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

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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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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,

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

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

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:

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

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

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