Energy 71 (2014) 388–398

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

On modeling global solar irradiation using air temperature for Alagoas State, Northeastern Brazil

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ARTICLE INFO

Article history:
Received 22 June 2013
Received in revised form
19 November 2013
Accepted 23 April 2014
Available online 5 June 2014

Keywords:
Solar radiation
Empirical models
Bristow & Campbell
Hargreaves & Samani

ABSTRACT

The present study assesses the performance of nine empirical models: the models of Bristow & Campbell and Hargreaves & Samani (together with their modified versions) in estimating the daily and monthly solar irradiation using just extraterrestrial solar irradiation and air temperature extremes (maximum and minimum) as input data. Two schemes to calculate the air temperature amplitudes (ΔT_1 and ΔT_2) were used. The data used in this study cover the period from 2007 to 2009 and were collected at eight solarimetric stations in Alagoas State (Northeastern Brazil); three are located in the interior, two in the hinterlands and three in the humid/coastal zones. Statistical parameters were used to evaluate the model performance. The estimates obtained with the ΔT_1 scheme are better than those using the ΔT_2 scheme for the interior (1.10%) and hinterlands (2.50%). The daily (0.160–0.201) and monthly (0.158–0.199) values of the coefficients of the original Hargreaves and Samani model did not show significant differences among them; this was not the case of Bristow and Campbell model. Have a special from the coastline (thermal amplitude, humidity and cloudiness) and altitude (bulk thermal capacity and optical depth of the atmosphere). On the daily basis, the original model of Hargreaves & Samani yields better estimates than those obtained with the Bristow & Campbell model: 2.30% (interior) and 5.20% (hinterlands). The latter had a better performance mainly for the sites along the humid/coastal zone (10.20%).

1. Introduction

The global solar irradiance (R_g), although considered an important variable in many areas of human activities (e.g. agriculture, climatology and renewable energy), is not measured with an adequate space and time resolution due to the maintenance cost and the frequent calibration procedures of the instruments [1,33]. Indeed, the number of weather stations that measure R_g on an operational basis is quite small when compared to that of meteorological stations. For instance, among the 3731 surface stations in Spain only 200 measure the sunlight duration and from these, mere 56 include measurements of R_g [2]. Only 69 surface meteorological stations in India out of a total of 194 monitor the global solar irradiance [34]. Measurements of R_g in Brazil, even with the present network consisting of 523 automatic stations operated by the National Institute of Meteorology, are insufficient due to the continental size of the country. Therefore the number of empirical models that have been developed to overcome the scarcity of R_g measurements is not surprising. These models estimate global solar irradiation (H_g) – the integral of R_g – on an hourly [3], daily [4], monthly [5] and annual [6] bases quite satisfactory. The most sophisticated models use several types of meteorological variables (e.g. relative humidity, precipitation, water vapor pressure and air temperature) as input data. Most empirical models are based on Ångström [7] who found a linear relation between the daily averaged H_g (normalized by the extraterrestrial solar irradiation, H_o) and the sunlight duration (ratio of the sunshine period and the daytime length) [35].

Bristow & Campbell [8], while searching for an empirical relation between air temperature and global solar irradiation, suggested a

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http://dx.doi.org/10.1016/j.energy.2014.04.116
0360-5442/

relation between H_g/H_o and the maximum and minimum air temperature differences for three localities in the USA. This model has since been modified by many authors. Meza & Varas [9] adjusted the model for different locations in Chile by keeping the coefficients β_1 (=0.75) and β_3 (=2.0) constant, while β_2 was free to change as part of the model calibration. Donatelli & Campbell [10] modified the original model of Bristow & Campbell by adding the monthly mean of the thermal amplitude (ΔT_m). Weiss et al. [11] included H_o, but kept β_1 (=0.75) and β_3 (=2.0) fixed, just as done by Meza & Varas, with β_2 playing the role of a free parameter. Abraha & Savage [12] adjusted the same model by keeping the coefficients β_1(=0.75) and β_3 (=2.0) constant and inserting the monthly mean thermal amplitude (ΔT_m) into the exponential; their coefficient β_2 is determined by calibration procedures. Assuming that the difference between the daily maximum and minimum air temperatures gives general information on the cloudiness, Hargreaves & Samani [13] proposed to estimate H_g as a function of H_o and the air temperature difference. Annandale et al. [14] introduced the altitude factor for nine sites in North America in a multiplicative form following Allen's [15] suggestion. Hargreaves et al. [16] modified the Hargreaves & Samani model aiming to improve its performance by keeping two coefficients (β_1 and β_2) in an additive) and multiplicative forms. Hunt et al. [17] proposed a modification in the model of Hargreaves & Samani by inserting the coefficient β_2 additively.

The main objectives of this work are: 1 – to assess the performance of two methods using thermal amplitudes in their adjustment, 2 – to determine the coefficients of their nine empirical models (using air temperature as input data) for H_g at eight sites in Alagoas State, on a daily and monthly bases and 3 - to assess the performance of each model.

2. Sites and measurements

2.1. Sites and data

The study uses meteorological data collected at eight automatic stations located in different climate regions within the Alagoas State, Northeastern Brazil: a) interior (Água Branca, Pão de Açúcar and Santana do Ipanema), b) hinterlands (Arapiraca and Palmeira dos Índios) and c) humid/coastal zones (Maceió, Coruripe and São José da Laje). Table 1 and Fig. 1 show their geographical positions together with the average annual precipitation and temperature.

The H_g measurements were made with a black and white Eppley pyranometer [measurement band: 285–2800 nm and cosine response: ±2.0% ($0° < \Theta_z < 70°$)], where, Θ_z is the zenith angle. The maximum and minimum air temperatures were measured using a HMP45C Väissällä Inc. sensor [measurement band: −40 °C to +60 °C (accuracy: ±0.20 °C); 20 °C to a 40 °C (accuracy: ±0.50 °C)]. The sensors used in the field experiments had been purchased just before the beginning of the measurements (September, 2007) and were frequently calibrated using the Eppley Precision Spectral Pyranometer throughout the experiment duration. The end of the measurements stage was December, 2009. The radiometers were installed on a 10-m high tower, with no obstacles around and were connected to a data acquisition system (CR100, Campbell Scientific, Utah, USA), programmed to make measurements every five seconds and store the averages every minute.

Table 1
Main characteristics of the observation sites – Lat. = southern latitude in degrees, Long. = western longitudes in degrees, Alt. = altitude in meters, $\overline{P}$ = annual average precipitation in mm and $\overline{T}$ = annual average air temperature in (°C).

ID	Site	Lat. (S)	Long. (W)	Alt. (m)	$\overline{P}$ (mm)	$\overline{T}$ (°C)
1	Água Branca	9.25	37.93	593.0	1051.4	23.7
2	Pão de Açúcar	9.74	37.43	46.0	571.87	27.6
3	Santana do Ipanema	9.37	37.23	279.4	754.7	26.5
4	Palmeira dos Índios	9.40	36.65	328.0	869.6	25.3
5	Arapiraca	9.70	36.60	239.0	1055.2	24.3
6	Maceió	9.47	35.83	127.0	1817.6	25.4
7	Coruripe	10.02	36.27	108.7	1563.1	26.1
8	São José da Laje	8.97	36.06	344.7	1248.9	24.8

2.2. Definitions

According to Paulescu et al. [18] the empirical models used to estimate H_g with meteorological data, may be classified into two distinct classes. The first class consists of models that make use of air temperature and other meteorological variables (precipitation and relative humidity e.g. Munner et al. [32]); models of the second class use only air temperature as input data. All the models used in this study belong to the second class and are listed in Table 2, similar to Liu X et al. [19].

2.3. Data analysis

The thermal amplitude, ΔT, is defined as the difference between the largest and smallest values in the temperature series, and is given by two different methods. They express the air temperature interval, ΔT_1 [13] and ΔT_2 [8] using, respectively,

$$\Delta T_1(i) = T_{\max}(i) - T_{\min}(i) \quad (1)$$

$$\Delta T_2(i) = T_{\max}(i) - \frac{[T_{\min}(i) + T_{\min}(i+1)]}{2} \quad (2)$$

where, ΔT_1 (i) and ΔT_2 (i) are the diurnal air temperature variations for the i-th day; $T_{\max}$ (i) is the maximum air temperature for the i-th day and $T_{\min}$ (i) and $T_{\min}$ (i+1) are the minimum air temperatures for the i-th and the following day, respectively. The models were validated using both temperature schemes. H_o was calculated as a function of the local latitude (φ), solar declination (δ), day (d_n), the solar constant (S_o = 1367 W m^{-2}) and solar hourly angle (ϖ) [20]. The models were calibrated using data collected during 2007 and 2008; the data set obtained in 2009 was used only to validate them, by comparing observations and model outputs.

The models were analyzed on a daily and monthly base using two quality control criteria to guarantee data reliability. The filtering used by Ceballos et al. [21] implies: a) the daily averaged irradiation must fall within the interval (2.59 MJ m^{-2}, 34.56 MJ m^{-2}) and b) the difference between the observed and estimated values in the day must, in absolute value, be less than 8.64 MJ m^{-2}. Additionally, it was imposed that the number of pairs of observed and estimated values should not be less than 15 in the month. These criteria eliminated less than 1% of the original data set used in this study. To assess the model performance in terms of H_g, the *MBE* (mean bias error) [22], *RMSE* (root mean square error) [23], correlation coefficients (r) and t-test [23] were used. Some of them are given below:

$$\text{MBE} = \frac{\sum_{i=1}^{N}(P_i - O_i)}{N} \quad (3)$$

$$\text{RMSE} = \left[\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}\right]^{\frac{1}{2}} \quad (4)$$

where P_i and O_i are the estimated and observed irradiation, respectively. N is the number of observations. Positive MBE values

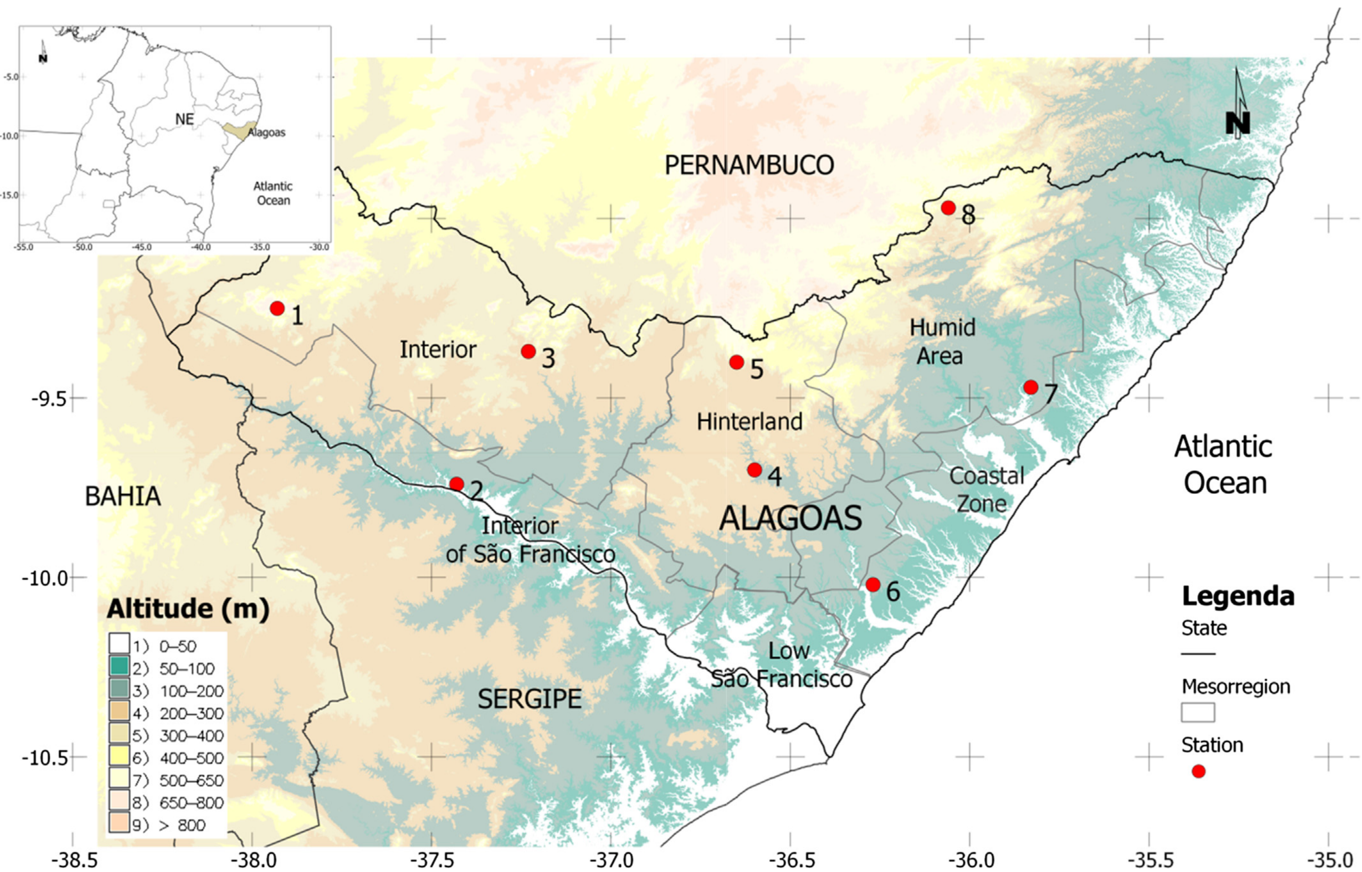

Fig. 1. Location of the solarimetric stations in Alagoas States, Northeastern Brazil.

indicate an overestimate and give long term information on the model performance, associated with systematic errors. The less the absolute value of MBE, the better will be the performance of the tested. RMSE, a non-negative number, gives a short term measure of the spreading of the estimates with respect to the observed data, being always expressed in the same units used in the original data and is associated with random errors. *T*-test allows model inter-comparison, indicating whether the estimates are or not significant.

3. Results and discussions

3.1. Coefficients for the daily global solar irradiation (H_g^d)

The values of the daily coefficients (Table 3) for the nine models and the eight selected sites of Alagoas, showed little difference (overall average: 3.7%), regarding the use of ΔT_1 or ΔT_2 in agreement with Liu X et al. [19], although the ΔT_1 scheme may yield a better precision, in particular for high altitudes. The reason for this lack of sensitivity is, probably, the absence of large scale thermal advection within the Tropics, as pointed out by Ref. Bristow & Campbell [8]. Chen et al. [24] noticed that model 1 gives better estimates in tropical rather than in extratropical latitudes, where maximum and minimum temperatures are largely determined by temperature advection. However, the values of the coefficients are quite different from those found by Ref. Liu X et al. [19] for the Haerbin province in China, a fact that reinforces the need of calibration with local data. Coefficient β_2 of models 1 and 3 did not exhibit any clear pattern for the different regions of this study, but the other two coefficients (β_1 and β_3) showed a linear dependence with respect to latitude and longitude (Fig. 2).

Table 2
Models used in this work.

Model identification number	Model	Coefficients	Authors
1	$H_g/H_o = \beta_1[1-\exp(-\beta_2\Delta T^{\beta_3})]$	β_1, β_2 and β_3	[8]
2	$H_g/H_o = 0.75[1-\exp(-\beta_2\Delta T^2)]$	β_2	[9]
3	$H_g/H_o = \beta_1[1-\exp(-\beta_2\Delta T^{\beta_3}/\Delta T_m)]$	β_1, β_2 and β_3	[10]
4	$H_g/H_o = 0.75[1-\exp(-\beta_2\Delta T^2/H_0^g)]$	β_2	[11]
5	$H_g/H_o = 0.75[1-\exp(-\beta_2\Delta T^2/\Delta T_m)]$	β_2	[12]
6	$H_g/H_o = \beta_1(\Delta T)^{\frac{1}{2}}$	β_1	[13]
7	$H_g/H_o = \beta_1(1+2.7\times10^{-5}\times \text{Altitude})(\Delta T)^{\frac{1}{2}}$	β_1	[14]
8	$H_g/H_o = \left(\beta_1(\Delta T)^{\frac{1}{2}}+\beta_2\right)$	β_1 and β_2	[16]
9	$H_g/H_o = \beta_1(\Delta T)^{\frac{1}{2}}+\beta_2/H_o$	β_1 and β_2	[17]

ΔT = thermal amplitude (°C); ΔT_m = monthly average of ΔT (°C), H_g = daily global solar irradiation (MJ m^{-2}) and H_o = daily global solar irradiation at the top of the atmosphere (MJ m^{-2}).

Table 3
Daily coefficients of the models, using ΔT_1 (in models 6, 7, 8 and 9) and ΔT_2 (in models 1, 2, 3, 4 and 5).

Site	Água Branca			Pão de Açúcar		
Model/coeff.	β_1	β_2	β_3	β_1	β_2	β_3
1	0.887*	0.078*	1.164*	0.844*	0.091*	1.207*
2	–	0.019*	–	–	0.018*	–
3	0.887*	0.719*	1.164*	0.844*	0.949*	1.207*
4	–	0.635*	–	–	0.603*	–
5	–	0.173*	–	–	0.186*	–
6	0.187*	–	–	0.191*	–	–
7	0.184*	–	–	0.191*	–	–
8	0.248*	−0.188*	–	0.223*	−0.103*	–
9	0.218*	−3.371*	–	0.199*	−0.899*	–
Site	Santana do Ipanema			Palmeira dos Índios		
Model/coeff.	β_1	β_2	β_3	β_1	β_2	β_3
1	0.838*	0.080*	1.096*	0.604*	0.085*	1.861*
2	–	0.012*	–	–	0.021*	–
3	0.838*	0.954*	1.096*	0.604*	0.700*	1.861*
4	–	0.405*	–	–	0.613*	–
5	–	0.145*	–	–	0.185*	–
6	0.168*	–	–	0.186*	–	–
7	0.167*	–	–	0.184*	–	–
8	0.196*	−0.098*	–	0.187*	−0.003*	–
9	0.176*	−0.936*	–	0.174*	−1.257*	–
Site	Arapiraca			Maceió		
Model/coeff.	β_1	β_2	β_3	β_1	β_2	β_3
1	0.762*	0.103*	1.248*	0.707*	0.033*	2.113*
2	–	0.018*	–	–	0.024*	–
3	0.762*	0.906*	1.248*	0.707*	0.259*	2.113*
4	–	0.632*	–	–	0.811*	–
5	–	0.162*	–	–	0.185*	–
6	0.185*	–	–	0.201*	–	–
7	0.184*	–	–	0.200*	–	–
8	0.222*	−0.111*	–	0.307*	−0.300*	–
9	0.199*	−1.421*	–	0.255*	−5.302*	–
Site	Coruripe			São José da Laje		
Model/coeff.	β_1	β_2	β_3	β_1	β_2	β_3
1	0.580*	0.018**	2.517*	0.771*	0.082*	1.171*
2	–	0.018*	–	–	0.012*	–
3	0.580*	0.163**	2.517*	0.771*	0.810*	1.171*
4	–	0.611*	–	–	0.420*	–
5	–	0.162*	–	–	0.119*	–
6	0.178*	–	–	0.160*	–	–
7	0.178*	–	–	0.159*	–	–
8	0.140*	−0.116*	–	0.206*	−0.147*	–
9	0.148*	−3.144*	–	0.180*	−2.214*	–

*Significant to 95% confidence interval. **Non significant.

The determination coefficient (R^2) was 0.61 for the multiple linear regression model with an adjustment between β_1 and β_3 (dependent variables) and the geographic coordinates (independent variables). This indicates that the latitudinal and longitudinal variation explain most of the variability of these coefficients. The coefficient β_2 in models 1 and 3 did not show any statistical significance in their adjustment ($p < 0.05$) with respect to the geographical coordinates. Coefficient β_2 was more sensitive than the other two regarding the air temperature schemes. Coefficient β_1 changed from 0.580 to 0.887, with the largest values observed in the sites farther from the coastline and coefficient β_3 remained within the closed interval [1.096; 2.517] while increasing linearly inland. Coefficient β_1 increases linearly northward and westward (inland), while the pattern of β_3 was just the opposite (increasing southward and eastward). Coefficient β_1 in model 1 (Bristow and Campbell's original model) gives the upper asymptote of the H_g/H_o curve (maximum value for the transmissivity) and, therefore, is associated with the atmospheric transmissivity of clear sky (which is a function of the local atmospheric composition). β_2 and β_3 are shape factors which define the rate that β_1 is attained as a function of the thermal amplitude; they may be considered an energy partition between sensible and latent heat forms which depend on the climate type and seasonality (dry and rainy periods) [8]. Under clear sky conditions, oxygen, ozone and water vapor are mainly responsible for the attenuation of the solar radiation which is weakly dependent of the optical depth due to the relatively low topography of the region [40,41]. Other gases as well aerosols and pollutants contribute in a less extent to the attenuation of solar energy. Transmissivity is also affected by altitude.

The distance from the coastline, associated with a decrease in the total precipitation, creates a zonal gradient of humidity with the most humid areas being the coastal region, lower São Francisco River and the humid zone; the driest being the semi-arid hinterland and upper São Francisco basin and the hinterlands being the transition zone. Agua Branca is an isolated exception to this pattern due to the local topography what explains why the site is more humid than its surroundings. This atmospheric water content gradient is well established during summer (also the dry season), when the maximum values of transmissivity are expected. As β_1 is an indirect measure of the clear sky transmissivity and also due to the selective water vapor attenuation bands, one may find the smallest values of this coefficient (corresponding to the largest attenuation) near the coastal zone and gradually larger values toward the dry interior. Another reason to explain the behavior of this coefficient is the topography with higher values away from the coastline. The meridional changes in β_1 (increase northward) is

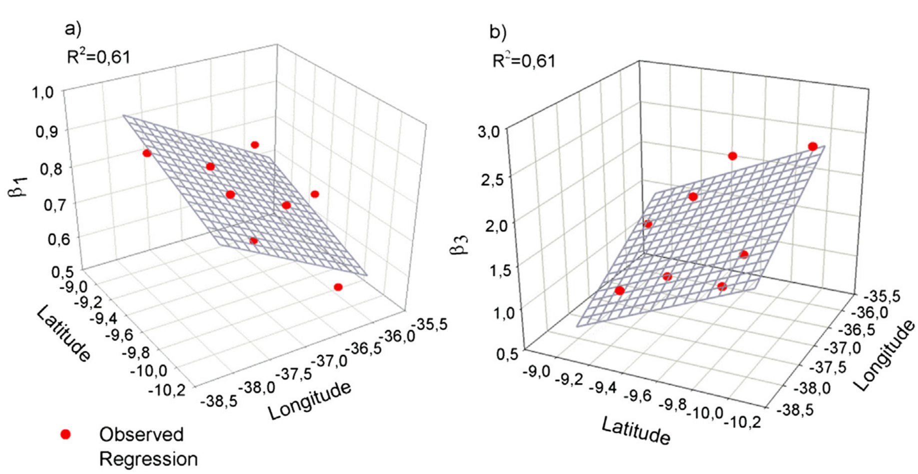

Fig. 2. Relation between the coefficients a) β_1 and b) β_2 of the Bristow–Campbell model (model 1) for the global daily solar radiation and the latitude and longitude.

associated with the large topography gradient in this direction, with the lower regions located to the south, close to São Francisco Valley (<50 m) and the highest regions in the neighborhood of Borborema Mase (up to 650 m). As the altitude increases, the optical depth decreases and transmissivity increases [15]. The larger (smaller) β_3 the smaller (larger) are the thermal amplitudes and their variations in order to reach maximum values of transmissivity. Therefore regions close to the coast, show larger values of β_3 as expected due, to the smaller thermal amplitude brought about by lack of continentality. As a result, β_3 tend to decrease westward. This decrease is also due to topographic change, which also increases westward and favors an increase in the thermal amplitude. The north-south change pattern of β_3 (northward decrease) is explained by the topographic features already cited.

The coefficients β_2 of models 3 and 1 were one order of magnitude different and coefficients β_1 and β_3 of model 3 did not differ significantly from those of model 1, for all sites considered in this study. The coefficients β_2 of models 2, 4 and 5 were all different among the sites; their values were between 0.012 and 0.024 (model 2), 0.405 and 0.811 (model 4), and 0.119 and 0.186 (model 5). The constant values of β_1 and β_3 in models 2, 4 and 5 resulted in large differences for the adjusted value of β_2; these differences were not observed in models 1 and 3, both with β_1 and β_3 adjusted before for the climatic conditions in Alagoas State. In general, the differences among the three coefficients were quite small, for both air temperature schemes. Concerning models 1 and 3, their coefficients β_1 (Arapiraca and São José da Laje) and coefficient β_3 (for Maceió and Coruripe) were very close to the corresponding coefficients of models 2 and 5 ($\beta_1 = 0.75$ and $\beta_3 = 2$).

The values of all coefficients, for all sites used in this study were different from those of Bristow & Campbell [8] with variations of 0.580–0.887 (for β_1) and 0.018 to 0.103 (for β_2); the coefficient β_3 changed from 1.196 to 2.517. Meza & Varas [9] used $\beta_1 = 0.70$ and $\beta_3 = 2.4$ and adjusted the remaining coefficient for 21 sites in Chile. They found that β_2 changes from 0.0015 to 0.0194, values different from those of Goodin et al. [25] and Weiss et al. [11], and also from those obtained in this study with local calibrations. For model 6, Annandale et at. [14], Allen et al. [26] and Hargreaves & Samani [13] proposed fixed values of $\beta_1 = 0.16$ (inland) and $\beta_1 = 0.19$ (coastal regions). For the coastal sites of Maceió and Coruripe, the differences among the proposed values of coefficient β_1 were 5.5% lower than those of the adjusted values. However, the agreement was good for Pão de Açúcar, a site located in the interior region but at the margin of São Francisco River. The values of coefficient β_1 in this study changed from 0.160 to 0.201, depending on the model (6 or 7) and the region. This range was different from that found by Ref. Liu X et al. [19] (0.135–0.166), for the Haerbin province in China. Ball et al. [27] also noticed a large variation of 0.130–0.170 for 13 sites in USA; again, these differences reinforce the need of adjustment with local data. The coefficients β_1 of models 6 and 7 were not very different from each other, probably due to the smooth topography of the region.

Within the range of altitudes of the sites used in this study, the differences between altitude-corrected and non-corrected values of β_1 in model 7 were less than 1.6%. Coefficients β_1 of models 6 and 7 also showed a strong dependence on the geographical coordinates with $R^2 = 0.86$ (Fig. 3), decreasing from the coastal region inland (~36.96° W), and then, increasing toward the westernmost part of Alagoas State. Regarding latitudinal changes, the values increased from south to the central part of the State (~9.66° S) followed by a northward decrease. The calculation of β_1 for models 6, 7, 8 and 9 was almost independent of the temperature schemes, even for models 6 and 7 which had the altitude correction included.

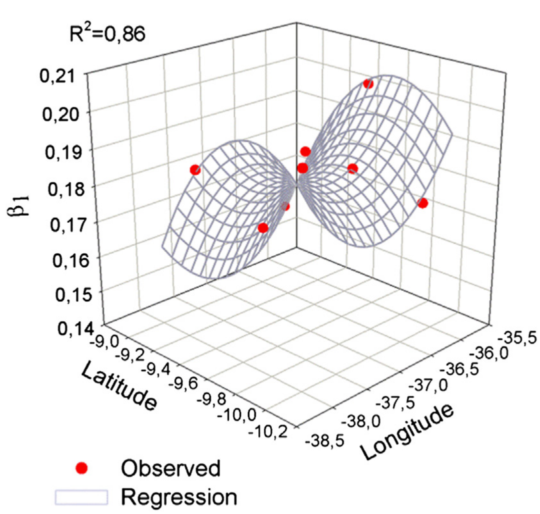

Fig. 3. Relation between the coefficient β_1 of Hargreaves & Samani model (model 6) for the global daily solar radiation and the latitude and longitude.

Table 4
Averaged daily monthly coefficients of models using ΔT_1 (models 6, 7, 8 and 9) and ΔT_2 (models 1, 2, 3, 4 and 5).

Site	Água Branca			Pão de Açúcar		
Model/coeff.	β_1	β_2	β_3	β_1	β_2	β_3
1	0.654*	0.049**	1.706*	0.684*	0.041**	1.769*
2	–	0.019*	–	–	0.017**	–
3	0.654*	0.451**	1.706*	0.684*	0.381**	1.769*
4	–	0.632*	–	–	0.566*	–
5	–	0.173*	–	–	0.177*	–
6	0.185*	–	–	0.190*	–	–
7	0.182*	–	–	0.190*	–	–
8	0.190*	−0.013**	–	0.181*	−0.030**	–
9	0.191*	−0.611*	–	0.184*	−0.676*	–
Site	Santana do Ipanema			Palmeira dos Índios		
Model/coeff.	β_1	β_2	β_3	β_1	β_2	β_3
1	0.721*	0.012**	1.078**	0.571*	0.003**	1.465**
2	–	0.012**	–	–	0.020*	–
3	0.721*	0.110**	1.078**	0.571*	0.115**	1.465**
4	–	0.392*	–	–	0.689*	–
5	–	0.141*	–	–	0.170*	–
6	0.167*	–	–	0.187*	–	–
7	0.165*	–	–	0.185*	–	–
8	0.143*	−0.083**	–	0.120**	−0.194**	–
9	0.155*	−1.377*	–	0.158**	−2.938*	–
Site	Arapiraca			Maceió		
Model/coeff.	β_1	β_2	β_3	β_1	β_2	β_3
1	0.728**	0.013**	1.065**	0.720*	0.034**	1.841**
2	–	0.018*	–	–	0.023*	–
3	0.728**	0.130**	1.065**	0.720*	0.267**	1.841**
4	–	0.604*	–	–	0.781*	–
5	–	0.155*	–	–	0.177*	–
6	0.184*	–	–	0.199*	–	–
7	0.183*	–	–	0.198*	–	–
8	0.183*	−0.003**	–	0.315*	−0.324*	–
9	0.186*	−0.216*	–	0.240*	−3.973*	–
Site	Coruripe			São José da Laje		
Model/coeff.	β_1	β_2	β_3	β_1	β_2	β_3
1	0.557*	0.060**	1.891**	2.700**	0.050**	0.61*
2	–	0.017*	–	–	0.012*	–
3	0.557*	0.543**	1.891**	2.700**	0.883**	0.61*
4	–	0.587*	–	–	0.411*	–
5	–	0.155*	–	–	0.116*	–
6	0.178*	–	–	0.158*	–	–
7	0.178*	–	–	0.157*	–	–
8	0.062**	−0.350*	–	0.175*	−0.053**	–
9	0.132*	−4.822*	–	0.162*	−0.470*	–

*Significant to 95% confidence interval. **Non significant.

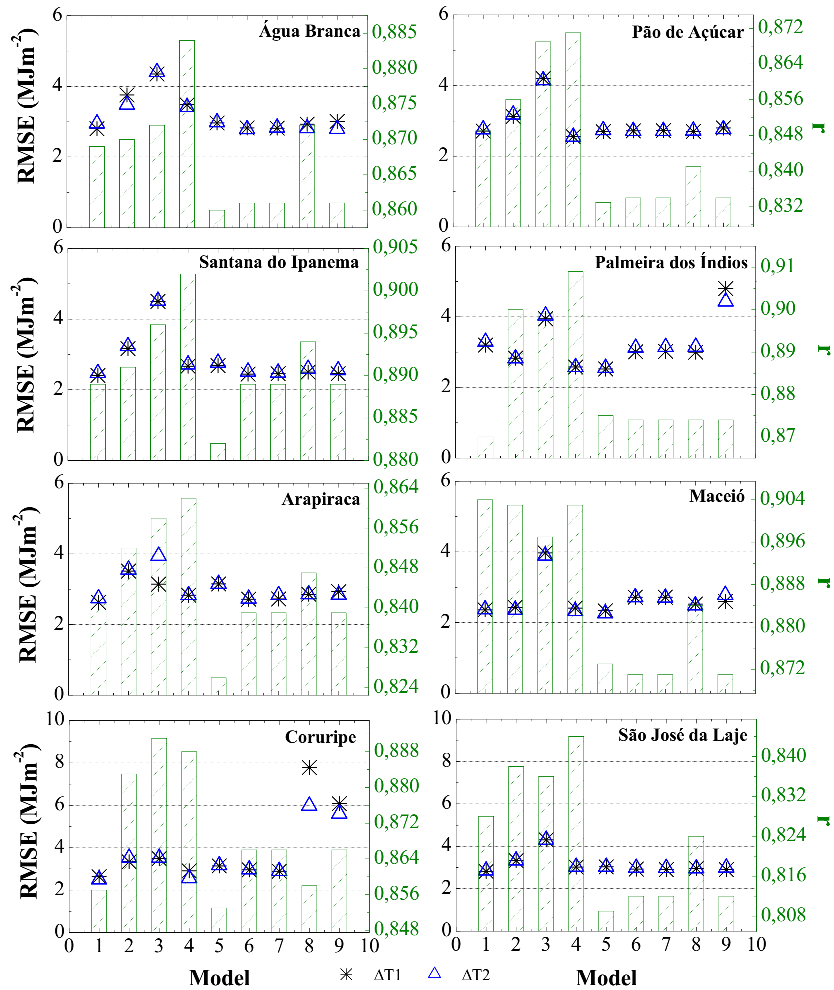

Fig. 4. Root mean square error (*RMSE*) based on the two air temperature schemes (ΔT_1 and ΔT_2) and the correlation coefficient (r) using ΔT_1 (models 6, 7, 8 and 9) and ΔT_2 (models 1, 2, 3, 4 and 5).

Changes in β_1 are expected for models 6 and 7 in order to satisfy the relation between H_g/H_o and the $\Delta T^{0.5}$ [15]. Furthermore, larger values of β_1 are expected for coastal regions or near large bodies of water or humid regions (where the temperature amplitude is reduced by either land/sea contrast or atmospheric humidity). Inversely, smaller values of this coefficient are expected in dry regions or sufficiently away from moisture sources [15,28]. Under these conditions, the increase (decrease) in humidity implies smaller (larger) thermal amplitudes. β_1 coefficient of model 6 (Hargreaves & Samani) tends to be larger (smaller) than those of the other models in order to compensate for the effects of smaller (larger) thermal amplitudes.

Table 5
Performance of the models with the best estimations of the daily global solar irradiation for each site and their statistical indicators [root mean square error (*RMSE*) and correlation coefficient (r)].

Daily global solar irradiation			
Site	Model	*RMSE* (MJ m^{-2})	r
Água Branca	6 and 7	2.821	0.861
Pão de Açúcar	8	2.701	0.841
Santana do Ipanema	6 and 7	2.452	0.889
Palmeira dos Índios	4	2.574	0.909
Arapiraca	6 and 7	2.722	0.839
Maceió	1	2.372	0.904
Coruripe	1	2.498	0.857
São José da Laje	1	2.846	0.828

This pattern is present in this work, as shown by a regression analyses between β_1 and the geographical coordinates given in Fig. 3. A pattern of zonal change was noted at the sites near the coast and westernmost region of Alagoas (the humid region of Água Branca) with the largest values of β_1; the smallest values are found in the central part of the state (subhumid and semiarid). Regarding the meridional variations, the largest values of β_1 occurs near the central northern part of the state (more humid) and decreasing northward and southward (drier regions). Due to the nonlinear relation between H_g/H_o and $\Delta T^{0.5}$, β_1 did not show any linear trend, as noticed for the coefficients of model 1 (Bristow & Campbell model).

Coefficients β_2 of models 8 and 9 were more sensitive to the ΔT schemes than the corresponding coefficients β_1. In addition, coefficients β_2 of these models were larger, in absolute values, when the ΔT_1 scheme was used. One also notices that coefficients β_1 of model 8 for all sites (but Coruripe) were larger than those of model 9. Coefficients β_2 of these models for all sites were negative with a large dispersion regarding the geographical positions. These results were all similar to those of Chen et al. [24] who obtained (for model 8) β_1 changing from 0.140 to 0.307 (average 0.193) and β_2 changing from −0.003 to −0.300 (average 0.130). As the model adjustment is not much affected by the choice of the air temperature scheme, the estimates of the global solar irradiation are discussed in this study using the results of Hargreaves & Samani model (and its modified versions) with the ΔT_1 scheme and Bristow & Campbell model (and its adaptations) using the ΔT_2 scheme.

Table 6
Performance of the models with the best estimations of the daily global solar irradiation for each region and their statistical indicators [root mean square error (*RMSE*) and correlation coefficient (*r*)].

Daily global solar irradiation			
Region	Model	*RMSE* (MJ m^{-2})	*r*
Interior (Sertão)	6 and 7	2.665	0.864
Hinterland (Agreste)	6 and 7	2.867	0.852
Humidity area (Coastal Zone) Zona da Mata/Litoral	1	2.572	0.863

3.2. *Coefficients for the daily monthly averaged global solar irradiation (H_g^m)*

The coefficients for H_g^m are shown in Table 4. In general, they appear to be not very sensitive to the choice of the air temperature scheme, although the model of Bristow & Campbell and its modified versions show conspicuous differences for some sites. Therefore, the discrepancy among the coefficients is not statistically significant with β_1 and β_2 decreasing and β_3 increasing. No regional pattern for the coefficients was noticed for the interior, hinterlands and humid/coastal zones. São José da Laje showed the largest value of β_1 (2.700). The coefficients β_2 and β_3 of these models at Palmeira dos Índios were 0.003 and 1.465, respectively. An appreciable difference in the values of β_2 (model 4), regarding the temperature scheme, was noticed only for Água Branca (in the interior and with a higher altitude) namely $\beta_2 = 0.632$ (using the ΔT_2 scheme) and $\beta_2 = 0.173$ (using the ΔT_1 scheme); this difference may be attributed to topographic effects. Meza & Varas [9] noticed that model 1 is more appropriated to estimate daily values and, practically useless, to obtain monthly averages by extrapolation.

Coefficients β_1 of model 6 did not show any pattern for any site; São José da Laje (humid zone but hilly) had the smallest value (0.158) and Maceió (coastal zone but flat terrain), the largest 0.199. An analysis of the coefficients β_1 of models 6 and 7 showed that they are independent of the temperature scheme (practically the same values were obtained) what means that the altitude correction used in model 7 did not bring any improvement. On the other hand, the coefficients β_1 and β_2 of models 8 and 9 showed some, but not strong, dependence with respect to the air temperature scheme, with the largest value of $\beta_1 = 0.315$ (model 8 at Maceió). As observed for the daily estimates, the choice of the temperature scheme does not affect significantly the results on a monthly scale. The ensuing results are still based on the calibration of Hargreaves & Samani model (and its modifications) using the ΔT_1 scheme and Bristow & Campbell model (and its adaptations) with the ΔT_2 scheme.

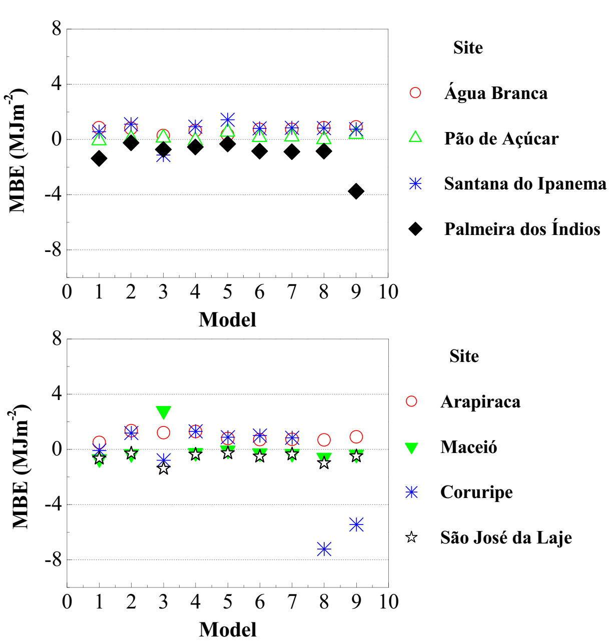

Fig. 5. Mean bias error (*MBE*) for the models and stations, using the temperature schemes ΔT_1 (models 6, 7, 8 and 9) and ΔT_2 (models 1, 2, 3, 4 and 5).

3.3. *Estimates of the daily global solar irradiation (H_g^d)*

The *RMSE* values (Fig. 4) show that the results do not depend much on the temperature schemes except for Arapiraca (model 4) and Coruripe (models 2, 5 and 8). The same results were independent of the site altitude, what apparently seems to be contrary to the results of Liu X et al. [19]. This seemingly contradiction can be explained recalling that the topographic features of the stations in China (ranging from 3 to 2295 m, as shown by the authors) and Alagoas State (30 m at Pão de Açúcar and 593 m at Água Branca) are quite different; the maximum altitude in Alagoas is only 26% of that in China. The smallest *RMSE* values for the interior sites were found at Santana do Ipanema, quite close to the values found for Água Branca and Pão de Açúcar. The *RMSE* indices obtained with the ΔT_1 scheme were consistently smaller than those using the ΔT_2 scheme at Arapiraca, São José da Laje and Santana de Ipanema for all models. The average for all sites using the ΔT_1 scheme (3.08 MJ m^{-2}) was 0.55% smaller than the corresponding one with the ΔT_2 scheme (3.10 MJ m^{-2}). The average *RMSE* for all sites in the interior (Água Branca, Pão de Acúcar and Santana do Ipanema), using models 2, 4 and 5 was 3.00 MJ m^{-2} and 2.91 MJ m^{-2} for the hinterlands sites (Arapiraca and Palmeira dos Índios), with models 2, 4 and 5. This shows that the use of different temperature schemes does not change significantly the results and therefore most of the models are capable of estimating H_g^d quite satisfactorily for all the sites in Alagoas State. In practice, fixing the coefficients in the initial calibration stages makes the model performance significantly worse (see Models 2, 4 and 5, in particular, for the interior sites). The use of models with only one coefficient (models 2,4,5, 6 and 7) yielded larger errors at São José da Laje and Água Branca both located in hilly terrain; this error was relatively larger at Maceió and Coruripe (coastal and plain sites). These results are quite similar to those found for 64 stations in Iran [36] with an average RMSE of 2.80 MJ m^{-2} and evidenced the possibility of overestimation during warm periods or underestimation during cold periods.

The changes introduced in model 1 were not efficient and did not produce any improvement in the estimates. The performance of model 2 (variation of Bristow & Campbell's model, with pre fixed values of $\beta_1 = 0.75$ and $\beta_3 = 2$) was worse than that of models 4 and 5, for most of the sites in this study. Model 4 had a better performance than that of model 1 just at Palmeira dos Índios. For this reason, the original model of Bristow & Campbell (model 1) is preferred rather than their modified version. This statement agrees with that of Liu X et al. [19] in which model 1 had a much better performance than the modified version [9–12,25].

The principal results on the performance of the models in estimating the daily global solar irradiation are given in Table 5, showing the most suitable models for each one of the sites of this study, according to their statistical indicators (*RMSE* and correlation coefficient). Model 1 was more accurate than model 6 for Maceió, Coruripe (both within the coastal zone) and São José da Laje (in the humid area) and yielded similar results to those of Supit & Kappel [29] for some sites in Europe. Models 6 and 7 show better performance than that of model 1 for Água Branca and Santana do Ipanema (in the interior) and Arapiraca (in the hinterlands); models 8

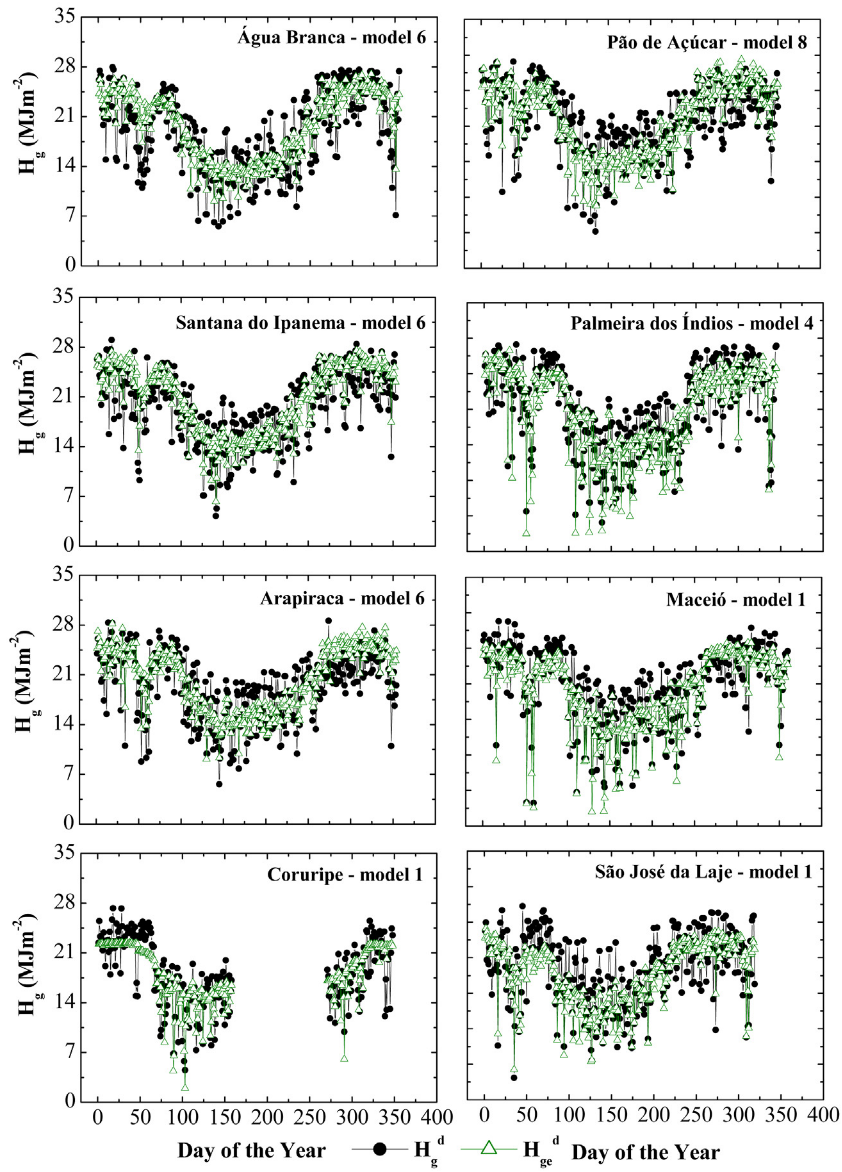

Fig. 6. Daily observed (H_g^d) and estimated (H_{ge}^d) variations of the global solar irradiation for some stations in Alagoas State 2009.

and 4 are considered the most adequate for Pão de Açúcar and Palmeira dos Índios, respectively. Bandyopadhyay et al. [30] found the original model 6 and the one adapted by Allen et al. [26] more accurate in estimating the crop evapotranspiration for some regions in India. The FAO-56 Bulletin recommends the use of the model adapted by Allen et al. [26], when H_g data are missing or dubious. Considering the local results, the RMSE values are similar or even better than those found by Linares-Rodríguez et al. [37] for Andaluzia, Spain (RMSE between 2.83 and 3.01 MJ m^{-2}) obtained with an artificial neural network.

Table 6 summarizes the results on the models' performance in a regional context. Model 1 is the one that produced the best estimates for all the sites located in the humid and northern coastal areas; models 6 and 7 are considered more appropriate for the interior and hinterlands. Allen [15] obtained similar results with model 6 (Hargreaves & Samani model) yielding better estimates of H_g for the sites in the interior rather than the coastal ones. In the present study, a large variability in the coastal cloud coverage was noticed due to the prevailing weather systems (e.g., sea/land breezes and trade winds) and their interaction with the local topography, what explains the large changes in H_g [31]. The presence of the ocean produces small temperature amplitude and, since the relationship between H_g and the thermal amplitude is nonlinear, the combined effect of high variability in H_g and small temperature amplitudes is likely to produce large dispersion and errors in H_g [15].

There was a significant difference between the H_g^d and H_{ge}^d series (the observed and estimated daily global solar irradiation, respectively) when the *t*-test was used, although the statistical parameters (*RMSE* and *r*) indicated acceptable estimates. In general, the Bristow & Campbell model (model 1) underestimated the daily global solar irradiation in Pão de Açúcar ($MBE = -0.083$ MJ m^{-2}), Palmeira dos Índios ($MBE = -1.370$ MJ m^{-2}), Maceió ($MBE = -0.681$ MJ m^{-2}), Coruripe ($MBE = -0.090$ MJ m^{-2}) and São José da Laje ($MBE = -0.638$ MJ m^{-2}), and overestimated it for the rest of the sites (Fig. 5). Models 2, 4 and 5 showed a trend to overestimate H_g^d at Água Branca, Arapiraca, Santana do Ipanema and Coruripe and underestimate it at Palmeira dos Indios, Maceió and São José da Laje. Hargreaves & Samani's [13] model and the modified models 7, 8 and 9 underestimated H_g^d at Palmeira dos Índios, Maceió and São José da Laje, and overestimated it at Água Branca, Arapiraca and Santana do Ipanema. Overestimates (with models 6 and 7) and underestimates (with models 8 and 9) for the regions of Pão de Açúcar and Santana do Ipanema were also observed.

The observed and estimated annual variations of H_g^d with the most suitable models for each site are shown in Fig. 6. It can be seen that the largest deviations are associated with large variations in cloudiness, and consequently with the scattering of solar radiation. The irradiation changes throughout the year, with the largest values occurring during the dry period (Spring and Summer) and the smallest ones during the rainy period (Autumn and Winter). The solar declination has a secondary role in contributing to these seasonal differences [31]. The fluctuations observed in January and February were brought about by the heavy episodes of precipitation in the entire Alagoas State, with totals of 244.3 mm (Coruripe, southern coastal zone) and 75.2 mm (Arapiraca, hinterland).

3.4. Estimates of the monthly daily averaged global solar irradiation (H_g^m)

Good estimates of H_g^m were obtained using all models for all sites stud (Fig. 7), with models 1 and 6 leading the list. The worst estimates came from models 3 and 8 which consistently showed high *RMSE* values for Santana do Ipanema, Arapiraca, Palmeira dos Índios and São José da Laje. The initial calibration of these models did not improve their overall performances. The model of Hargreaves & Samani [13] and the one modified by Annadale et al. [14] showed similar statistical indicators implying that the altitude correction is not needed for these sites, in agreement with Liu X et al. [19]. Models 8 and 9 (adaptations of model 6) had a poorer performance when compared to that of model 6; model 8 yielded *RMSE* values of 14.53 MJ m^{-2} (Palmeira dos Índios) and 25.11 MJ m^{-2} (Coruripe). However, the correlation coefficients obtained with different models at Água Branca varied from 0.932 to 0.954 with the best estimated value of H_g^m given by model 8 (*RMSE* = 1.39 MJ m^{-2} and r = 0.941). Therefore, the statistical indicators show that both models 8 and 9 had similar good performance em Água Branca, Arapiraca, Maceió e São José da Laje. This was confirmed by the *t*-test which did not detect any significant differences between model estimates and measurements. However, these indicators did show that model 1 yielded the best estimates of H_g^m at Pão de Açúcar (*RMSE* = 1.47 MJ m^{-2}), Santana do Ipanema (*RMSE* = 1.12 MJ m^{-2}), Arapiraca (*RMSE* = 1.39 MJ m^{-2}) and Coruripe (*RMSE* = 1.63 MJ m^{-2}). These results were also consistent with the correlation (r) between the estimates and observations (all in the closed interval [0.919, 0.987]). In particular, *RMSE* = 1.95 MJ m^{-2} (model 4) and *RMSE* = 1.25 MJ m^{-2} (model 6) were obtained at Palmeira dos Indios. These errors are smaller than those of Eskisehir (RMSE between 3.640 and 3.711 MJ m^{-2}, r between 0.817 and 0.824 and MBE between −3.541 and −3.434), but equal or larger than those obtained for sites in Turkey [38], probably due to the different climatic conditions. H_g^m values at Maceió were better estimated (RMSE = 0.68 MJ m^{-2}, r = 0.98) with models 6 and 7. Models 6 and 7 showed small values of *RMSE* and high values of r for Palmeira dos Índios, São José da Laje and Maceió.

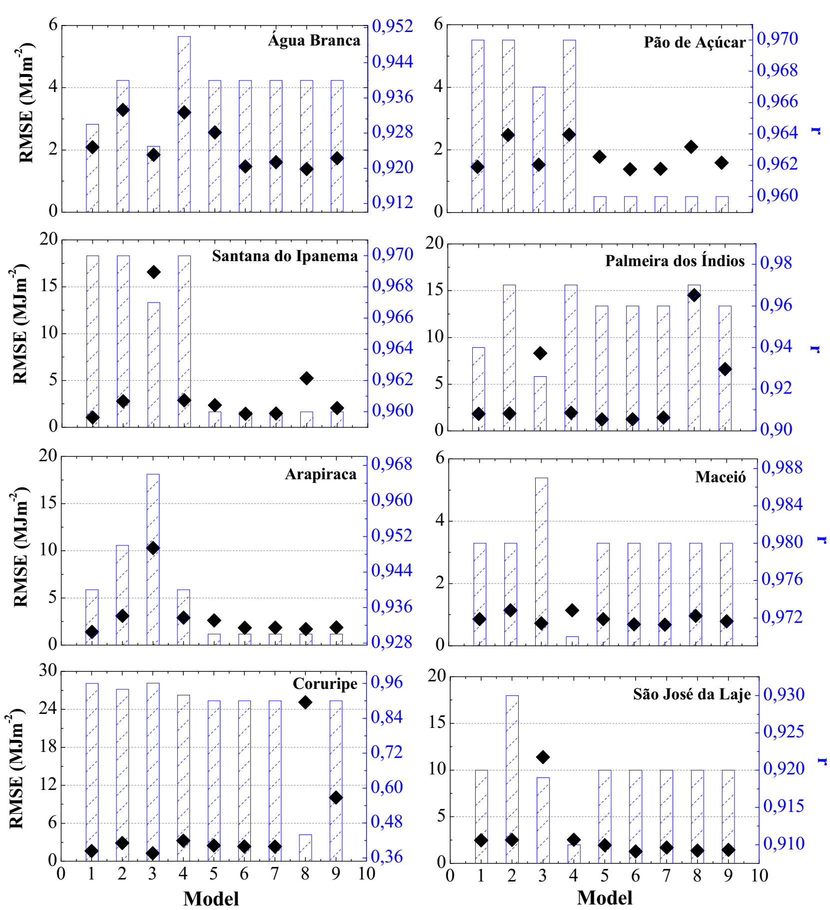

Fig. 7. Root mean square error (*RMSE*) and the correlation coefficient (r) for stations in Alagoas States using models 6, 7, 8 and 9 (with the ΔT_1 temperature scheme) and models 1, 2, 3, 4 and 5 (with the ΔT_2 temperature scheme).

The comparison between the results for Alagoas and those in Iran [39] showed that the former ones were larger than those of Karaj (RMSE between 2.16 and 3.16 MJ m^{-2}) and Tabriz (RMSE between 2.38 and 2.66 MJ m^{-2}), but similar to those of Tehran (RMSE between 1.38 and 1.61 MJ m^{-2}), Shiraz (RMSE between 1.03 and 2.10 MJ m^{-2}) and Mashhad (RMSE between 0.71 and 1.56 MJ m^{-2}). Our results were only smaller than those Isfahan (RMSE between 0.510 and 0.823). The differences above are quite likely due to different climatic conditions and techniques to achieve the best adjustment of the model coefficients.

As seen in Fig. 8, the overall performance of the models was satisfactory for all the sites as evidenced by the low absolute values of MBE. Models using the ΔT_2 scheme (models 1, 2, 3 4 and 5) resulted: Palmeira dos Índios and Santana do Ipanema (with model 3 greatly underestimating H_g^m) Arapiraca (model 3 with a relatively smaller underestimate) and São José da Laje (overestimated by model 2). Models using the ΔT_1 scheme (models 6, 7, 8 and 9) did not show a satisfactory performance mainly for Coruripe and Palmeira dos Índios (models 8 and 9 greatly underestimating H_g^m) and Santana do Ipanema (underestimated by model 8 only). The worst cases of underestimating H_g^m were observed for Coruripe (MBE = −24.88 MJ m^{-2}, model 8) and Santana do Ipanema (MBE = −16.37 MJ m^{-2}, model 3).

4. Conclusions

The model coefficients used in this study were insensitive with respect to the selection of the air temperature scheme (ΔT_1 and ΔT_2). The model performance using the ΔT_2 scheme does not statistically differ much from that of the models using the ΔT_1 scheme. The use of the former scheme is easier and recommended. The generated coefficients used to estimate the global solar irradiation are different for all the sites which require that all of them be calibrated with local data. β_1 and β_3 coefficients of the original Bristow & Campbell's model and β_1 of the Hargreaves & Samani's model showed a spatial dependence with respect to the coastal environment, local climate conditions (dry or wet climate) and cloudiness.

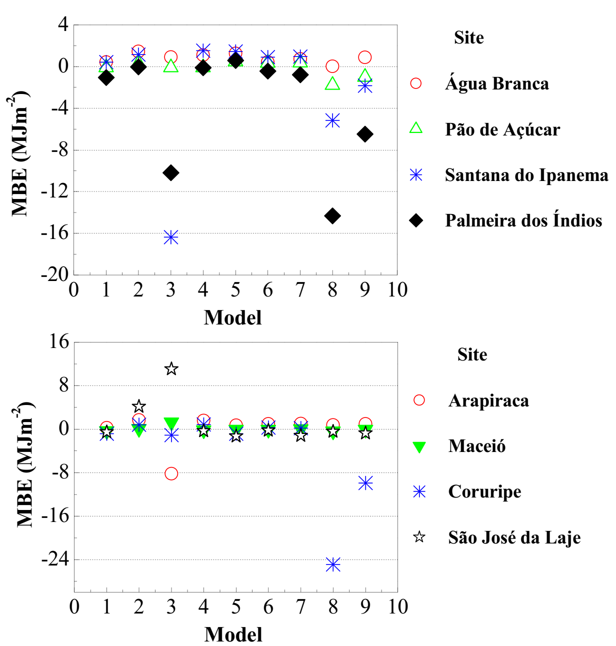

Fig. 8. Mean bias error (*MBE*, in MJ m^{-2}) for all models and for all sites of this study using models 6,7, 8 and 9 (using the ΔT_1 temperature scheme) and models 1, 2, 3, 4 and 5 (using the ΔT_2 temperature scheme).

Simplifications as those used in the Bristow & Campbell model (model 1), by keeping β_1 and β_3, fixed should be avoided, whenever possible. Model 3 (a modified version of the former) yielded the worst daily and monthly estimates for all of the eight sites. The modified model of Hargreaves & Samani (model 6) produces derived the best estimates of daily H_g for the stations situated in the hinterlands and interior. The model of Bristow & Campbell was the one with the best performance when applied to the sites within the humid/coastal zones. The original model of Hargreaves & Samani is recommended for the hinterlands and interior and the original Bristow & Campbell for humid/coastal zones, both requiring local calibrations.

Acknowledgments

The authors thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Centrais Elétricas Brasileiras S. A (Eletrobrás).

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