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Original Article

Comparison between global solar radiation models in Aquidauana, "Alto Pantanal" region, Brazil

Gabriel Queiroz de Oliveira[1]*, Guilherme Augusto Biscaro[1], Adriano da Silva Lopes[2], Leandro Henrique Jung[1], Francielli Schwerz[1]

[1]Universidade Federal da Grande Dourados, Dourados, MS, Brasil
[2]Universidade Estadual de Mato Grosso do Sul, Aquidauana, MS, Brasil
*Corresponding author, e-mail: gabrielqo@hotmail.com

Abstract

Solar radiation is a meteorological component of great importance to soil-plant-atmosphere processes, and the majority of weather stations do not register this component since they do not have the equipment for its quantification. The objective of this study was to evaluate the efficiency of models to estimate solar radiation for the annual, rainy and dry periods in Aquidauana "Alto Pantanal" region of Mato Grosso do Sul, Brazil. This study was conducted using meteorological data obtained from January 2008 to December 2011. The automatic meteorological station was located in Aquidauana, and belongs to the network of the Instituto Nacional de Meteorologia (INMET). The data collected included maximum and minimum temperatures, and solar radiation. The Annandale, Bristow-Campbell, Hargreaves-Samani and Weiss empirical models were evaluated, and all were compared with the solar radiation value measured by the meteorological station. In Aquidauana, the Alto Pantanal region of Mato Grosso do Sul, regardless of the time of year, the Bristow-Campbell model is recommended to estimate solar radiation.

Keywords: Bristow-Campbell, meteorological stations, empirical models, air temperature

Comparação entre modelos de radiação solar global em Aquidauana, região do Alto Pantanal Sul Mato-Grossense

Resumo

A radiação solar é um componente meteorológico de grande importância dentro dos processos da relação solo-planta-atmosfera, sendo que a maioria das estações meteorológicas não registra seus valores por não dispor de equipamentos para quantificá-la, tendo que recorrer a modelos empíricos para sua estimativa. O objetivo deste trabalho foi avaliar a eficiência de quatro modelos de estimativa de radiação solar, em período anual, chuvoso e seco, em Aquidauana, Alto Pantanal Sul Mato-Grossense. O trabalho foi realizado utilizando dados meteorológicos obtidos entre janeiro de 2008 e dezembro de 2011, na estação automática localizada em Aquidauana, pertencente à rede de estações meteorológicas do Instituto Nacional de Meteorologia (INMET). Os dados coletados foram temperatura máxima e mínima e radiação solar. Os modelos empíricos avaliados foram o de Annandale, Bristow-Campbell, Hargreaves-Samani e Weiss, no qual todos foram comparados com a radiação solar obtida pela estação meteorológica. Na região de Aquidauana, Alto Pantanal Sul-Mato-Grossense, independente da época do ano, recomenda-se para a estimativa da radiação solar, o modelo de Bristow-Campbell.

Palavras-chave: Bristow-Campbell, estações meteorológicas, modelos empíricos, temperatura do ar

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Introduction

Solar radiation is defined as all electromagnetic radiation that reaches the Earth from the Sun, being extremely important for life since it is responsible for most biological and physiological processes of plants, as well as directly responsible to provide energy for soil-plant-atmosphere processes (Querino et al., 2006). Although temperature and photoperiod are the main factors that influence plant development in terms of quantity and quality, solar radiation is essential for the development and growth of plants in agriculture, as observed in photomorphogenic and photosynthetic processes (Kunz et al., 2007).

Solar radiation is measured by instruments such as radiometers, bimetallic actinographs and more recently, pyranometers, which is most used in Brazil (Dornelas et al., 2006). However, these instruments are quite expensive to acquire.

Given the ease of obtaining some meteorological elements and a viable alternative to overcome the difficulties in measuring solar radiation, some researchers have developed empirical models that use air temperature to estimate solar radiation, such as the Hargreaves and Bristow-Campbell models (Silva et al., 2012).

Solar radiation on a flat horizontal surface is only a fraction of the solar radiation at the top of the atmosphere (Ra). This fraction of radiation reaching the earth's surface depends on local weather conditions, which characterize the atmospheric transmittance for the short-wave radiation (Borges et al., 2010).

The climate of the Pantanal region is classified as being between sub-humid and semi-arid with most rainfall occurring in the period referred to as the rainy season, from November to March. The dry season occurs during the other months (Oliveira et al., 2006). There are few climatic studies in regions of the Alto Pantanal, especially for the solar radiation; and this region is an important Brazilian ecosystem with great potential for agricultural activities, particularly when incorporating irrigation. Therefore, estimation of solar radiation in this particular region has direct applicability on the rational planning of water use, since it is closely related to the evapotranspiration process.

The objective of this study was to evaluate the effect of three time scales (all data, rainy and dry season) on accuracy of solar radiation based on temperature models for Aquidauana, "Alto Pantanal" region, Brazil.

Material and Methods

The study was conducted using meteorological data obtained during the period of January 1, 2008 to December 31, 2011 at an automatic weather station of the National Institute of Meteorology (INMET), located in Aquidauana-MS, Brazil (20° 20' S, 55° 48' W and altitude of 155 m). The Alto Pantanal regional climate is classified according to Köppen as Aw, defined as sub-tropical hot and humid, with rainy summer and dry winter, and annual rainfall of 1200 mm. The rainy season extends from October to March and the dry season from April and September, with the lowest rainfall occurring in July and August. Maximum and minimum air temperatures and solar radiation were collected daily. The models presented below are those used to calculate the estimated solar radiation (Rs).

Annandale model (AN)

Solar radiation estimated by the model of Annandale et al. (2002) (Eq. 1) is a modification of Hargreaves and Samani model, which was corrected for altitude.

$$Rs_{(AN)} = 0.16\left(1+2.7\times10^{-5}\,ALT\right)\left(T_x - T_n\right)^{0.5} Ra \quad (1)$$

Where: $Rs_{(AN)}$ – solar radiation predicted by the AN model, MJ m^{-2} day^{-1}; ALT – average altitude above sea level, m; Tx – maximum air temperature, °C; Tn –minimum air temperature air °C; Ra - solar radiation at the top of the atmosphere, MJ m^{-2} day^{-1}, estimated according to Eq. 2 (Allen et al., 1998):

$$Ra = \frac{24.(60)}{\pi} G_{sc} d_r [W_s \, sen(\varphi)\, sen(\delta) + \cos(\varphi)\cos(\delta)\, sen(W_s)]$$

Where: Gsc – solar constant (0.082 MJ m^{-2} day^{-1}); dr – square of the distance between the sun and Earth, radian, estimated according to Eq. 3. Ws – hour angle at sunset, radian (Eq. 4); δ – solar declination, radian (Eq. 5), φ – local latitude, radians.

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \quad (3)$$

Where: J – Julian day of each year. The following are the equations for calculating Ws and δ (Eq. 4 and 5).

$$W_s = \arccos\left[-\tan(\varphi)\tan(\delta)\right] \quad (4)$$

$$\delta = 0.409 \operatorname{sen}\left(\frac{2\pi}{365} J - 1.39\right) \quad (5)$$

Bristow-Campbell model (BC)

Bristow & Campbell (1984) proposed one equation (6) to estimate Rs, in which the air temperature is the main input variable, in an exponential function of temperature range (Δt).

$$Rs_{(BC)} = 0.7\left[1 - \exp\left(-0.007(\Delta t)^{2.4}\right)\right]Ra \quad (6)$$

Where: $Rs_{(BC)}$ – solar radiation estimated by the BC model, MJ m^{-2} day^{-1}. ΔT is defined in Eq. 7.

$$\Delta T = T_{xi} - \left(\frac{T_{ni} - T_{n(i+1)}}{2}\right) \quad (7)$$

Where: T_{xi} – maximum air temperature for the present day, °C, T_n – minimum air temperature, where i is a subscript indicating the current day and i +1 indicative of the next day.

Hargreaves-Samani model (HS)

Hargreaves & Samani (1982) were the first to propose a predictive model of incident solar radiation from the air temperature, using the atmospheric transmittance from Eq. 8.

$$Rs_{(HS)} = 0{,}16(T_x - T_n)^{0.5} Ra \quad (8)$$

Where: $Rs_{(HS)}$ – solar radiation estimated by the HS model, MJ m^{-2} day^{-1}, and;

Weiss model (WS)

The model of Weiss et al. (2001) is applied at various agricultural regions of the United States, identified in the present study as the Weiss model (WS). This model uses the air temperature range (ΔT). It is noteworthy that the WS is a modified version of the Bristow & Campbell (1984) method, shown in Eq. 9. Goodin et al. (1999) state that modification of BC model provides reasonably accurate irradiance estimates at locations that lack radiation sensors, and that the model can be successfully used in locations off-site calibration.

$$Rs_{(WS)} = 0.75\left[1 - \exp\left(-0.226\frac{\Delta T^2}{Ra}\right)\right]Ra \quad (9)$$

Where: $Rs_{(WS)}$ – solar radiation estimated by the WS model, MJ m^{-2} day^{-1}.

Indicators for evaluation of the solar radiation models

The empirical models for estimating solar radiation were compared with the observed solar radiation for the annual, rainy and dry periods. To evaluate the efficiency of each model to estimate solar radiation, the coefficient of determination (r^2, Eq. 10) and the concordance index "d" of Willmott (1981) were utilized (Eq. 11).

$$r^2 = 1 - \left[\frac{\sum(Pi - Oi)^2}{\sum(Oi - O)^2}\right] \quad (10)$$

$$d = 1 - \left[\frac{\sum(Pi - Oi)^2}{\sum(|Pi - O| + |Oi - O|)^2}\right] \quad (11)$$

Also we used the root mean square error indicator (RMSE) (Eq. 12). According to Legates & McCabe Jr. (1999), is suitable to quantify the error in the same units of variable, in which case the incident solar radiation expressed in MJ m^{-2} day^{-1}.

$$RMSE = \left[\frac{\sum(Pi - Oi)^2}{N}\right]^{0,5} \quad (12)$$

Where: Pi – values estimated by the models; Oi - observed values, O - average of the observed values and, N - number of observations.

Evaluation criteria for indication of the best solar radiation models were in accordance with the dimensionless indicators of concordance between the estimated and observed values, where the best model presented the highest values of r^2 and d. For good accuracy of the models, the values of r^2 and d should be near 1. In all models evaluated the original coefficients proposed were maintained, i.e. local calibration of the models was not the objective of this study.

However, adoption of only the r^2 as a criterion for definition of model quality is not appropriate, since this model does not establish the type and magnitude of the differences between a standard value and values predicted by estimative models or other measurement mechanisms different from the standard (Barros et al., 2009). The "d" value expresses a measure of model accuracy and is considered a reliable indicator, which quantifies the dispersion of points surrounding the regression line and the 1:1 line, where y = x, in the case of perfection.

Results and Discussion

Figure 1 presents the average monthly radiation values at the top of the atmosphere, as well as the observed and predicted solar radiation. As expected, the highest average observed solar radiation was found during October, November, December, January, February and March when the southern hemisphere receives greatest amount of energy from the Sun. The lowest were observed in May to August. On average, solar radiation in December was 45% higher than in June (Figure 1).

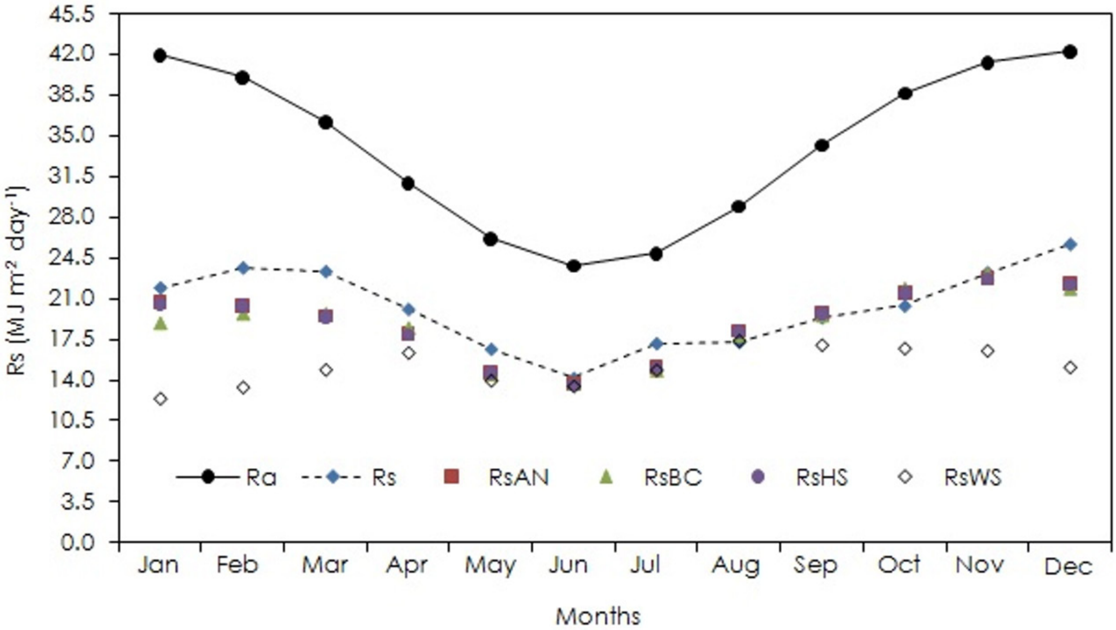

Figure 1. Average monthly solar radiation for the years 2008 and 2011 in Aquidauna, "Alto Pantanal" region, Brazil. Ra = radiation at the top of the atmosphere; Rs = solar radiation observed and estimated by models (RsAN, RsBC, RsHS and RsWS = solar radiation estimated by the Annandale, Bristow-Campbell, Hargreaves-Samani and Weiss models, respectively).

During the fall, which coincides with the early dry season, the photoperiod decreases and the zenith angle of solar rays gradually increases, indicating a lower incidence of solar surface as approaching the winter solstice (Heldwein et al., 2012).

The estimated solar radiation proposed by Annandale (AN) presented its highest values in the months of November and December (22.753 and 22.291 MJ m^{-2} day^{-1}, respectively). Similar behavior of solar radiation was observed in the Bristow-Campbell (BC) and Hargreaves-Samani (HS) models. The lowest values of solar radiation for the AN, BC and HS models were observed in June, with values on the order of 13.660, 13.716 and 13.603 MJ m^{-2} day^{-1}, respectively (Figure1).

The relationship between observed and predicted solar radiation values in Figures 2, 3 and 4.

Regression analyses presented coefficients of determination (r^2) of 0.507, 0.491, 0.491 and 0.257 for the BC, AN, HS and WS models, respectively. During the rainy season, r^2 values were 0.410, 0.373, 0.373 and 0.335 for the BC, AN, HS and WS models, respectively, and in the dry season were 0.474, 0.420, 0.420 and 0.386 for the BC, AN, HS and WS models, respectively. It is noted that the AN and HS models obtained the same r^2 value in all periods evaluated (Figures 2A, 2C; 3A, 3C; 4A 4C). Both models are based on the difference in square root between the maximum and minimum temperature, with an adjustment coefficient of 0.16, but varying only with respect to the altitude correction , which in this case is almost negligible (155 m).

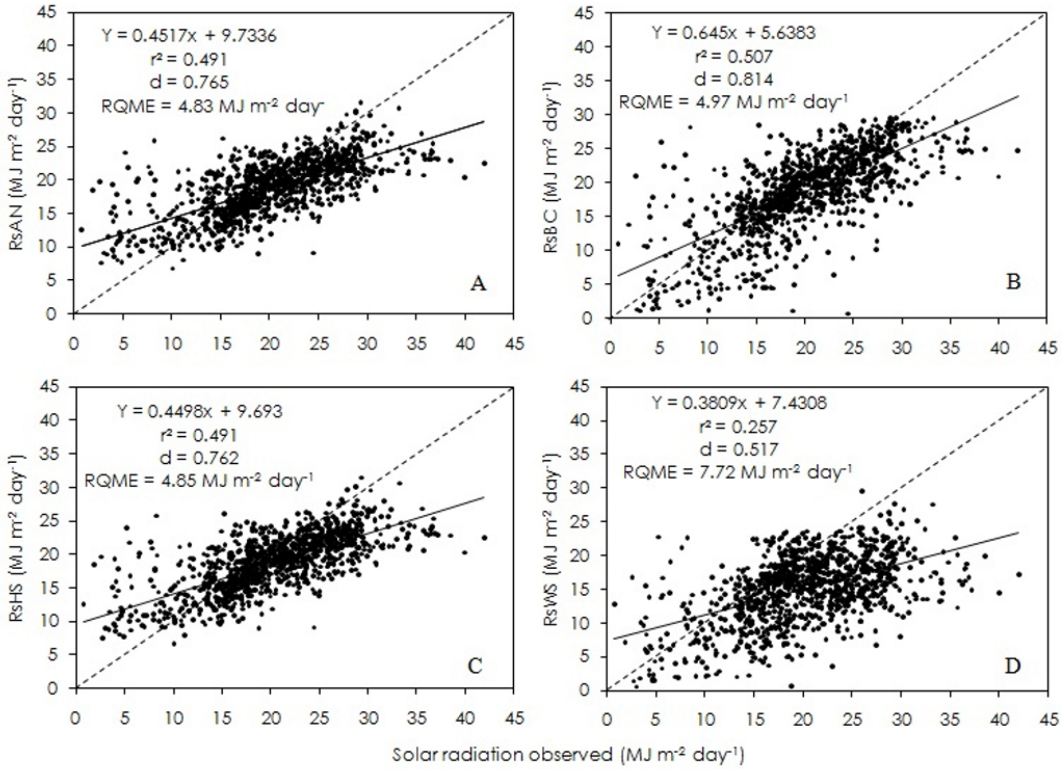

Figure 2. Relationship between the observed daily solar radiation (Rs) and solar radiation estimated by the Annadale (A), Bristow-Campbell (B), Hargreaves-Samani (C) and Weiss (D) models for annual periods in Aquidauana "Alto Pantanal", Mato Grosso do Sul, Brazil. The dashed line indicates the 1:1 line. N = 1449.

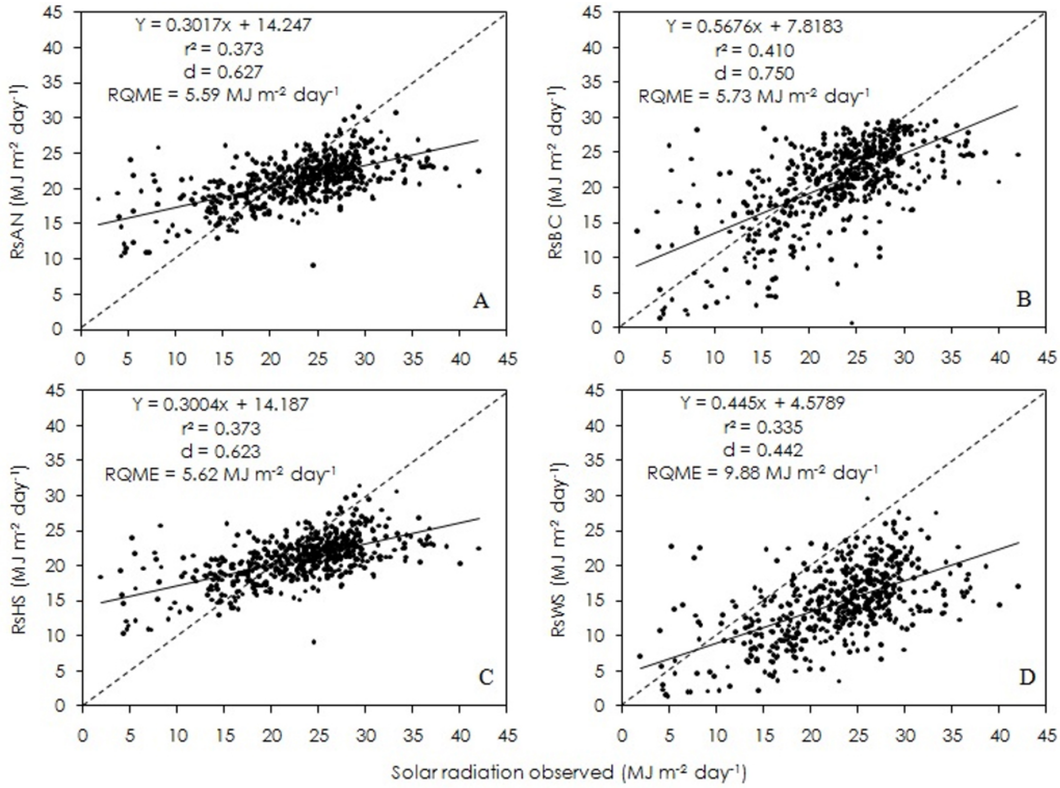

Figure 3. Relationship between the observed and estimated solar radiation by the Annadale (A), Bristow-Campbell (B), Hargreaves-Samani (C) and Weiss (D) models for the rainy period in Aquidauana "Alto Pantanal", Mato Grosso do Sul, Brazil. The dashed line indicates the 1:1 line. N = 719.

Borges et al. (2010), evaluating models of solar radiation in Cruz das Almas, BA, found that the HS and WS models presented r^2 values of 0.668 and 0.716, respectively, and both models tended to underestimate solar radiation.

The highest values of the agreement index (d) for the annual period were found using the BC model, followed by the AN and HS models with very similar values, while the lowest accuracy was obtained with the WS model (Figure 2). The BC model presented the highest values of "d" in all periods, with 0.814 for the annual period, 0.750 for the rainy period and 0.807 for the dry period. In this case, given the variables analyzed, it can be stated that the BC model best fits to the observed solar radiation and is considered the best model to estimate solar radiation in the Alto Pantanal of Mato Grosso do Sul. Silva et al. (2012) concluded in their study for Northwest region of Minas Gerais that the BC model accurately estimated solar radiation, presenting r^2 and "d" values of 0.612 and 0.878, respectively, and that the AN and HS models presented the same statistical indices.

In the climatic conditions for Barbalha-CE, Brazil, use of the model proposed by HS for estimating daily solar radiation is inviable, requiring direct measurement of solar radiation (Lêdo et al., 2012).

The AN and HS models presented good results for the annual and dry periods with "d" values greater than 75%, permitting their utilization for estimating solar radiation during these times.

The WS model showed to be inadequate for estimating solar radiation at the Alto Pantanal region of Mato Grosso do Sul both for the annual and rainy periods, since very low evaluation coefficients were obtained for application at this location. Similar performance was observed by Ball et al. (2004) and Borges et al. (2010) when using the WS model to estimate solar radiation, emphasizing the limitations for transferability of the model to other regions without proper local calibration.

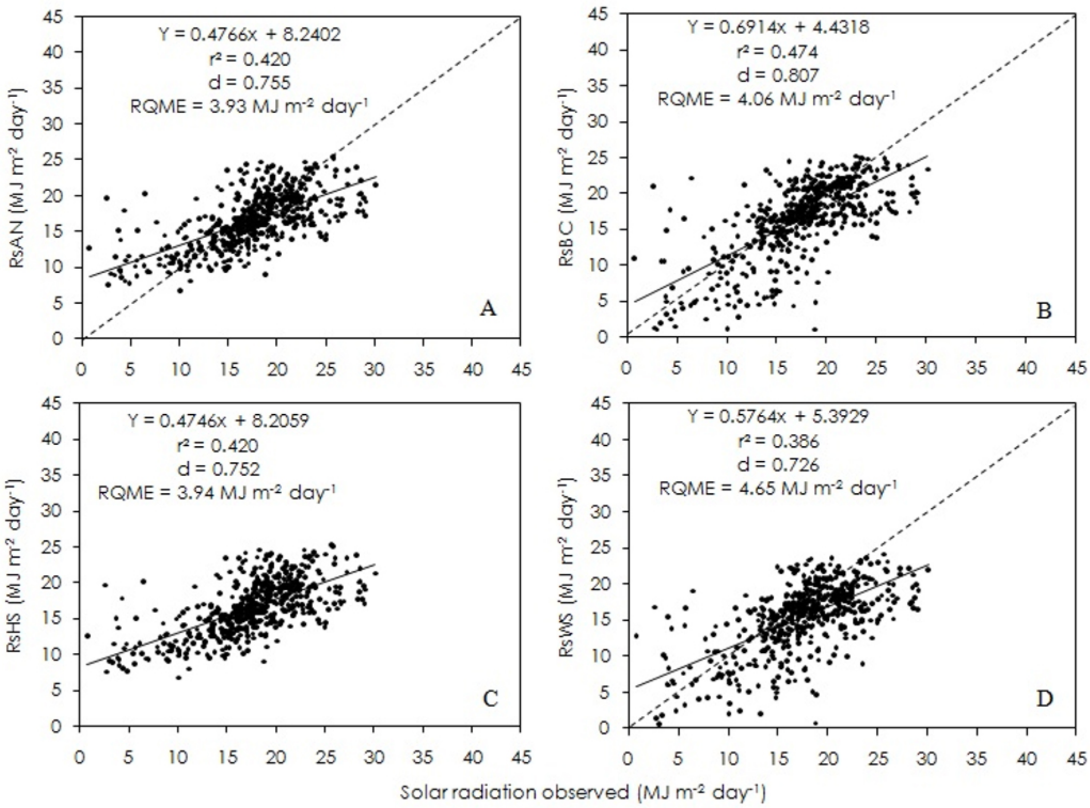

Figure 4. Relationship between daily observed solar radiation (Rs) and that estimated by the Annadale (A), Bristow-Campbell (B), Hargreaves-Samani (C) and Weiss (D) models for the dry period in Aquidauana "Alto Pantanal", Mato Grosso do Sul, Brazil. The dashed line indicates the 1:1 line. N = 730.

Conclusions

According to the data observed in Aquidauana, Brazil, in the absence of solar radiation data at any time of year, the method to estimate solar radiation Bristow-Campbell, is the best method. The method of Annandale and Hargreaves-Samani is indicated to estimate solar radiation, during the rainy and dry period.

All solar radiation models studied present a tendendy for underestimation when compared with the observed radiation.

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