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# Empirical models of daily and monthly global solar irradiation using sunshine duration for Alagoas State, Northeastern Brazil

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ABSTRACT

The Ångström–Prescott model called M1 together with ten modified versions, all based on the sunshine duration were adjusted to estimate the daily global and monthly averaged solar irradiation for some sites in the hinterland of Alagoas State in the eastern coast of the Northeastern Brazil. The models were adjusted with meteorological data from 2007 to 2010 and their skills were analyzed using: the Mean Bias Error, Root Mean Square Error and Willmott's Index of Agreement. The results indicate that the fitted coefficients depend on the geographical coordinates, altitude and local microclimate with 15% differences among the coefficients and estimates. The largest errors are observed in the regions with more cloudiness. Mean Bias Error and Root Mean Square Error for the daily evaluation of models M1, M9 and M11 were similar, with high values of Willmott's Index. The daily estimates obtained with models M1 and M11 did not differ more than 5%. Models M9 and M11 showed a better performance than that of M1 on a monthly basis. Finally, models M1 and M11 yielded the best results and due to their efficiency and simplicity are recommended to estimate the daily and monthly solar irradiation where sunshine duration data are available.



## Introduction

Surface global solar irradiation ($H_g$) is used in meteorology, climatology, radiation and energy budgets, water treatment processes, heating and natural lighting, agriculture and forestry and use of renewable energy [1]. Indeed, solar energy seems to be the most important, promising and sustainable form of energy able to mitigate the environmental problems humankind is to face in the future [2]. Despite its unquestionable importance, $H_g$ measurements are not globally operational due to the high cost of acquisition, maintenance, calibration and technical complexities [3,4]. Particularly in Brazil, there are relatively few studies concerning $H_g$ [6–8] and long time series of this variable are relatively rare, due to the continental size of the country [9].

The most appropriated method to quantify $H_g$ is to use pyrometer data [10]. However, empirical methods that employ meteorological variables (such as air temperature [11,12], water vapor pressure [13], relative humidity [5] and precipitation [14], all cheaply measured) are frequently used to overcome these observational difficulties. The Ångström–Prescott (A–P) [15,16], among many others using sunshine duration as input data, outstands for its simplicity and better statistical performance under different climatic conditions and time scales [17–19]. Some studies suggested that modified models (such as quadratic, cubic, logarithmic and exponential) may improve $H_g$ estimates [20–27].

Empirical models are used to provide solarimetric data series and are useful tools to estimate $H_g$ where measurements are scarce or non-existing [28]. Not all models are capable of estimating $H_g$ correctly under conditions different from those used originally in their development [17,29]. Thus, it is necessary to fit their

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coefficients using local data and test them to determine the uncertainties in estimating $H_g$. Several sites in Brazil have long time series of sunshine duration and these data could be used to estimate $H_g$ with empirical models [30–32]. However, the quality of these estimates depends, again, on a fitting with local data. Tiba [6] estimated Ångström–Prescott model coefficients $\beta_1$ and $\beta_2$ for sites in Northeastern Brazil (NEB) and noticed a high variability ($0.22 < \beta_1 < 0.35$ and $0.31 < \beta_2 < 0.58$). Andrade-Junior et al. [33] calculated them for the climatic conditions prevailing in Piauí state also in NEB ($\beta_1 = 0.3107$, $\beta_2 = 0.5383$ for the rainy season and $\beta_1 = 0.3130$, $\beta_2 = 0.5086$ for the dry season). They did not notice any statistically significant difference when seasonal or annual coefficients were used.

Jerszurki and Souza [34] observed similar results for other regions of Brazil [($0.17 < \beta_1 < 0.23$ and $0.35 < \beta_2 < 0.45$) for the monthly scale and ($\beta_1 = 0.19$ and $\beta_2 = 0.41$) for the annual scale in Paraná state, southern Brazil]. Daniele et al. [35] obtained $0.241 < \beta_1 < 0.345$ and $0.430 < \beta_2 < 0.515$ (monthly scale) and $\beta_1 = 0.278$, $\beta_2 = 0.498$ (annual scale) for Brasilia DF in central Brazil. Carvalho et al. [36] obtained $0.252 < \beta_1 < 0.299$ and $0.397 < \beta_2 < 0.504$ (monthly scale) and $\beta_1 = 0.295$, $\beta_2 = 0.417$ (annual scale) for Seropédica in Rio de Janeiro, southeastern Brazil. There were no statistically significant differences regarding the use of monthly and annual coefficients in these studies. Despite its location in NEB, studies on the adjustment of empirical models (such as those considered here) are scare for Alagoas region. Furthermore, long time series of $H_g$ as estimated from the sunshine duration are used to quantify its time and space variability what is essential in designing solar energy plants and agricultural projects.

In the present study, the Ångström–Prescott model and seven modified versions [20–26] are adjusted and assessed on both daily and monthly scales for three sites: Água Branca, Pão de Açúcar and Palmeira dos Índios in the interior of Alagoas State. In addition, three other models are proposed. The model coefficients are fitted with local data to yield the best estimate for each of these sites and sensitivity studies to prevailing weather systems and climate patterns were carried out.

## Materials and methods

### *Sites and data*

The daily measurements of $H_g$ and sunshine duration ($n$) at Água Branca, Pão de Açúcar and Palmeira dos Índios were obtained at the solarimetric stations (Fig. 1), for the 2007–2010 period. The Brazilian Instituto Nacional de Meteorologia (INMET) using conventional Campbell-Stokes heliographs provided sunshine duration series (in hours).

Daily global solar irradiation ($H_g^d$, in MJ m$^{-2}$) were obtained by integrating (trapezoidally method) the daily solar irradiance ($I_g$, in W m$^{-2}$) between 06:00 LT and 17:00 LT (Local Time) Eq. (1). $I_g$ was measured using black and white Eppley pyranometer [dependence on temperature: ±1.5% (−20 °C to +40 °C); linearity: ±1.0%, (0–1400 W m$^{-2}$); cosine response: ±2.0% ($0 < \theta_z < 70°$) and ±5.0% ($70 < \theta_z < 80°$); measurement bandwidth: (285–2800 nm)]. The pyranometers were connected to a datalogger (CR1000, Campbell Scientific Inc., Logan, Utah) programmed to make measurements every second and store 1 min averaged values [9]:

$$H_g^d = \int_{t_o}^{t_f} I_g^h \tag{1}$$

where ($I_g^h$) is the hourly solar global irradiance and $t_o$ = 06:00 LT and $t_f$ = 17:00 LT. Sunrise and sunset intervals were neglected because of its small contribution to the entire integral.

Monthly averaged global solar irradiation ($H_g^m$) was calculated using the averaged values of $H_g^d$ for all days in the month:

$$H_g^m = \frac{1}{N'}\sum_{i=1}^{N'} H_g^d \tag{2}$$

where $N'$ is the number of days in the month.

The data were sorted out into two groups; data measured in 2007, 2009 and 2010 were used to fit the model coefficients, and the data collected in 2008 to validate and assess them. This choice was made randomly in order to avoid any trends in the results. Fig. 2 shows the monthly climatological air temperature and rainfall for the three sites, as calculated using data from 1961 to 2010 from INMET.

The climate of Água Branca (in the interior with a mountain like microclimate) according to the Köppen-Geiger classification is "As" – tropical humid, with rainy season during autumn/winter (May to August) and dry season in summer (December to February). The annual air temperature is 23.6 °C (20.9 °C in July and 25.6 °C in December) and annual rainfall is 1,090 mm, with minimum in October (23.9 mm) and maximum in June (193.5 mm) (Fig. 2A). In Palmeira dos Índios, the monthly air temperature changes from 22.6 °C (July) to 27.2 °C (December) (Fig. 2B), with an annual average of 25.1 °C. The total annual precipitation is 881 mm with a minimum in November (13.9 mm) and maximum in June (173 mm). The climate is also classified as "As" – Tropical Humid. The climate of Pão de Açúcar is "Bsh" – Dry Climate (annual rainfall of 591 mm ranging from 13.4 mm in November to 94.2 mm in June) (Fig. 2C) with the dry season in summer and monthly air temperature of 24.9 °C (August) and 29.8 °C (December) and annual average of 27.5 °C.

### *Ångström–Prescott model and its modified versions*

In 1924 Ångström [15] suggested a simple linear relation between the expected $H_g^d$ in a cloudless day and daily maximum sunshine or daylight hours ($N$) and in 1940, Prescott [16] included the extraterrestrial solar irradiation ($H_o$) using Eq. (3) (Model M1):

$$\frac{H_g}{H_o} = \beta_1 + \beta_2\left(\frac{n}{N}\right) \tag{3}$$

The empirical coefficients ($\beta_1$ and $\beta_2$) are normally fitted using linear regression ($Y = \beta_1 + \beta_2 X$), so $Y = H_g/H_o$ and $X = n/N$. The first coefficient may be interpreted physically as the fraction of the $H_g$ reaching the Earth's surface in an overcast day and depends mainly on the type and thickness of the clouds [37]. It is a difficult task to estimate it accurately, due to the ceaseless atmospheric motions [38]. The other coefficient ($\beta_2$) is a complement that gives the total of $H_g$. Their sum, ($\beta_1 + \beta_2$), is the potential fraction of solar irradiation at the top of the atmosphere available to reach the surface (that is, $H_g$ in a clear day). Therefore, this sum is affected by the optical thickness, composition and interaction of the air constituents. During its penetration in the atmosphere, the solar radiation is scattered by air molecules, water (in its three phases) and aerosols or particulates. The extent of the dispersion depends on the number and size [with respect to the wave length, ($\lambda$)] [39].

Modifications introduced in the original Ångström–Prescott model in order to make it usable in different sites and under climatic conditions yielded other models. Table 1 shows eleven models all based on sunshine which were assessed in this work, regarding the estimative of $H_g$ in the daily ($H_g^d$) and monthly ($H_g^m$) partitions: quadratic (M2) [20], cubic (M3) [21], logarithmic (M4) [22], linear logarithmic (M5) [23], exponential (M6) [24], linear exponential (M7) [25] and power (M8) [26]. The senoidal models: (M9) [40], (M10) [41] and (M11) [42] were originally proposed