/R_a>1$. The percentage of omitted days was calculated by the period considered.

Radiation models

Most models used in this study required the daily total extraterrestrial radiation (R_a, MJ m^{-2}). Therefore, R_a was calculated using the equations detailed by Allen et al. (1998). The only input required to calculate these daily values, for a specific day of the year, is the latitude of the location.

$$R_a = 37.6 d_r (hn \sin\phi \sin\delta + \cos\phi \cos\delta \sin hn) \quad (1)$$

$$d_r = 1 + 0.033\cos\left(NDA \frac{360}{365}\right) \quad (2)$$

$$\delta = 0.409 \sin\left(\frac{360}{365} NDA - 1.39\right) \quad (3)$$

$$hn = \arccos\left(-\tan\phi \tan\delta\right) \quad (4)$$

where d_r is the eccentricity correction factor of the Earth's orbit, hn the hour angle of the sun at sunrise (radian), $\emptyset$ the latitude of the site (radian, south negative), δ is the solar declination (radian) and NDA is the day of year (1 for January first and 365 or 366 at December 31).

Hargreaves Model (Ha)

Hargreaves (1981) elaborated a simple equation to estimate daily R_s which requires only the air temperature range and R_a:

$$R_s = a\sqrt{\Delta T_1} R_a \quad (5)$$

where a is an empirical coefficient and ΔT_1 is the daily maximum (T_{max}) minus minimum (T_{min}) air temperature. The coefficient a must be derived for the site where data measurements are available. This model has served as the initial basis for daily solar radiation prediction by temperature-based models.

Allen et al. (1998) recommended use a=0.16 for interior locations, where land mass dominates and air masses are not strongly influenced by a large water body. Therefore, in order to evaluate how the Ha model with an uncalibrated coefficient (a=0.16) would affect the model performance, we include it denoting as Ha-*fixed*.

Chen et al. Model (Ch)

Similar to the Hargreaves model, Chen et al. (2004) proposed the estimation of daily R_s from air temperature and R_a, but using a logarithmic relationship with two coefficients:

$$R_s = \left(a \ln \Delta T_1 + b\right) R_a \quad (6)$$

where a and b are empirical coefficients.

Bristow and Campbell Model (B-C)

Bristow and Campbell (1984) also developed a simple equation to estimate solar radiation based on the range of air temperature (ΔT_2) in which R_s is an exponential function of ΔT_2 with three coefficients:

$$R_s = a\left[1 - exp\left(-b\Delta T_2^c\right)\right] R_a \quad (7)$$

where a, b and c are empirical coefficients. To help reduce the effect of large-scale hot or cold air masses which may move through the area, ΔT_2, is calculated as the difference between maximum and average minimum air temperature of the two consecutive days as:

$$\Delta T_2 = T\max_i - (T\min_i + T\min_{i+1})/2 \quad (8)$$

where i is the current day and i+1 is the next day.

These empirical coefficients have some physical explanation. The coefficient a represents the maximum solar transmittance which can be expected on a clear day and the coefficients b and c determine how soon the maximum R_s is achieved as ΔT_2 increases (BRISTOW; CAMPBELL, 1984).

Li et al. Model (Li)

Since R_s is a quasi-periodic phenomenon on a yearly cycle due to seasonal effects, sinusoidal correlations give excellent fitting (LI et al., 2010). The model uses sine and cosine wave correlations as follows:

$$R_s = a + b\sin\left(\frac{2\pi c}{365} NDA + d\right) + e\cos\left(\frac{2\pi f}{365} NDA + g\right) \quad (9)$$

where a, b, c, d, e, f and g are empirical coefficients and NDA is the day of year.

De Jong and Stewart Model (J-S)

Commonly, for empirical models, more input variables promote greater chance of an improved fit of the observed data (LIU; SCOTT, 2001). De Jong and Stewart (1993) used rainfall combined with ΔT_1 for estimating R_s as follows:

$$R_s = a\Delta T_1^b (1 + cP - dP^2) R_a \quad (10)$$

where *a*, *b, c* and *d* are empirical coefficients, *P* is the daily rainfall (mm), and ΔT_1 is defined as in Eq. (5).

Calibration and statistical evaluation

In the period analyzed (three years), one year was used to calibrate the coefficients of models applying the nonlinear least square fitting method. The fitting process was performed with free *R* statistical software, version 2.13.1 through *NLS* function (nonlinear least-square) that outputs coefficient values and residual standard error (*RSE*) of the model which is the estimate of standard deviation of model error. Subsequently, the fitted models were validated using the second set of data (another year) for the same station. To ensure stability of the coefficients, solved by an iterative method using the R software, a range of coefficient values were used.

Models performance was evaluated in terms of the following statistical parameters: coefficient of determination *R*-squared (R^2), root mean-square error (*RMSE*), the mean bias error (*MBE*) and the intercept (*a*) and slope (*b*) of the least-squares regression. These parameters are the most commonly applied in comparing models of solar radiation estimations (YORUKOGLU; CELIK, 2006).

RESULTS AND DISCUSSION

Li model did not fit the set of data used in this work and its results were omitted. In this model, during the fitting process, different initial values resulted in different coefficients. Li model uses only day of the year like input, which makes it more suitable to describe the normal variation of R_s along of the year. Therefore, model calibrations that use only one year of data do not express cyclical component in the dataset. Li et al. (2010) used series of at least 10 years to calibrate the model, generating results more promising. Other models using the same approach like Bulut (2003) and Kaplanis and Kaplani (2007) would have the same restriction, requiring more than a year of data for proper calibration procedure.

Table 2. Calibrated model coefficients for all sites (1-9) for N=366 to 2008 or 365 to 2009.

Model		Sites									
		1	2	3	5	5	6	7	8	9	**Mean**
Ha	*a*	0.150	0.174	0.179	0.168	0.159	0.166	0.157	0.149	0.160	**0.162**
	RSE	3.116	3.543	3.268	2.846	3.272	3.638	2.997	3.137	3.176	
Ch	*a*	0.302	0.404	0.350	0.366	0.352	0.309	0.345	0.330	0.330	**0.343**
	b	-0.224	-0.389	-0.241	-0.327	-0.328	-0.186	-0.304	-0.301	-0.264	**-0.285**
	RSE	2.971	3.138	3.099	2.594	3.083	3.392	2.663	2.865	2.861	
B-C	*a*	0.789	0.737	0.704	0.697	0.720	0.674	0.738	0.753	0.706	**0.724**
	b	0.046	0.012	0.012	0.009	0.015	0.006	0.039	0.036	0.009	**0.020**
	c	1.272	2.059	2.149	2.166	1.854	2.451	1.445	1.396	2.127	**1.880**
	RSE	2.84	2.936	2.817	2.464	3.1	2.932	2.761	2.905	2.541	
J-S	*a*	0.126	0.120	0.185	0.149	0.143	0.246	0.098	0.107	0.176	**0.150**
	b	0.573	0.660	0.495	0.552	0.544	0.362	0.689	0.629	0.472	**0.553**
	c	-0.014	-0.013	-0.020	-0.004	-0.013	-0.023	-0.007	-0.008	-0.011	**-0.013**
	d	1.5E-4	1.3E-4	3.5E-4	5.6E-6	2.6E-4	3.8E-4	8.8E-5	9.9E-5	8.9E-5	-
	RSE	2.899	3.062	2.987	2.707	3.17	3.252	2.72	2.919	2.952	
	R_{smean}	18.1	20.29	20.75	20.87	20.85	20.42	18.08	18.7	20.76	

a, b, c* and *d*: fitted coefficients of the models; ***RSE*: residual standard error (MJ m-2) of nonlinear model fitting; *Rsmean*: mean daily solar radiation (MJ m-2). *N*: number of data used in calibration. *Models*- Ha: Hargreaves; Ch: Chen et al.; B-C: Bristow and Campbell; J-S: De Jong and Stewart. *Sites*- 1: Águas Vermelhas; 2: Chapada Gaúcha; 3: Espinosa; 4: Mocambinho; 5: Montalvânia; 6: Pirapora; 7: Rio Pardo de Minas; 8: Salinas; 9:São Romão.

The B-C model resulted in improved fit, with average *RSE* of 2.81 MJ m-2, and the Ha had the worst, with an average *RSE* of 3.22 MJ m-2. The Ch and the J-S models presented similar average *RSE* of about 2.96 MJ m-2. Despite the differences, all *RSE* values are similar, indicating that all models similarly describe the variation of R_s.

For the Ha model, the coefficient varied from 0.149 to 0.179 with 0.162 in average and close to 0.16 suggested by Allen et al. (1998) without calibration. The Ch model coefficients ranged from *a* = 0.302 to 0.404 and *b*= -0.389 to -0.186 with averaged values of *a* = 0.343 and *b* = -0.285, being close to the original calibration (*a* = 0.28 and *b* = -0.15).

For the B-C model, *a* ranged from 0.697 to 0.789 with an average of 0.724. Typical values for *a* is 0.7 (MEZA; VARAS, 2000). Liu et al. (2009) observed in China a trend of larger *a* coefficient in areas with higher altitude and lower rainfall (drier climate), where the values of *a* increased from 0.11 (lower altitudes) to 0.29 (higher altitudes). This sensitivity depends upon the local partitioning of solar energy that varies with altitude and season (LIU et al., 2009). In the present work, *b* ranged between 0.006 and 0.046 with an average of 0.020 and *c* ranged between 1.272 and 2.127 with an average of 1.879. In general, the coefficients remained within the range of calibrations obtained for other locations according researches of Liu and Scott (2001), Liu et al. (2009) and Almorox et al. (2011).

For the J-S model, low values for coefficients *c* and *d* indicate reduced influence of rainfall as compared to air temperature on estimation of R_s. Therefore, the inclusion of rainfall improves slightly the model, which is evident by the lower value of *RSE*. In part, this is explained by the fact that the number of days without rain was greater for all locations studied, making rainfall less important.

Model performance

The models that use air temperature data only (B-C, Ch and Ha) had a mean *R2* value close to 0.60 (Table 3). For most sites, the B-C model resulted in the highest *R2* (0.69) compared to the other models. There is no reference values for *R*2, but higher values indicate a more parsimonious model.

Table 3. Performance of models by *R2*, *RMSE*, *MBE* errors and the intercept (*a*) and slope (*b*) of the linear regression between observed and estimated daily solar radiation for the North of Minas Gerais State for 2009 or 2010.

Sites	Model	*Parameters* A	*Parameters* b	*R2*	*RMSE*	*MBE*
					-----(MJ m-2)-----	
	B-C	6.02	0.69	0.707	2.923	-0.193
1.Águas Vermelhas	Ch	6.81	0.64	0.695	2.982	0.178
N = 362	J-S	5.55	0.69	0.705	2.923	-0.108
R_{smean} = 18.55	Ha	8.32	0.56	0.663	3.200	0.196
	Ha-*fixed*	8.31	0.56	0.664	3.195	0.200
	B-C	5.20	0.74	0.712	2.707	-0.009
2.Chapada Gaúcha	Ch	6.60	0.66	0.641	3.016	-0.095
N = 361	J-S	6.32	0.67	0.687	2.835	-0.311
R_{smean} = 20.04	Ha	10.49	0.48	0.540	3.437	0.040
	Ha-*fixed*	10.47	0.48	0.541	3.419	0.024
	B-C	8.19	0.63	0.604	2.991	0.418
3.Espinosa	Ch	9.35	0.57	0.538	3.228	0.291
N = 355	J-S	8.55	0.60	0.631	2.878	0.187
R_{smean} = 21.14	Ha	10.58	0.51	0.498	3.353	0.200
	Ha-*fixed*	10.92	0.49	0.514	3.265	0.212
	B-C	6.78	0.69	0.677	2.754	0.265
4.Mocambinho	Ch	7.94	0.64	0.639	2.928	0.384
N = 362	J-S	8.73	0.61	0.631	2.969	0.418
R_{smean} = 21.04	Ha	10.83	0.50	0.566	3.231	0.397
	Ha-*fixed*	10.83	0.50	0.566	3.232	0.396
	B-C	7.84	0.64	0.582	3.069	0.089
5.Montalvânia	Ch	7.96	0.64	0.591	3.032	0.343
N = 362	J-S	9.30	0.58	0.564	3.122	0.251
R_{smean} = 21.71	Ha	10.27	0.53	0.551	3.161	0.142
	Ha-*fixed*	10.96	0.50	0.502	3.324	0.151
6. Pirapora	B-C	4.56	0.76	0.760	2.754	-0.398
N = 361	Ch	7.23	0.61	0.716	3.147	-0.789

R_{smean} = 20.49	J-S	8.30	0.57	0.679	3.302	-0.620
	Ha	8.97	0.52	0.678	3.391	-0.785
	Ha-*fixed*	8.63	0.51	0.689	3.631	-1.470
7.Rio Pardo de	B-C	5.93	0.67	0.684	3.157	-0.337
Minas	Ch	5.80	0.67	0.705	3.061	-0.371
N = 361	J-S	5.94	0.65	0.698	3.126	-0.526
R_{smean} = 18.90	Ha	8.20	0.55	0.671	3.325	-0.328
	Ha-*fixed*	8.37	0.56	0.670	3.281	0.045
	B-C	4.87	0.70	0.788	3.194	-0.767
8.Salinas	Ch	4.93	0.70	0.800	3.134	-0.762
N = 361	J-S	5.81	0.65	0.799	3.234	-0.755
R_{smean} = 18.88	Ha	7.57	0.57	0.807	3.408	-0.513
	Ha-*fixed*	8.11	0.61	0.807	3.317	0.791
	B-C	2.44	0.80	0.709	3.382	-1.627
9.São Romão	Ch	5.57	0.65	0.717	3.308	-1.609
N = 361	J-S	7.29	0.59	0.714	3.247	-1.271
R_{smean} = 20.78	Ha	8.67	0.52	0.702	3.440	-1.340
	Ha-*fixed*	8.69	0.52	0.701	3.421	-1.304

N: number of data evaluation set; R_{smean} : mean daily solar radiation observed (MJ m-2). *Models*- B-C: Bristow and Campbell; Ch: Chen et al.; J-S: De Jong and Stewart; Ha: Hargreaves.

Models with $R2$ higher than 0.60 showed a good quality of adjustment with researchers who used same models (YORUKOGLU, CELIK, 2006; ABRAHA, SAVAGE, 2008; ALMOROX et al., 2011). When using both rainfall and air temperature data (J-S), $R2$ was 0.61. This suggests that despite the inclusion of rainfall in the J-S model, it resulted in little improvement in $R2$. For *RMSE,* a better performance for all sites was obtained using the B-C model, with a mean value of 2.69 MJ m-2, followed by the models of Ch (2.76 MJ m-2), J-S (2.78 MJ m-2) and Ha (2.99 MJ m-2). The *RMSE* for each location and model followed the same sequence as for the *RSE* values from calibration, except for the São Romão station, where improved performance was obtained using the J-S model. Similar trends in *RMSE* and *RSE* is an indication of similar data distribution in calibration and performance data set. Generally, the values of the *RMSE* decrease as the $R2$ increase (YORUKOGLU, CELIK, 2006).

The results for *MBE* were similar for the various models ranging from -1.627 to 0.418 MJ m-2 for B-C model, -1.609 to 0.418 MJ m-2 for Ch model, -1.271 to 0.418 MJ m-2 for J-S model and -1.340 to 0.397 MJ m-2 d-1 for the Ha model. In general, there was an underestimation in R_s. The greater absolute *MBE* values for air temperature based models were found for São Romão and Salinas sites, probably due to lower air temperature range in validation data set compared to the calibration set. Many factors besides R_s could affect levels of maximum and minimum air temperature, especially on a daily basis, e.g. cloudiness, wind speed, atmospheric water vapor content, availability of soil water for evaporation, elevation, precipitation, aerosol, frontal weather systems and others (ALLEN, 1997). These factors confound the relationship used in air temperature based solar radiation models. Improvement in model performance was evident for increased elevation and days with clear sky events. Larger ΔT generally results in better predictive accuracy (Liu et al., 2009). Abraha and Savage (2008) found that the B-C model was improved with higher elevations than with lower ones. This could be due to reduced attenuation of R_s and therefore more heating of the air.

The intercept (a) and slope (b) of linear regression provide information about trends of models throughout the observed R_s. The B-C model had lower values of a (2.44-8.19) and b was closer to 1 (0.63-0.80) when compared with other models at all sites. Otherwise, Ha and Ha-*fixed* models had the highest values of a (7.57-10.96) and the lowest for b (0.48-0.61). High values for parameter a and lower for b can lead to an overestimate of lower values of R_s and an underestimate of higher values of R_s. In the north of Minas Gerais, most of rainfed crops are cultivated in the beginning of the rainy season. It coincides with longer period of cloudy days and hence a greater number of days with lower values of R_s. Therefore, Ha and Ha-*fixed* models may be inappropriate in crop yield and evapotranspiration simulation models because in cloudy days the observed R_s had lower values.

Results for the Ha-*fixed* model were very closed to the Ha model, confirming that it can be used without calibration. However, it showed poor performance. The Ha model is the best-known air temperature model due to its simplicity, as uses only one coefficient. However, this leads to less adjustment freedom. Borges et al. (2010), on the other hand, found that the Ha model had the best performance of three uncalibrated air temperature models (*R*2=0.68, *RMSE* of 4.76 MJ m^{-2}) in Cruz das Almas, Brazil, using data from the years of 2004 to 2006, also from an automatic meteorological station of INMET. However, they did not evaluate Bristow-Campbell model.

CONCLUSIONS

The accuracy of estimation via available meteorological data was acceptable and comparable with the accuracy of classical models.

The accuracy of R_s was only slightly improved by adding rainfall records as input variable. Therefore, in the region studied, the choice of simpler models, having as input the daily maximum and minimum air temperature would not imply large error in the estimates.

For the set of data used in the current study, the model based only in the number of the year was not acceptable. In this case, datasets with a large period of time could generate more satisfactory results, given the characteristics of this model.

For most sites, Bristow and Campbell model had the best estimate of R_s with a *RMSE* of 2.69 MJ m^{-2} and R^2= 0.69, with the possibility to calibrate with available temperature data, becoming a practical and reliable model.

Hargraves model should be avoid due to its lower performance compared to the other models applied.

RESUMO: A estimativa da radiação solar diária (R_s) fornece uma alternativa importante em situações que não pode ser medida por piranômetros convencionais. O estudo utilizou dados meteorológicos de nove cidades do Norte do estado de Minas Gerais, Brasil, durante o período de 2008 a 2010, com o objetivo de mensurar a precisão e aplicabilidade de modelos empíricos simples nas regiões onde a R_s não pode ser medida . Cinco modelos foram avaliados para estimar R_s com base nos dados meteorológicos disponíveis. As equações foram previamente calibradas para cada município estudado. Modelos meteorológicos empíricos que estimam a radiação solar diária são ferramentas adequadas desde que os parâmetros sejam calibrados para os diferentes locais a serem utilizados. Estes modelos têm a vantagem de utilizar dados meteorológicos, que estão comumente disponíveis. Todos os modelos foram considerados adequados para o uso, considerando-se a maior disponibilidade de dados de temperatura do ar e aplicação em estudos que não exigem grande precisão na estimativa da R_s. A precisão da R_s apenas foi melhorada pela adição de registros de precipitação como variável de entrada. Assim, na região estudada, a escolha de um modelo mais simples, tendo como entrada a temperatura mínima e máxima do ar diária, não implica um grande erro na estimativa. Para a maioria das regiões, o modelo de Bristow e Campbell teve a melhor estimativa da R_s com um *RMSE* de 2.69 MJ m^{-2} e R^2= 0.69, e a possibilidade de calibração com os dados de temperatura disponíveis, tornando-se um modelo prático e confiável. O modelo de Hargraves deve ser evitado devido seu pior desempenho comparado aos outros modelos propostos.

PALAVRAS-CHAVE: Modelos meteorológicos. Temperatura do ar. Comparação de modelos. Centro do Brasil.

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