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Daily Estimates of Global Radiation in the Brazilian Amazon by Simplified Models

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Abstract: Solar radiation is an element and a meteorological factor that is present in several processes, such as evapotranspiration, photosynthesis, and energy generation, among others. However, in some regions, there is a limitation in surface data measurements. In this study, 87 empirical models were evaluated to estimate global radiation (Hg) in the Brazilian Amazon Biome; these models were divided into five groups according to the input variables, such as insolation (group I), air temperature (group II), relative humidity (group III), astronomical variables (group IV), and hybrid models (group V) as input variables. The estimates were evaluated by their significance (t-test) and then according to the statistical metrics of the models' performance (R^2, MBE, RMSE, and d). The group V model [$Hg/Ho = a + b \ln\Delta T + c\ (S/So)^d$] presented the best statistical performance in all evaluated indicators, followed by the group I model [$Hg/Ho = a + b\ (S/So)^c$] and then the group II model [$Hg/Ho = a + b\Delta T + c\ \Delta T^{0.25} + d\ \Delta T^{0.5} + e\ (Tmed/Ho)$]. The group III models presented low statistical performance, and the group IV models were not significant (NS) in all evaluated meteorological stations. In general, it was found that the simple or hybrid models based on insolation and air temperature were efficient in estimating Hg in the Brazilian Amazon Biome.

Keywords: solar radiation; solar energy; minimum meteorological data; empirical estimation models; statistical indicators; Amazon biome

1. Introduction

Solar radiation is a clean, abundant, continuous, and renewable energy source with great potential for expanding its use in Brazil and worldwide. In the current context, the spatial and temporal variability of the incidence of global radiation (Hg) on the Earth's surface can be considered one of the main drivers of its use, especially in climate change [1,2]. These variations, according to Souza et al. [3], depend on the Earth's movements (rotation and translation), geographic factors (latitude, longitude, altitude, orientation and inclination of the surface) and atmospheric factors (mainly due to the interaction with greenhouse gases and water vapor) and clouds.

In short, when passing through the atmosphere, the electromagnetic waves that form solar radiation can be attenuated by reflection, absorption and diffusion due to contact with the gases that make up the atmosphere, clouds and/or suspended particles. However, these phenomena are insufficient to retain the entire spectrum of electromagnetic waves from solar radiation. A percentage passes through the atmosphere without any interaction (direct radiation), which, together with the diffuse component (selective and non-selective, depending on the dimensions of the attenuating particle), hits the ground surface, forming global radiation [3].

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Knowledge of global radiation incidents on natural and/or forced surfaces with different inclination angles and exposure faces can be applied in many scientific and technological areas. Accurate information on Hg is widely needed in several chemical, physical and biological applications and processes [4] and in several sectors, such as renewable energy, meteorology, agriculture, hydrology, ecology, environmental comfort, epidemiology, and industry [5,6].

Despite its importance, in many regions, especially in underdeveloped countries, measuring Hg is still a challenge due to the high costs of instruments (sensors) and their periodic recalibration and maintenance needs; these activities are recurrent and necessary in meteorological stations, even if they are automatic [7]. In addition, Hg data sets are often characterized by many measurement failures or inconsistent data, mainly due to lack of maintenance (dirt deposited on sensors, shading, and lack of sensor calibration). These problems occur even in countries with a high density of Hg monitoring stations [4,8,9]. Therefore, great efforts have been made to estimate Hg based on meteorological variables with lower monitoring costs that are widely available and monitored at meteorological stations worldwide [1].

In Brazil, this reality is no different, especially in the Amazon Biome, which is located in the North of the country and occupies 49% of the national territory; this region has the lowest ratio between automatic meteorological stations (AMSs) and conventional meteorological stations (CMCs) per area of the station network of the National Institute of Meteorology (INMET). In addition to the low number of stations installed for surface monitoring, the percentages of failures in the existing databases vary from 10 to 60% [10–12], thus limiting seasonal assessments of the behavior of incident Hg. And, even in countries that invest more in research, these problems are observed, as reported by Fan et al. [5], evaluating 122 meteorological stations in China, observed failures of 0.3 to 7.5% in the databases.

The spatial-temporal characterization of global radiation requires a series of long-term measurements. Despite the importance and interest of the scientific and governmental community, knowledge of this is still developing in the Amazon biome. This is mainly due to the large territorial extension, limited land access and low population density (number of cities). Information on daily Hg levels in this biome is necessary for several applications associated with environmental sciences, since solid scientific evidence indicates that a representative part of this ecosystem is being affected by anthropogenic actions, particularly by the expansion of agricultural activities, the increasing frequency and severity of forest fires and the degradation and reduction of natural vegetation [13–15].

To meet the relevant needs for obtaining global radiation data, several models have been developed for Hg estimates based on other meteorological data and have been commonly made available/evaluated worldwide [11,16,17]. It is no different for regions such as the Brazilian Amazon, where, despite some studies already carried out [10,12], there is still a need to evaluate simplified Hg estimation models for constructing continuous data series for agricultural and environmental applications.

Evaluations of simplified and/or parameterized models for Hg estimates require regional calibrations of statistical coefficients that can provide good estimates through indirect relationships with other meteorological variables, as long as these are simple to monitor, have greater database availability, or have good correlation with Hg, as is the case with insolation, air temperature, relative humidity and rainfall [4–7,18].

The first empirical model for estimating Hg based on insolation (S) was proposed by Angström [19] and later modified by Prescott [20]; in honor of the authors, it became known as the Angstrom-Prescott (A-P) model. Regarding air temperature, the first simplified model was proposed by Hargreaves & Samani [21], when they proved that the daily thermal amplitude (ΔT = Tmax - Tmax) presents good correlations with incident Hg; later, Bristow & Campbell [22] proved that there is an exponential correlation between ΔT and Hg.

Studies based on insolation present a superior performance when compared to studies based on other meteorological variables, such as air temperature [23,24]; however, in the Brazilian context, the availability of insolation data is lower for most biomes and states, unlike air temperature, which is

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measured in practically all CMSs and AMSs [1,25]; this disparity is more pronounced in the context of the Brazilian Amazon. Therefore, there are several possibilities for adjusting models based on other meteorological or geographic variables that correlate with Hg, as this allows for increased application possibilities for different situations according to data availability and improves Hg's predictive capacity.

After the widespread dissemination of the Angstrom-Prescott [20], Hargreaves & Samani [21] and Bristow & Campbell [22] models, several authors proposed modifications such as polynomial, logarithmic, potential and exponential adjustments. In the literature review, Pietro & García (2022) [6] reported the existence of 165 different models, which can be classified according to the meteorological and non-meteorological variables used: i) models based on insolation (S), in hours (Group I); ii) models based on maximum, average and minimum air temperature, in ºC (Group II); and iii) models that consider the combination of variables such as insolation, maximum, average and minimum air temperature, relative humidity, latitude, atmospheric pressure, solar declination, wind speed and rainfall (Group III). Empirical models have been studied in different regions of the world for Hg estimates on a daily scale, especially based on these three groups mentioned above. Highlights include studies based on insolation (S) for China [4,17,27,28], Spain [29], Turkey [30–33], Sudan [34], Egypt [35], Saudi Arabia [36], Nigeria [24], Iran [16] and South Korea [37].

Therefore, other studies involving models based on air temperature (daily maximum, average and minimum) were developed for different locations by different authors, such as: Egypt [7], China [1,4,5,17,38–40], United States [18,22,41–43], Italy [18], United Kingdom [18], Netherlands [18], South Africa [18], Australia [18], Nigeria [23,24,44], Saudi Arabia [45], Africa [46], Iran [16,47], India [2,48] and Turkey [9]; models based on relative humidity were in Nigeria [23], Bahrain [34], Turkey [50] and Nigeria [24,44]; models based on astronomical variables in Jordan [51], Turkey [32,50], Nigeria [24] and hybrid models for China [4,5,17,27,40], Nigeria [23,24,44,52,53], Sudan [49], Bahrain [49], Saudi Arabia [36], Turkey [9,50] and South Korea [37].

The most comprehensive study involving Hg estimates was conducted in the Amazon Biome with the Angstrom-Prescott model for 20 meteorological stations (MSs) [54]. Studies developed in several regions of Brazil also presented point estimates for some locations in the Amazon [3,10,11,55]. Given the environmental importance of this biome and Hg for several agro-environmental applications, the objective of this study was to evaluate and determine which models based on meteorological and astronomical variables present the best performance in estimating daily global radiation (Hg) in the Brazilian Amazon, using meteorological and astronomical variables.

2. Materials and Methods

2.1. Study Area

The study area is concentrated in the Brazilian Amazon biome, which encompasses a large area of 4,196,943 km^2, distributed across nine states: Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, and part of Tocantins, Mato Grosso, and Maranhão (Figure 1). Twenty locations with meteorological stations (MSs) that presented simultaneous automatic (MSAs) and conventional (MSCs) measurements (Table 1) were selected, considering the following daily databases: i) MSAs - maximum, average, and minimum temperature (Tmax, Tmed, and Tmin), average relative humidity (RHmed), and global horizontal radiation (Hg); ii) MSCs - insolation (S). These databases were obtained from the website of the National Institute of Meteorology (INMET) (https://portal.inmet.gov.br/). Although the INMET station network is larger than that selected in this study for the Amazon region, it is worth noting that only those that presented concomitant measurements of Hg and S were selected.

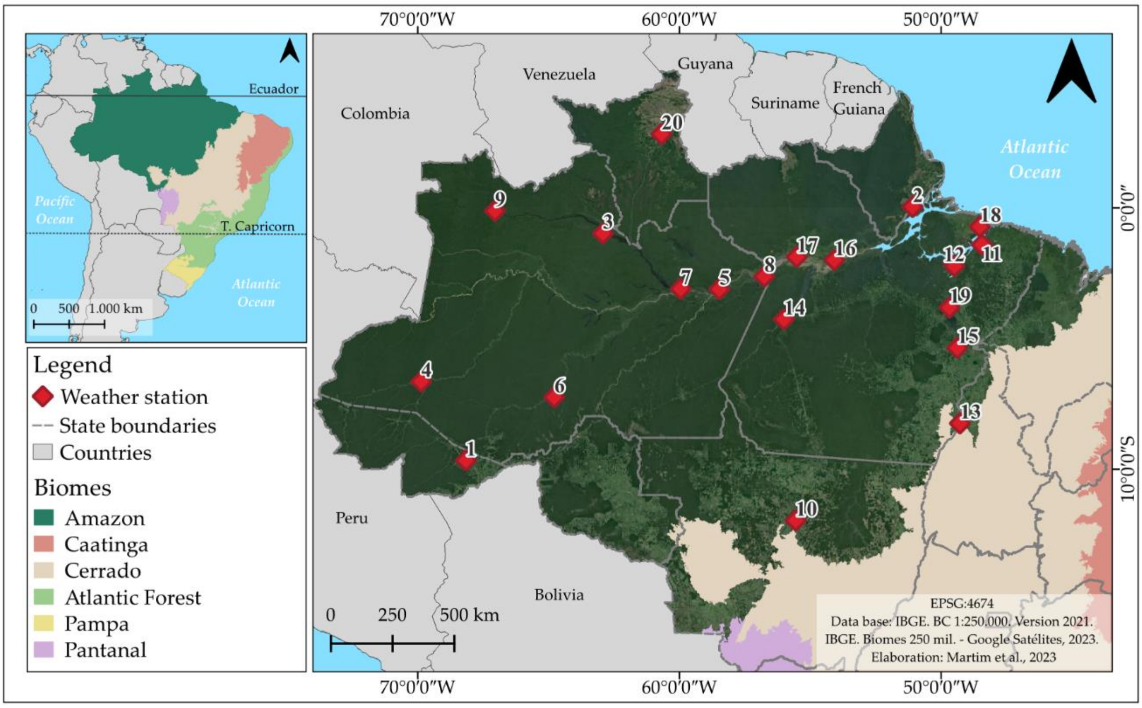

Figure 1. The location of the 20 meteorological stations evaluated in this study is in the Amazon biome, Brazil. (The numerical order of the stations is presented in Table 1).

Table 1. Meteorological stations in the Brazilian Amazon and their respective locations, climate classification, geographic coordinates and data period.

State	Meteorological station	CCKP*	Lat.	Lon.	Alt.	Data period
Acre (AC)	1 – Rio Branco	Am	-9.67	-68.16	163	2015-2022
Amapá (AP)	2 – Macapá	Am	0.035	-51.08	16	2013-2022
Amazonas (AM)	3 – Barcelos	Af	-0.98	-62.92	29	2008-2022
	4 – Eirunepé	Af	-6.65	-69.87	121	2012-2022
	5 – Itacoatiara	Af	-3.12	-58.47	41	2008-2022
	6 – Lábrea	Am	-7.25	-64.78	61	2008-2018
	7 – Manaus	Af	-3.1	-59.95	61	2000-2022
	8 – Parintins	Af	-2.63	-56.75	18	2008-2018
	9 – São Gabriel da Cachoeira	Af	-0.12	-67.05	79	2011-2022
Mato Grosso (MT)	10 – Sinop	Aw	-11.85	-55.55	366	2006-2017
Pará (PA)	11 – Belém	Af	-1.41	-48.43	21	2003-2022
	12 – Cametá	Af	-2.23	-49.48	9	2008-2022
	13 – Conceição do Araguaia	Aw	-8.25	-49.27	175	2008-2022
	14 – Itaituba	Af	-4.27	-56.00	24	2008-2022
	15 – Marabá	Aw	-5.36	-49.37	116	2009-2022
	16 – Monte Alegre	Am	-2	-54.07	100	2012-2022
	17 – Óbidos	Am	-1.88	-55.51	89	2012-2017
	18 – Soure	Am	-0.72	-48.51	12	2008-2017
	19 – Tucuruí	Am	-3.82	-49.67	137	2008-2017
Roraima (RR)	20 – Boa Vista	Am	2.82	-60.68	82	2010-2022

Latitude (Lat.); Longitude (Lon.); Altitude (Alt.); *Source: Alvares et al. [56].

According to the Köppen Classification, the 20 stations are included in three subclasses of tropical climates: Am (monsoon), Af (with dry season) and Aw (with dry winter), with high

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precipitation (over 3600 mm year^{-1}) in the North of the biome and with reduction towards the South of the Amazon [56]. Geographically, the AMSs and CMSs are located between latitudes 0.035° to -11.97° and longitudes -48.43° to -69.87° (three distinct time zones), while altitudes vary from 9 to 366 meters. The longest data series evaluated was 22 years (2000 to 2022) at the Manaus station (AM), and the shortest data series was five years (2012 to 2017) at the Soure station (PA) (Table 1).

The meteorological data were subjected to filters to identify inconsistencies and failures, in which case, days that presented daily failures of Tmax, Tmed, Tmin, S, and RHmed and hourly failures of Hg between 10 am and 2 pm (local solar time) were excluded; days with insolation ratio (Ri) > 1.0 and Kt > 0.85 were also excluded. Subsequently, by AMS, the data series was divided into 70% for calibration of the model coefficients, and the remainder (30%) was used to evaluate the statistical performance. This separation of the databases was carried out, ensuring the representativeness and proportionality of the periods of the year (months) in both databases.

2.2. Simplified Models for Estimating Global Radiation (Hg)

All simplified models evaluated are based on extraterrestrial radiation (Ho), which corresponds to radiation that has not yet interacted with atmospheric elements; this variable was obtained by Equation 01, which depends on the eccentricity factor of the Earth's orbit (dr - equation 02), solar declination (δ - equation 03) and the daily hour angle (h - equation 04). In addition to Ho, some simplified models depend on the photoperiod (So - equation 05) or atmospheric transmissivity (Kt - which represents the fraction of radiation that reaches the Earth's surface - equation 06) or the insolation ratio (Ri - which represents the fraction of time of incidence of direct radiation throughout a day - equation 07) [10,57].

$$\mathrm{Ho} = 37.59 * \mathrm{dr} * \left(\frac{\pi}{180} * \mathrm{h} * \mathrm{sen}\,\phi * \mathrm{sen}\,\delta + \cos\phi * \cos\delta * \mathrm{sen}\,\mathrm{h}\right) \quad (01)$$

$$\mathrm{dr} = 1 + 0.033 * \cos\left(\frac{360 * \mathrm{DJ}}{365}\right) \quad (02)$$

$$\delta = 23{,}45 * \mathrm{sen}\left[\frac{360}{365}\,(\mathrm{DJ} + 284)\right] \quad (03)$$

$$\mathrm{h} = \cos^{-1}(-\tan\phi * \tan\delta) \quad (04)$$

$$\mathrm{So} = \frac{2 * \mathrm{h}}{15} \quad (05)$$

$$\mathrm{Kt} = \frac{\mathrm{Hg}}{\mathrm{Ho}} \quad (06)$$

$$\mathrm{Ri} = \frac{\mathrm{S}}{\mathrm{So}} \quad (07)$$

where: ϕ is the local latitude of the stations (º); δ and dr are dependent only on the time of year (DJ, which indicates the ordering of the days throughout the year (1 $\leqslant$ DJ $\geqslant$ 365 or 366 days); h is dependent on the time of year and latitude; the values of Kt and Ri are dimensionless.

Based on the literature review, 87 simplified models for daily Hg estimates were obtained, presenting differences in the input variables or the analytical estimation model. These models were divided into 5 Groups according to the input variables, generating the following combinations:

- Group I: empirical models based on insolation (S), photoperiod (So) and extraterrestrial radiation (Ho) (Table 2);
- Group II: empirical models based on maximum, mean and minimum air temperature (Tmax, Tmed, Tmin) and extraterrestrial radiation (Ho) (Table 3);
- Group III: empirical models based on relative humidity (RH) and extraterrestrial radiation (Ho) (Table 4);
- Group IV: empirical models with astronomical variables, such as solar declination (δ), Julian day (DJ) and extraterrestrial radiation (Ho) (Table 4);
- Group V: hybrid empirical models, based on two or more variables such as S, Tmax, Tmed, Tmin, RHmed and latitude (ϕ), photoperiod (So) and extraterrestrial radiation (Ho) (Table 5).

Local calibrations of the estimates of the empirical coefficients ("a", "b", "c," and "d") of the simplified models were performed for each station with data grouping, using the iterative Gauss-

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Newton algorithm for nonlinear optimizations by the least squares method, in the Statistica 14.0.0.15 software (TIBCO Software Inc), together with evaluation of the maximization of the coefficients of determination (R^2) and restrictions for Hg < Ho. Sequentially, analyses for the groupings of the models are presented.

2.2.1. Simplified Models Based on Insolation (S) – Group I

The Angstrom-Prescott model was the precursor of this type of estimation (Table 2) and linearly correlates the insolation ratio (Ri) and atmospheric transmissivity (Kt); in this case, the linear coefficient ("a") and angular coefficient ("b") are dependent on regional atmospheric conditions and need to be calibrated locally. Although these coefficients are empirical, they describe two physical possibilities of Hg incidence: i) when Ri tends to zero, the linear coefficient (a) indicates the minimum transmissivity of the atmosphere in the region, given by diffuse radiation; ii) when Ri tends to 1.0, the sum of the two coefficients indicates the maximum transmissivity of the atmosphere in the region on clear days, and the contributions of diffuse and direct radiation [29].

Table 2. Empirical models for indirect estimates of global radiation, based on insolation.

Nº	References	Models
1	Angström [19]; Prescott [20]	Hg/Ho = a + b (S / So)
2	Ögelman et al. [31]	Hg/Ho = a + b (S / So) + c $(S / So)^2$
3	Bahel [59]	Hg/Ho = a + b (S / So) + c $(S / So)^2$ + d $(S / So)^3$
4	Newland [28]	Hg/Ho = a + b (S / So) + c ln (f(S) / So)
5	Togrul & Onat [32]	Hg/Ho = a + b/Ho + c (S / So) / Ho
6	Togrul et al. [33]	Hg/Ho = a + b ln (f(S) / So)
7	Almorox & Hontoria [29]	Hg/Ho = a + b EXP (S / So)
8		Hg/Ho = a EXP (b S / So)
9	Elagib & Mansell [34]	Hg/Ho = a $(S / So)^b$
10		Hg/Ho = a + b $(S / So)^c$
11	El-Metwally [35]	Hg/Ho = $a^{1/(f(S) / So)}$
12	Bakirci [30]	Hg/Ho = a + b EXP (S / So) + c (S / So)
13	Li et al. [38]	Hg/Ho = a + b/Ho + c S / Ho

This methodology is based on obtaining S using Campbell-Stockes heliographs, positioned and aligned according to local latitude, showing the concentration and projection of solar rays in the heliograms, according to the apparent diurnal movement of the Sun (zenith angle). Although simplified, this analysis can indicate changes in the incidence pattern of direct radiation due to the increase in atmospheric multireflection and horizontal brightness when S tends to 0.0 [51]. Furthermore, it is worth noting that there may be an incidence of global radiation at a level below that necessary for the burning of heliograms (estimated at around 120 W m^{-2}); however, these energy levels can be computed as diffuse radiation in cloudy sky conditions [58].

Models 2 to 13 were developed as modifications to the Angstrom-Prescott model, with the insertion of second and third-degree polynomial terms, logarithms, exponentials and potentials, and are functions of the variables S, So and Ho. It was necessary to insert the expression f(S) = (S + 1) in place of S represented in models 4, 6 and 11 because they are models limited to days where there is no sunlight (S = 0). This condition represents 4.5% of the historical series of meteorological stations in the Amazon biome.

2.2.2. Simplified Models Based on Air Temperature (S) – Group II

In general, insolation (S) measurements are limited to a few meteorological stations [4,18]. For example, in China, "S" is monitored in only 30% of the country's stations [1]; specifically, in the

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Amazon biome (region of this study), it is around 27%. In developing countries, air temperature is typically the meteorological variable with the greatest spatial and temporal diffusion of measurements due to the sensors' simplicity and wide application [45].

Models 14 to 45 (Table 3) are based on different daily correlations between Hg and statistical variations in air temperature, such as maximum temperature (Tmax), mean temperature (Tmed), minimum temperature (Tmin), mean monthly thermal amplitude (ΔTmed), daily thermal amplitude (ΔT = Tmax – Tmin); these models can also be classified into five subgroups, depending on the different combinations of input variables: (Tmax, Tmin, Ho), (Tmed, Ho), (Tmin, Ho), (Tmax, Ho) and (Tmax, Tmed, Tmin, Ho).

Table 3. Empirical models of daily estimates of global radiation based on air temperature.

Nº	References	Models
14	Hargreaves & Samani [21]	$Hg/Ho = a\ \Delta T^{0.5}$
15	Bristow & Campbell [22]	$Hg/Ho = a\ (1 - EXP(-b\ \Delta T^{c}))$
16	Hargreaves et al. [46]	$Hg/Ho = a + b\ \Delta T^{0.5}$
17	Ertekin & Yaldiz [50]	$Hg/Ho = a + b / Ho + c\ Tmed / Ho$
18	Goodin et al. [41]	$Hg/Ho = a\ (1 - EXP(-b\ \Delta T^{c} /Ho))$
19	Thornton & Running [42]	$Hg/Ho = 1 - EXP(- a\ \Delta T^{b})$
20	Weiss et al. [43]	$Hg/Ho = 0.75\ (1 - EXP(- a\ \Delta T^{2} / Ho))$
21	Chen et al. [17]	$Hg/Ho = a + b \ln \Delta T$
22	Abraha & Savage [18]	$Hg/Ho = 0.75\ (1 - EXP(- a\ \Delta T^{2} / \Delta Tmed)$
23	Falayi et al. [24]	$Hg/Ho = a + b\ Tmin$
24		$Hg/Ho = a + b\ Tmax$
25	Panday & Katiyar [48]	$Hg/Ho = a + b\ Tmax / Tmin$
26		$Hg/Ho = a + b\ Tmax / Tmin + c\ (Tmax / Tmin)^{2}$
27		$Hg/Ho = a + b\ Tmax / Tmin + c\ (Tmax / Tmin)^{2} + d\ (Tmax / Tmin)^{3}$
28	Adaramola [23]	$Hg/Ho = a + b\ Tmed$
29		$Hg/Ho = a + b\ Tmin / Tmax$
30	Chen & Li [4]	$Hg/Ho = a + b\ \Delta T$
31		$Hg/Ho = a + b\ Tmin + c\ Tmax + d\ Tmin\ Tmax$
32		$Hg/Ho = a + b\ Tmin + c\ Tmax$
33	Li et al. [27]	$Hg/Ho = a/Ho + b\ Tmin + c\ Tmax$
34	Benghanem & Mellit [45]	$Hg/Ho = a/Ho + b\ \Delta T^{c}$
35	Li et al. [39]	$Hg/Ho = a + (b + c\ Tmed)\ \Delta T^{0.5}$
36	Hassan et al. [7]	$Hg/Ho = a + b\ \Delta T^{c}$
37		$Hg/Ho = a + b\ Ho\ Tmed^{c}$
38		$Hg/Ho = a\ Ho\ Tmed^{b}$
39		$Hg/Ho = a\ EXP(b\ Tmed^{c})$
40		$Hg/Ho = a + b\ Tmed + c\ Tmed^{2}$
41		$Hg/Ho = (a + b\ \Delta T + c\ \Delta T^{2})\ \Delta T^{d}$
42	Jahani et al. [16]	$Hg/Ho = a + b\ \Delta T + c\ \Delta T^{2} + d\ \Delta T^{3}$
43		$Hg/Ho = a + b\ \Delta T^{0.5} + c\ \Delta T^{1.5} + d\ \Delta T^{2.5}$
44	Fan et al. [5]	$Hg/Ho = a + b\ \Delta T + c\ \Delta T^{0.25} + d\ \Delta T^{0.5}$
45		$Hg/Ho = a + b\ \Delta T + c\ \Delta T^{0.25} + d\ \Delta T^{0.5} + e\ Tmed / Ho$

2.2.3. Simplified Models Based on Relative Humidity or Astronomical Variables – Groups III and IV

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In the literature, fewer models have been developed for these input variables since their relationships with global radiation are indirect and have longer response time intervals with Hg. Relative air humidity can be obtained by psychrometric sets (dry bulb and wet bulb) or capacitive sensors, and, in this case, in Brazilian conditions, there is greater availability of daily average values, with models 46 to 49 representing this group. In turn, models 46 to 54 are based on non-meteorological variables and are generally directly associated with the time of year, depending on solar declination (δ) and the numerical ordering of the days throughout the year (DJ – Julian day) and extraterrestrial radiation (Ho) (Table 4).

Table 4. Empirical models of daily estimates of global radiation based on relative air humidity (RHmed) and astronomical variables (δ, Ho, DJ).

Nº	References	Models
46	Elagib et al. [34]	Hg/Ho = a/Ho + b RHmed/Ho
47		Hg/Ho = a/Ho + b (RHmed - Ho)/Ho
48	Falayi et al. [24]	Hg/Ho = a + b RHmed
49	Kolebaje et al. [44]	Hg/Ho = a + b $RHmed^{0.5}$
50	Ertekin & Yaldiz [50]	Hg / Ho = a / Ho + b δ / Ho
51	Togrul & Onat [32]	Hg / Ho = a / Ho + b sen δ / Ho
52	Togrul & Onat [32]	Hg / Ho = a + b / Ho
53	Al-Salaymeh [51]	Hg / Ho= a / Ho + b sen (2 π DJ / c + d) / Ho
54	Al-Salaymeh [51]	Hg / Ho = (a + b DJ + c DJ^2 + d DJ^3 + e DJ^4) / Ho

2.2.4. Hybrid Models – Group V

Complex or hybrid models aim to improve the performance of simplified empirical models [16] since, in addition to the direct influence of global radiation on air temperature or insolation, other astronomical and geographic factors can directly interfere with the incidence of radiation on the Earth's surface [45]. Table 5 presents 33 models dependent on the relationships between ϕ, Ho, S, So, Tmax, Tmed, Tmin, RHmed, ΔT and δ.

Table 5. Hybrid empirical models of daily estimates of global radiation with meteorological and astronomical variables.

Nº	References	Models
55	Glover & McCulloch [60]	Hg/Ho = a cos ϕ + b (S / So)
56		Hg/Ho = a EXP (b (S / So - RHmed))
57	Swartman & Ogunlade [53]	Hg/Ho = a + b RHmed + c S / So
58		Hg/Ho = a $RHmed^b$ $(S / So)^c$
59	Ododo et al. [52]	Hg/Ho = a $Tmed^b$ $RHmed^c$ $(S / So)^d$
60		Hg/Ho = a + b Tmed + c RHmed + d Tmed + e(S / So)
61	Elagib et al. [34]	Hg/Ho = a/Ho + b (RHmed - ΔT - Ho)/Ho
62	Chen et al. [17]	Hg/Ho = a + b ln ΔT + c $(S / So)^d$
63		Hg/Ho = a + b Tmed + c (S / So)
64	Falayi et al. [24]	Hg/Ho = a + b Tmin + c (S / So)
65		Hg/Ho = a + b Tmax + c (S / So)
66		Hg/Ho = a + b Tmed + c RHmed + d (S / So)
67	El-Sebaii et al. [36]	Hg/Ho = a + b Tmed + c RHmed
68	Adaramola [23]	Hg/Ho = a + b (Tmin/Tmax) RHmed / 100
69		Hg/Ho = a + b Tmax + c ΔT + d RHmed

70	Korachagaon & Bapat [62]	Hg/Ho = a + b Tmax + c Tmin + d ΔT + e RHmed
71	Chen & Li [4]	Hg/Ho = a + b $\Delta T^{0.5}$ + c (S / So)
72		Hg/Ho = a + b Tmin + c Tmax + d (S / So)
73		Hg/Ho = a + b Tmax + c Tmin + d RHmed + e (S / So)
74		Hg/Ho = a + b $\Delta T^{0.5}$ + c RHmed
75	Li et al. [27]	Hg/Ho = a /Ho + b Tmin + c Tmax + d RHmed
76		Hg/Ho = a /Ho + b Tmin + c Tmax + d RHmed / Ho
77		Hg/Ho = a / Ho + b √ (ΔT) + c RHmed
78		Hg/Ho = a / Ho + b √ (ΔT) + c (RHmed / Ho)
79	Saffaripour et al. [47]	Hg/Ho = a + b / Ho + c Tmax / Ho + d (S / So) / Ho
80		Hg/Ho = a + b / Ho + c RHmed / Ho + d (S / So) / Ho
81		Hg/Ho = a + b sen δ + c (S / So)
82	Lee [37]	Hg/Ho = a + b $(S / So)^c$ + d ΔT^e
83	Li et al. [40]	Hg/Ho = a (1 + b RHmed) $\Delta T^{0.5}$
84		Hg/Ho = a (1 + b RHmed) (1 - EXP(-c ΔT^d))
85	Kolebaje et al. [44]	Hg/Ho = a + b ΔT / f(S)
86		Hg/Ho = a + b $((\Delta T + RHmed) / So)^{0.5}$
87	Yildirim et al. [9]	Hg/Ho = a + b RHmed + c S / So + d $(S / So)^2$ + e $(S / So)^3$

2.3. Statistical Performance of Empirical Models

After local calibrations of the coefficients of each model, the t-test (which is a hypothesis test) was performed to assess the significance (adopted value of $p < 0.05$) of the model coefficient (βa) about the standard error of the estimated coefficient (SEβa), to verify the possibility of using the coefficients and models in the estimation of Hg (equation 08).

$$\text{Test} - \text{t} = \frac{\beta_a}{SE_{\beta a}} \quad (08)$$

In the literature, several statistical indicators evaluate the performance of statistical or parametric models used in meteorological and climate estimates, including obtaining Hg [63,64]. In general, the use of the root means square error (RMSE), mean beans error (MBE), Wilmott's "d" index and the coefficient of determination or R^2 (equations 09 to 12, respectively) has been recommended.

According to Adaramola [23], the MBE indicator, when positive, represents overestimates, and, when negative, indicates underestimates of the variable studied; the disadvantage of this indicator is that high values with different signs may end up canceling each other out, generating a small error, which impairs the analysis of the estimation model. The RMSE index, on the other hand, is represented only by positive values and has values close to zero as ideal. Since it is a quadratic function, large variations in the data can increase the values; that is, it is a metric of how the estimated values are spread about the measured ones. The Willmott index or "d" is an indicator that provides dimensionless values between 0 and 1, and the higher the value, the better the model's performance. The coefficient of determination or R^2 indicates the quality of the linear relationship between the measured values (independent variable) and estimated values (dependent variable), which varies from 0 to 1, with values closer to 1 indicating better estimates. Although there are several statistical indicators, it is not recommended to use only one quality of fit index in isolation; that is, several indicators should be used together, as they may present different or similar responses regarding the statistical performance of the models analyzed [5,63].

$$\text{RMSE} = \left[\frac{\sum_{i=1}^{N}(Pi - Oi)^2}{N}\right]^{\frac{1}{2}} \quad (09)$$

$$\text{MBE} = \left[\frac{\sum_{i=1}^{N}(Pi - Oi)}{N}\right] \quad (10)$$

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

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Pi - Oi)^2}{\sum_{i=1}^{n}(Oi - O)^2} \quad (12)$$

where: Pi is the estimated value; Oi is the reference value observed at the meteorological stations; O is the average of the reference values; N is the number of observations.

3. Results

Although the Brazilian Amazon biome has a tropical climate, variability was observed between the averages of the meteorological variables in the different seasons evaluated (Table 6). The annual averages and standard errors of the Hg averages ranged from 15.1 ± 3.59 (Belém) to 20.6 ± 4.19 MJ m^{-2} d^{-1} (Monte Alegre) and generated average atmospheric transmissivity coefficients of 0.42 ± 0.12 (Belém) to 0.57 ± 0.11 (Monte Alegre); the annual averages of sunshine (S) ranged from 3.94 ± 2.70 (Eirunepé) to 7.57 ± 2.59 hours (Cametá), totaling sunshine ratios of 0.33 ± 0.22 (Eirunepé) to 0.63 ± 0.21 (Monte Alegre). Regarding air temperatures, variations of 30.94 ± 0.95 ºC (Soure) to 33.54 ± 2.75 ºC (Conceição do Araguaia) were observed for Tmax; from 25.41 ± 1.63 ºC (Sinop) to 27.83 ± 1.56 ºC (Roraima) for Tmed; and from 20.16 ± 2.11 ºC (Sinop) to 25.34 ± 1.51 ºC (Soure) for Tmin; therefore, the annual RHmed varied from 68.54 ± 10.17 (Roraima) to 83.88 ± 6.11% (Barcelos), and the total annual rainfall ranged from 1616 ± 100 (Roraima) to 3205 ± 129 mm (Belém). The annual averages of theoretical variables, such as radiation at the top of the atmosphere (Ho), showed small oscillations (35.76 ± 2.95 to 36.36 ± 2.55 MJ m^{-2} d^{-1}), depending on the local latitudes.

Table 6. Annual averages and standard errors of the averages of meteorological variables (Hg, S, Tmax, Tmed, Tmin, RHmed and rainfall – rainfall of the average annual totals) and astronomical (Ho) for the 20 meteorological stations studied in the Brazilian Amazon.

Stations	Hg (MJ m^{-2}	Ho (MJ m^{-2}	Kt	S (hours	Ri	Tmax (ºC)	Tmed (ºC)	Tmin (ºC)	RHmed (%)	Rainfall
1	17.17±4.	36.23±3	0.47±0.	5.58±3.	0.46±0.	31.29±2	25.60±2	21.68±1	78.42±12	2954±1
2	19.86±5.	36.12±1	0.55±0.	6.95±3.	0.58±0.	31.76±1	27.54±1	23.97±0	76.56±1.	2100±1
3	17.17±5.	35.99±1	0.48±0.	4.77±3.	0.40±0.	32.02±2	26.34±1	22.76±1	83.88±6.	2443±7
4	15.64±4.	36.36±2	0.43±0.	3.94±2.	0.33±0.	31.55±2	25.92±1	22.24±1	70.16±14	1952±7
5	16.12±5.	36.05±1	0.45±0.	5.78±3.	0.48±0.	31.52±2	27.24±1	24.01±0	79.57±6.	2339±1
6	17.15±3.	35.76±2	0.48±0.	5.24±3.	0.44±0.	32.75±2	26.70±1	22.57±1	78.86±5.	2230±1
7	16.34±5.	35.91±2	0.46±0.	5.52±3.	0.46±0.	32.30±2	27.74±1	24.32±1	75.86±9.	2206±9
8	17.52±5.	35.88±1	0.49±0.	6.17±3.	0.51±0.	31.29±2	27.15±1	24.24±1	81.09±6.	2343±1
9	15.22±4.	36.17±1	0.42±0.	4.73±2.	0.39±0.	31.30±2	26.41±1	23.14±1	81.46±7.	2867±4
10	19.13±4.	35.95±3	0.53±0.	6.03±3.	0.50±0.	32.35±2	25.41±1	20.16±2	72.04±15	1952±1
11	15.09±3.	36.04±1	0.42±0.	6.48±2.	0.54±0.	32.67±1	27.27±1	23.56±0	78.49±5.	3205±1
12	20.16±3.	35.91±1	0.56±0.	7.57±2.	0.63±0.	32.47±1	27.75±1	24.23±1	74.36±6.	2230±1
13	18.64±4.	35.79±3	0.52±0.	6.96±3.	0.58±0.	33.54±2	26.83±1	21.60±2	70.50±12	1686±1
14	18.75±4.	36.03±2	0.52±0.	6.24±3.	0.52±0.	32.67±2	27.58±1	23.85±0	74.87±7.	2069±9
15	18.25±3.	35.82±2	0.51±0.	6.36±3.	0.53±0.	32.26±1	26.59±1	22.40±1	76.53±7.	1885±1
16	20.61±4.	36.13±1	0.57±0.	7.53±2.	0.63±0.	31.66±1	27.54±1	23.97±1	75.30±6.	1661±1
17	16.64±4.	36.21±2	0.46±0.	6.70±3.	0.56±0.	33.08±2	26.84±1	22.74±0	78.22±8.	2572±1
18	19.82±4.	35.96±1	0.55±0.	6.89±3.	0.57±0.	30.94±0	27.71±1	25.34±1	76.98±6.	2093±7
19	16.95±3.	36.06±1	0.47±0.	6.22±2.	0.52±0.	31.43±1	26.73±1	23.36±0	78.42±7.	2400±1
20	19.35±4.	35.99±1	0.54±0.	6.49±2.	0.54±0.	33.51±2	27.83±1	23.70±1	68.54±10	1.616±1

Global radiation (Hg, MJ m^{-2} d^{-1}), extraterrestrial radiation (Ho, MJ m^{-2} d^{-1}), transmissivity coefficient (Hg/Ho), insolation (S, hours), photoperiod (So, hours), insolation ratio (S/So), maximum temperature (Tmax, ºC), average

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temperature (Tmed ºC), minimum temperature (Tmin, ºC), average relative humidity (RHmed, %) and rainfall (mm year^{-1}).

When analyzing the correlations between the meteorological variables (Figure 2) together for the 20 meteorological stations, it is observed that for global radiation, only in the correlation with the mean relative humidity (RHmed) does a decrease in Hg occur with an increase in RHmed; in this case, when adjusting the simple linear regression (Hg = 37.74 – 0.2627*RHmed), a correlation coefficient of -0.52 was obtained. On the other hand, the worst correlations are observed with Tmin (r = 0.081). Weak correlations between Hg and Tmin or RHmax are expected since these two variables are interdependent regarding the times of occurrence (normally at night – an absence of solar radiation). Stronger and increasing correlations of Hg with Tmed and Tmax are also observed, with correlation coefficients of 0.56 and 0.66, respectively; as for the insolation (S) measured in the heliographs, it is found that there is a linear coefficient that indicates the existence of S for minimum Hg values of approximately 2.0 MJ m^{-2} d^{-1}, with a correlation coefficient of 0.83 and smaller dispersions.

For the frequency distributions, normal distributions are observed for Tmax, Tmed and Tmin; for Hg and RHmed, the averages occur in percentiles above 60%. Regarding S, there are higher percentages of cloudy days (S = 0) and an increasing frequency of occurrence between 1 and 11 hours of insolation. The Hg interpolations show greater uniformity when associated with Tmax and S. To evaluate the behavior of global radiation throughout the year as a function of the seasonality of rainfall in the Amazon biome, the grouping of monthly data for the 20 meteorological stations was considered, and the values were plotted in boxplots (Figure 3).

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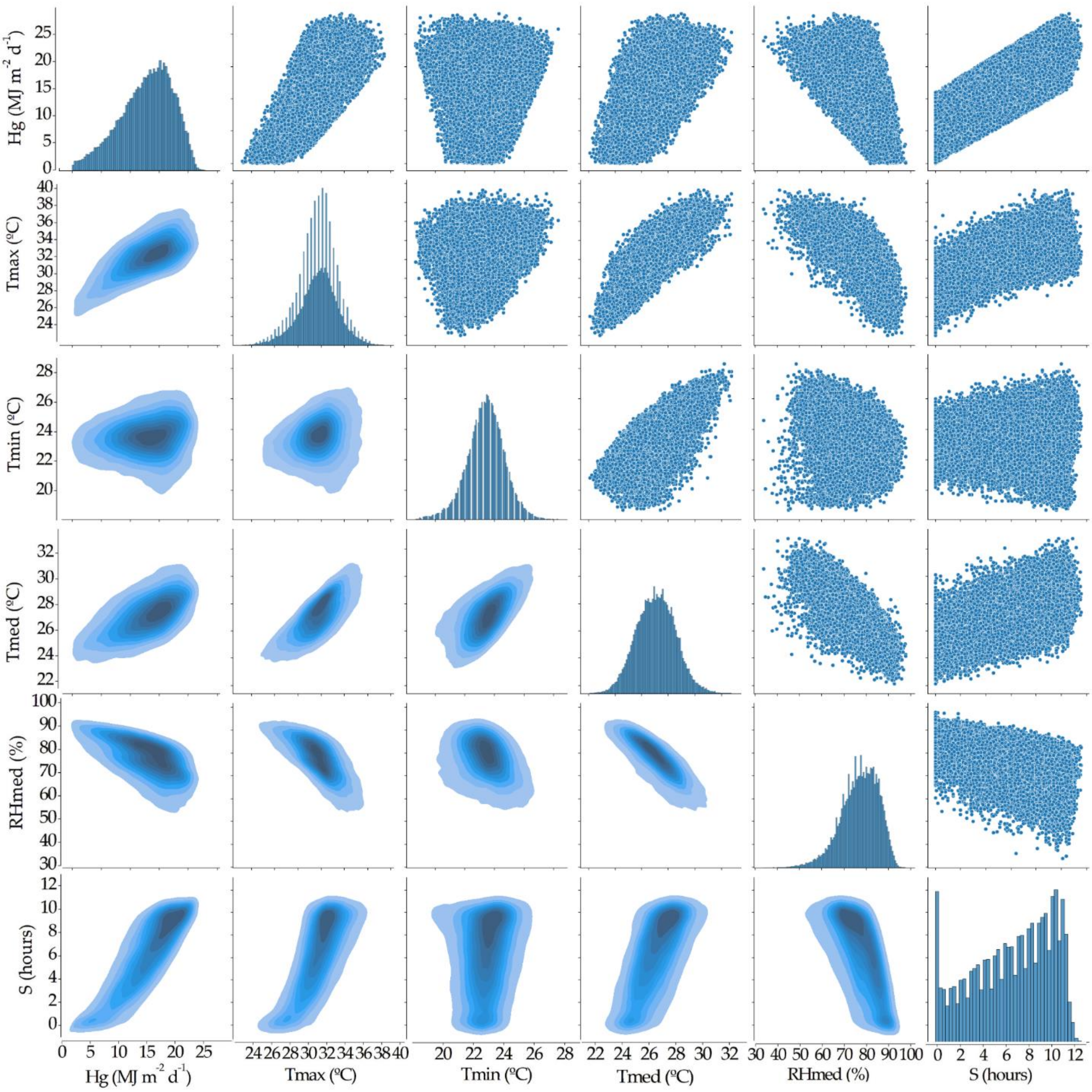

Figure 2. Correlations, frequency distributions and interpolation between meteorological variables (Hg, Tmax, Tmin, Tmed, RHmed, S) in the Brazilian Amazon biome.

Although many meteorological stations are located at close latitudes, the average incident global radiation can vary significantly among themselves; for example, at the meteorological stations of Macapá (0.035º N), Barcelos (-0.98º S) and São Gabriel da Cachoeira (-0.12º S), where the median Hg values were 21.52, 18.09 and 15.79 MJ m^{-2} d^{-1}, respectively; this behavior shows the influence of precipitation (cloudiness) on Hg, since at these meteorological stations, the annual rainfall totals are 2100, 2433 and 2867 mm, respectively. It is also possible to consider in the comparison between these same three meteorological stations that the effect of the proximity of large surfaces of free water (as occurs in Macapá), the incidence of Hg depends on the movements of regional or mesoscale atmospheric circulation; On water-free surfaces, there may be a potential increase in actual water vapor pressures (e_a) in the atmosphere, due to higher levels of direct water evaporation. However, this water vapor can be transported in the atmosphere to other regions by winds, thus reducing the attenuation of water vapor in Hg on a local scale.

In the rainy season (October to April), Hg averages are generally lower compared to the dry season (May to September) in the region. It is worth noting that the minimum values of global radiation as an outlier in the rainy season for most of the EMAs evaluated are related to the presence of clouds. However, they can also occur in the dry season when associated with fires, common in the region during this period. They emit particulate matter that remains suspended in the atmosphere, thus attenuating Hg through absorption and non-selective diffusion and reducing atmospheric transmissivity.

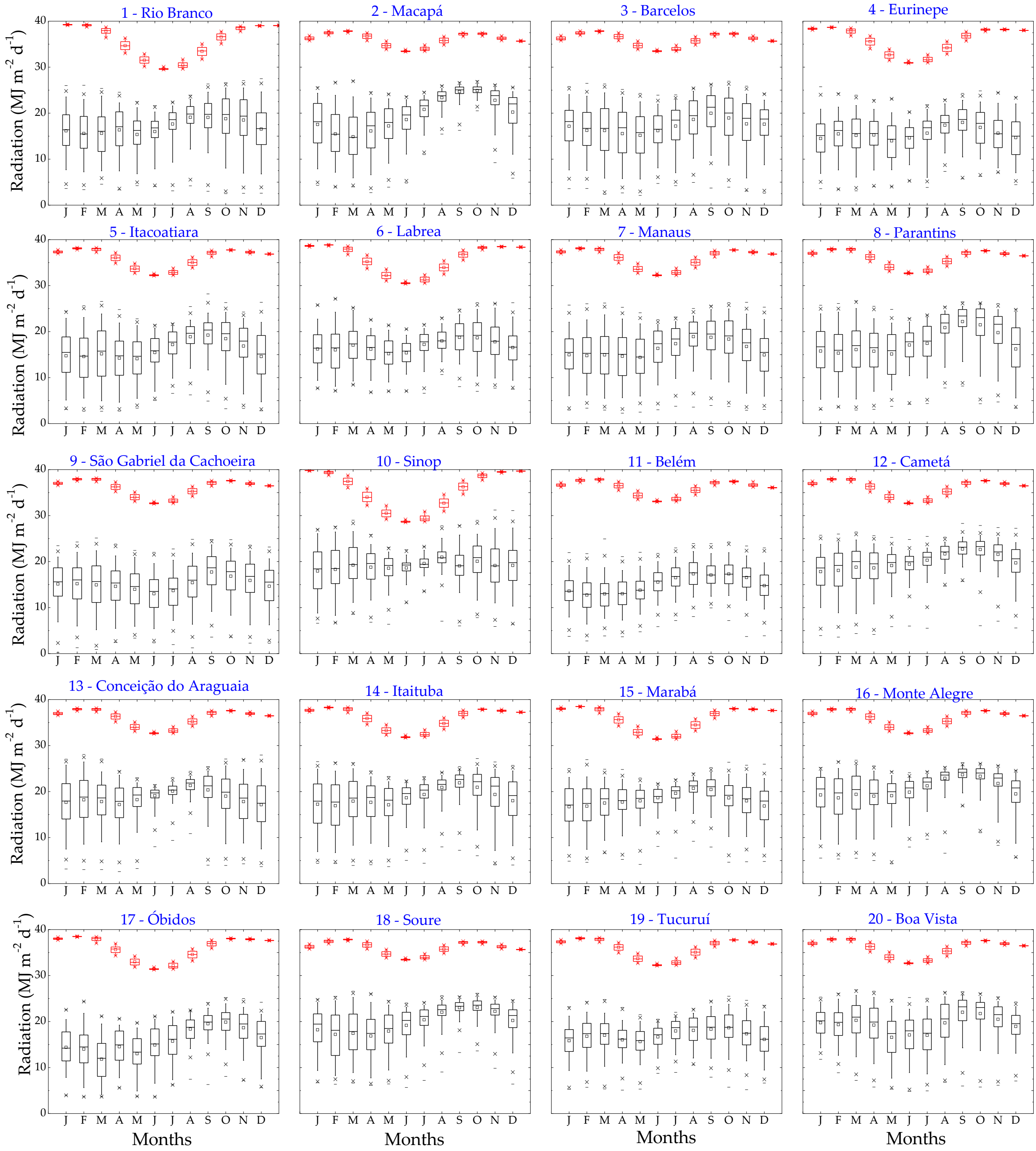

Figure 3. Boxplots of measured global radiation (Hg - black lines and markers) and calculated extraterrestrial radiation (Ho - red lines and markers) for 20 meteorological stations in the Brazilian Amazon, in monthly data clusters.

Another way to observe the variations of Hg in the Brazilian Amazon can be done between meteorological stations located at different latitudes of the biome (Figure 4) by comparing the daily seasonality of Hg throughout the analyzed period for the meteorological stations of Boa Vista (2.82° N), Manaus (3.10° S) and Sinop (11.85° S), it is noted that in Sinop the maximum Hg reached close to 30 MJ m^{-2} d^{-1}. There is less variation in the daily averages in the dry season than in the rainy season. Continuing, as the time of year influences extraterrestrial radiation (Ho), it is clear that in the dry season, due to the solar declination and the latitude of Sinop, the daily Ho values are lower, and, consequently, they can generate higher atmospheric transmissivity coefficients when compared to other meteorological stations in the biome.

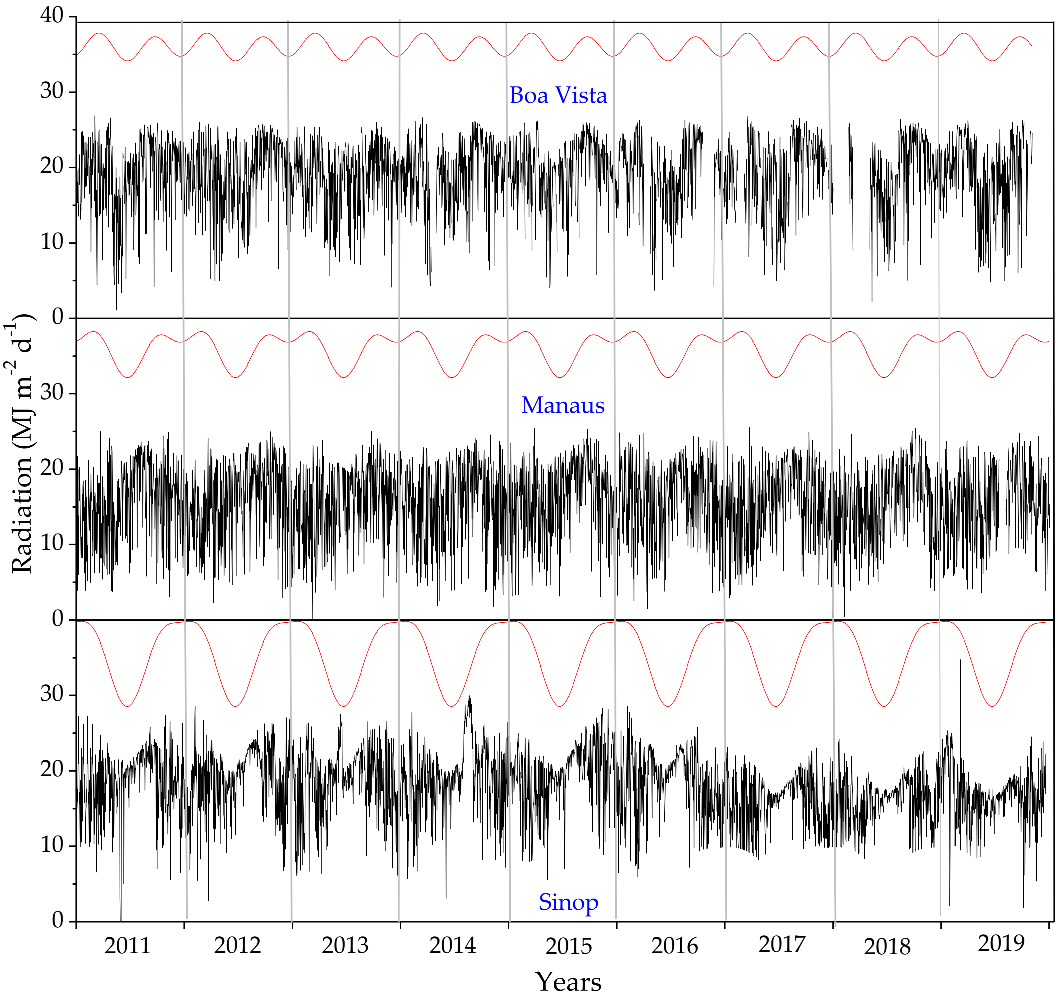

Figure 4. Variation of daily global (Hg - black lines) and extraterrestrial (Ho - red lines) radiation for the meteorological stations of Boa Vista, Manaus and Sinop, in the Brazilian Amazon, over different years of measurements.

Each simplified Hg estimation model's specific coefficients (a, b, c, d) were calibrated using the Statistica software. By using the t-test at a significance level of 5%, the significance of the adjusted coefficients for each model was verified. The values of the adjusted coefficients for the best models in the 20 meteorological stations evaluated can be found in Table 7. The results of the statistical performance indicators (MBE, RMSE and Willmott's "d") were presented only for the models with adjusted coefficients significant at 5%.

The statistical performance of the empirical models was represented in boxplots, grouping all the meteorological stations (Figure 5). Analyzing the models in group I, more significant improvements need to be made when comparing the polynomial changes of the traditional Angstrom-Prescott model (model 1). Overall, for this group, the values of the coefficients of determination (R^2), relative errors (MBE), spreads (RMSE) and fits (d) were, on average, 0.7780, -0.01 MJ m^{-2} d^{-1}, 2.09 MJ m^{-2} d^{-1} and 0.9310, respectively. In this group, model 11 (Hg/Ho = a(1/(f(S)/So))

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presented the worst statistical performances, with R2, MBE, RMSE and average d of 0.4980, -0.329 MJ m^{-2} d^{-1}, 3.34 MJ m^{-2} d^{-1}, 0.9140, respectively. And, when comparing the models that present the same analytical basis, it is observed that model 10 [Hg/Ho = a + b $(S/So)^c$] presented superior statistical performance to the remaining models dependent on insolation (S) with R^2, MBE, RMSE and average d of 0.7990, 0.017 MJ m^{-2} d^{-1}, 1.95 MJ m^{-2} d^{-1} and 0.9400.

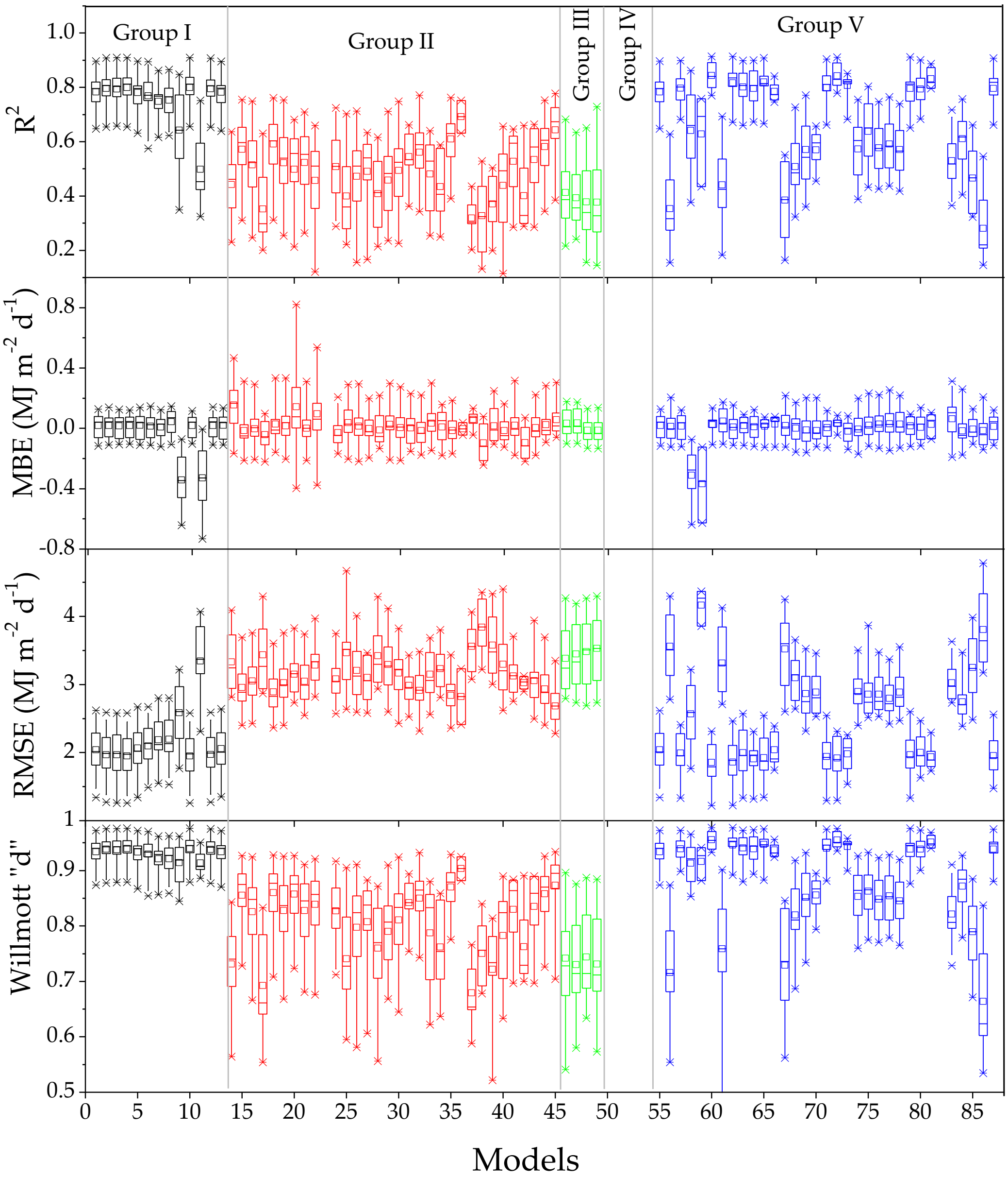

Figure 5. Boxplots of statistical performance indicators (R^2, MBE, RMSE, d) for 87 simplified Hg estimation models, considering the grouped values of 20 meteorological stations of the Brazilian Amazon biome. Where: coefficient of determination (R^2), mean beans error (MBE), root mean square error (RMSE) and Willmott's concordance index (d).

Regarding the simplified models of group II (based on air temperature), model 23 [Hg/Ho = a + b Tmin] was dependent only on Tmin, and Ho was NS for all meteorological stations evaluated. This behavior is expected because the minimum air temperature is not simultaneous with the incidence of solar radiation. Model 24 [Hg/Ho = a + b Tmax], dependent on Tmax and Ho, was the only model with significant coefficients in all meteorological stations evaluated; however, it did not present the best statistical performance indicators on average. In general, of the 32 models evaluated in this group

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(involving air temperature), model 17 [Hg/Ho = a + b/Ho + c Tmed/Ho] presented the worst statistical performance, with R^2, MBE, RMSE and Wilmott's d average of 0.3520, 0.099 MJ m^{-2} d^{-1}, 3.43 MJ m^{-2} d^{-1} and 0.6930, respectively; model 45 [Hg/Ho = a + b ΔT + c $\Delta T^{0.25}$ + d $\Delta T^{0.5}$ + e(Tmed/Ho)] presented the best performance with R^2, MBE, RMSE and average d of 0.6430, 0.056 MJ m^{-2} d^{-1}, 2.68 MJ m^{-2} d^{-1} and 0.8730, however, not presenting significant adjustments for the meteorological stations located in Cametá and Tucuruí.

Empirical models that employ the thermal amplitude (ΔT = Tmax – Tmin) as an input variable present a better estimate. Comparing the performance of models 14 [Hg/Ho = a ΔT0.5] and model 16 [Hg/Ho = a + b $\Delta T^{0.5}$], it is observed that the insertion of the linear coefficient significantly improves the statistical performance, since the R2 values varied from 0.4420 to 0.5150, with a reduction in MBE from 0.154 to -0.003 MJ m^{-2} d^{-1} and in RMSE from 3.33 to 3.05 MJ m^{-2} d^{-1}, and also with an increase in the adjustment index (d) from 0.7312 to 0.8257.

The simplified models of group III (based only on the average daily relative humidity - RHmed) did not present significant coefficients by the t-test at the meteorological stations of Eirunepé, São Gabriel da Cachoeira and Sinop. As a rule, the statistical performance of the models in group III was worse when compared to the models in the other groups. In this case, the best estimates in this group were generated by model 46 [Hg/Ho = a / Ho + b(RHmed/Ho)], with R^2, MBE, RMSE and d values of 0.4130, 0.034 MJ m^{-2} d^{-1}, 3.38 MJ m^{-2} d^{-1} and 0.7420, respectively. As for the models in group IV (based on astronomical variables), none presented statistical significance for any of the meteorological stations evaluated. In group V (hybrid models), the best estimates of Hg were generated by model 62 [Hg/Ho = a + b lnΔT + c $(S/So)^d$], with mean values of R^2, MBE, RMSE and d of 0.8170, 0.008 MJ m^{-2} d^{-1}, 1.86 MJ m^{-2} d^{-1} and 0.9460, respectively.

Considering only the models that presented the best statistical performances in each group (Figure 6), it is observed that in most meteorological stations, the best Hg estimates were generated by models 62 and 10. In this case, model 62 presented values ranging from 0.6714 to 0.9137 for R^2, from -0.112 to 0.154 MJ m^{-2} d^{-1} for MBE, from 1.22 to 2.46 MJ m^{-2} d^{-1} for RMSE, and from 0.8921 to 0.9772 for the adjustment index (d); Model 10 presented variations in R^2 from 0.6549 to 0.9091, MBE from -0.103 to 0.115 MJ m^{-2} d^{-1}, RMSE from 1.26 to 2.58 MJ m^{-2} d^{-1} and "d" index from 0.8793 to 0.9760.

The main difference between the input variables of these two models is the addition of the Naperian logarithm (ln) in the thermal amplitude (Tmax – Tmin) in model 62, which did not significantly improve the model's predictive capacity. However, it is noteworthy that these two models (62 and 10) are based on sunlight; therefore, in cases of minimum data availability, model 45, which depends only on air temperature, should preferably be used since it generates better responses than models associated with relative humidity.

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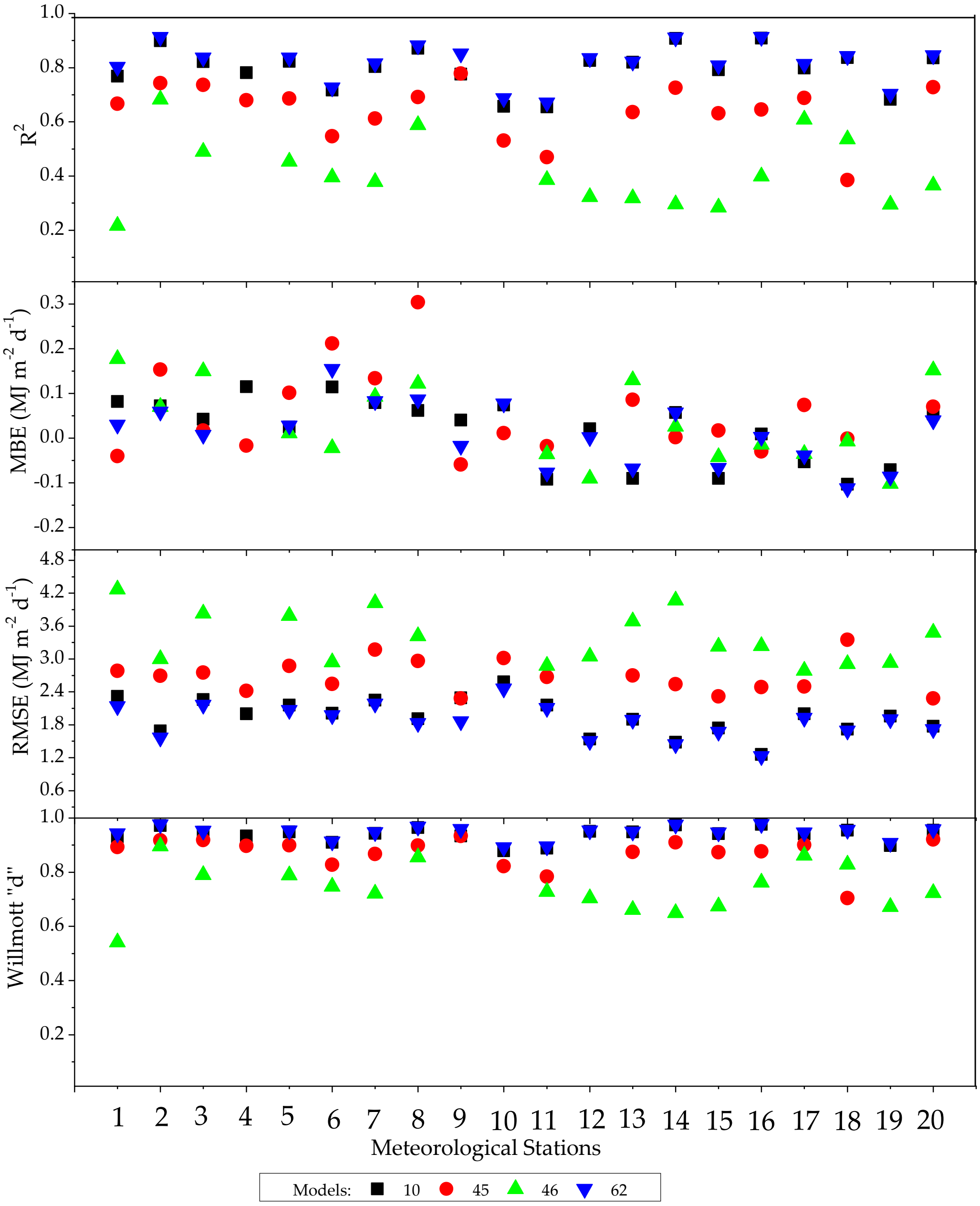

Figure 6. Statistical performance indicators of each group's best simplified estimation models (models 10, 45, 46 and 62) for 20 meteorological stations of the Brazilian Amazon biome. Where coefficient of determination (R^2), mean beans error (MBE), root mean square error (RMSE) and Willmott's concordance index (d).

Figure 7 presents the dispersions of Hg measured and estimated by models 10, 45 and 62 for the three aforementioned meteorological stations that represent the latitude variation in the Amazon biome (Boa Vista, Manaus and Sinop). In this case, four different classes of atmospheric transmissivity were considered, which represent the conditions of cloudy sky ($0 < Kt < 0.35$), partly cloudy with predominance of diffuse radiation ($0.35 < Kt < 0.55$), partly open with predominance of direct radiation ($0.55 < Kt < 0.65$) and open sky ($Kt > 0.65$), as recommended by Escobedo et al. [65] and Souza et al. [10]. Almost always, the global radiation estimated by models 10 and 62 are similar and follow close to the reference line (1:1), with greater dispersion of the estimated values when Kt is below 0.55.

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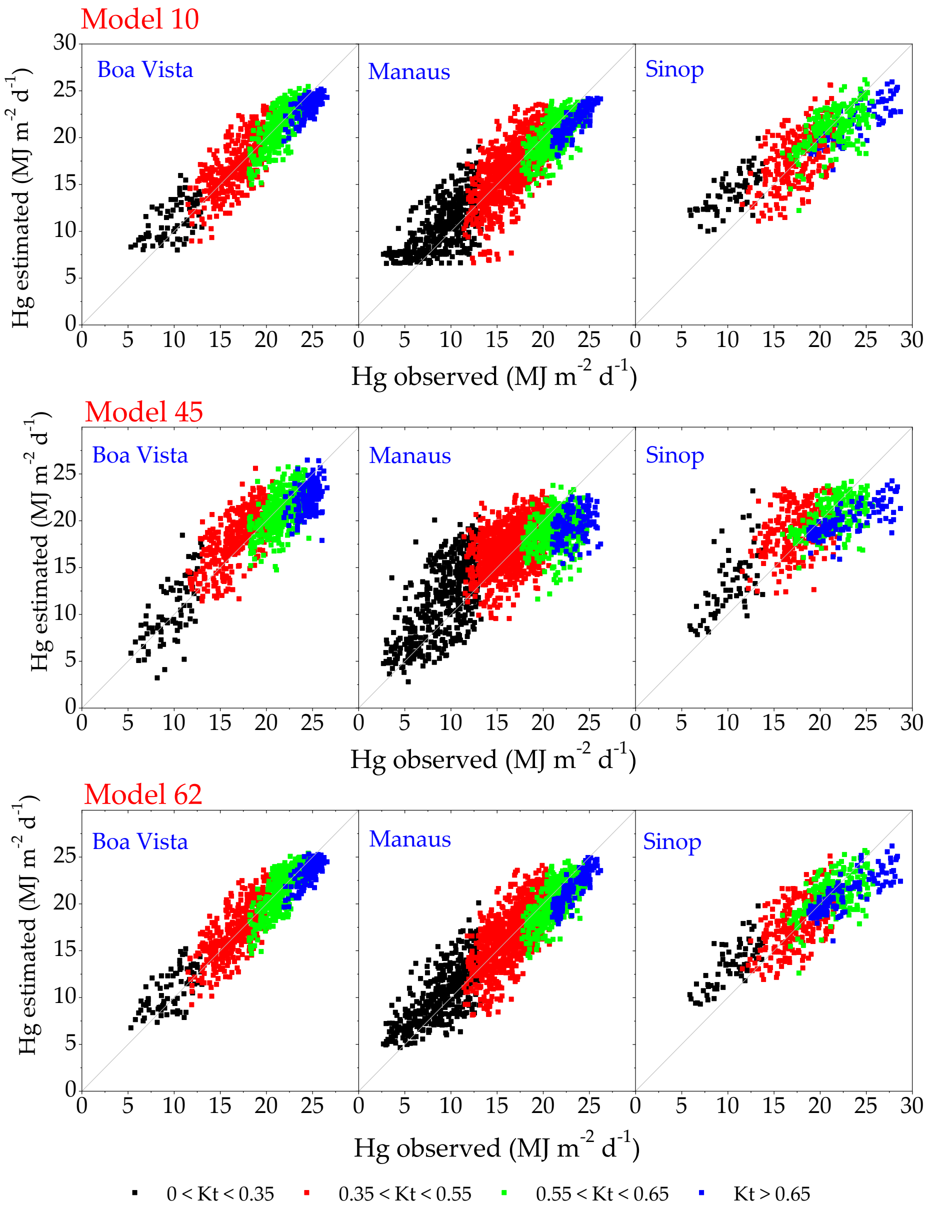

Figure 7. The dispersion between the global radiation measured and estimated by models 10, 45 and 62 for the meteorological stations of Boa Vista (RR), Manaus (AM) and Sinop (MT) in different classes of atmospheric transmissivity. (The gray line represents the relationship 1:1 or y = x).

The absolute accumulated error in the frequency of occurrence (Figure 8) up to the value of 2.0 MJ m-2 d-1 in the Hg estimate using models 10, 45 and 62 at the meteorological stations of Boa Vista was 84, 83, 85% and Sinop was 67, 68 and 68%, however in Manaus there was a significant difference in the values, with 75, 64 and 82%. Depending on the city evaluated, the frequency of the accumulated error up to 2.0 MJ m^{-2} d^{-1} can be high (Boa Vista) or low (Sinop); that is, local meteorological conditions directly influence the error.

The reduction of the accumulated absolute error by up to 2.0 MJ m^{-2} d^{-1} in meteorological conditions of low atmospheric transmissivity (0 < Kt < 0.35) is more efficient in the hybrid model 62 (55 to 85%) when compared to model 10 (33 to 80%) and mainly model 45 (38 to 74%), following the same trend in meteorological conditions of high atmospheric transmissivity (Kt > 0.65) with accumulated frequency of model 62 of 82 to 93%, model 10 of 78 to 87% and model 45 of 32 to 71% respectively. In the condition of partially cloudy skies with a predominance of diffuse radiation (0.35

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< Kt < 0.55), when comparing model 10 (67 to 81%) and model 62 (67 to 79%), there was no difference in the accumulated error, however model 45 (60 to 70%) had the greatest possibility of errors above 2.0 MJ m^{-2} d^{-1}, and this pattern was repeated in the condition of partially open skies with a predominance of direct radiation (0.55 < Kt < 0.65) with model 10 (87 to 93%), model 62 (88 to 92%) and model 45 (71 to 84%).

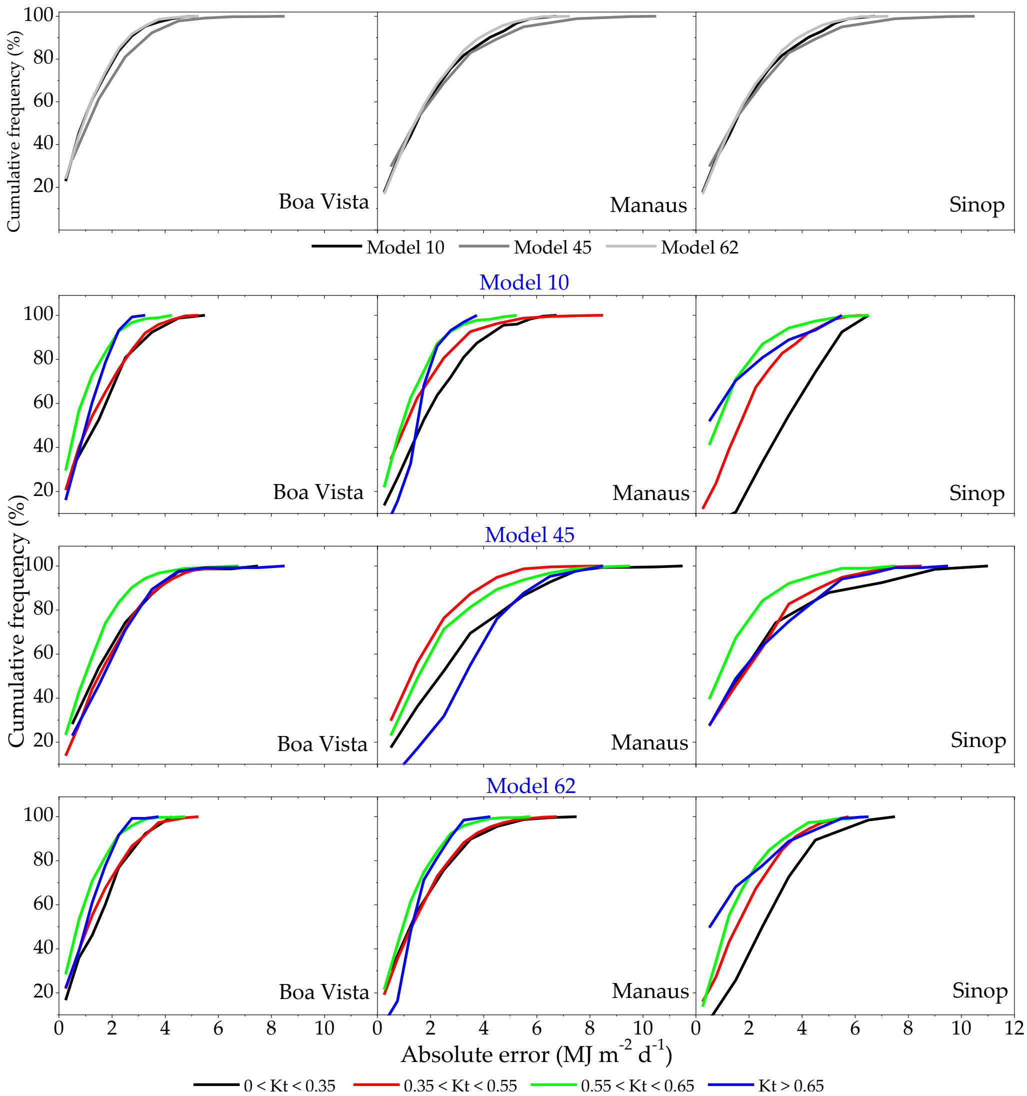

Figure 8. Absolute error frequency at the meteorological stations of Boa Vista, Manaus and Sinop, for models 10, 45 and 62 and different atmospheric transmissivities.

To allow applications and estimates of Hg, the adjusted coefficients are presented only for these three simplified models (10, 45 and 62), in the 20 meteorological stations evaluated in the Amazon biome (Table 7). In some cities, models 45 and 62 were NS (no signifcative), and for group II (based on air temperature), model 65 is recommended for the cities of Cametá [$Hg = (-0.0942 + (-0.2688 + 0.0179 * Tmed) * \Delta T^{0.5}) * Ho$] and Tucuruí [$Hg = (0.0655 + (-0.1478 + 0.0108 * Tmed) * \Delta T^{0.5}) * Ho$] and in group V (hybrid combination) model 72 presented the best performance for the city of Eirunepé [$Hg = (-0.0947 - 0.0077 * Tmin + 0.0188 * Tmax + 0.3163 * (S/So)) * Ho$].

Table 7. Calibrated coefficients for models 10, 45 and 62 of estimates of daily global radiation for each meteorological station evaluated in the Brazilian Amazon biome.

Met.	Model 10				Model 62				
Stations	a	b	c	R^2	a	b	c	d	R^2

1	0.2122	0.4784	0.7003	0.772	0.0324	0.1163	0.3607	0.8035	0.8052
2	0.1995	0.538	0.7178	0.8958	0.0396	0.1123	0.4516	0.8104	0.9071
3	0.2142	0.4846	0.5639	0.8045	0.0351	0.1127	0.3832	0.6435	0.8262
4	0.2233	0.4343	0.5737	0.758	-	-	-	-	-
5	0.1817	0.4678	0.6911	0.8221	0.0479	0.0936	0.3885	0.7413	0.8376
6	0.2769	0.3842	0.6852	0.7606	0.1265	0.0815	0.3178	0.683	0.7777
7	0.2041	0.4737	0.7516	0.7846	0.0518	0.0969	0.4094	0.8466	0.7992
8	0.1672	0.527	0.6562	0.8933	0.0733	0.0728	0.4662	0.7124	0.9003
9	0.1825	0.4718	0.6701	0.7713	-0.0453	0.1738	0.2741	0.9689	0.8673
10	0.3103	0.4191	0.852	0.6359	0.1515	0.0821	0.3388	0.8233	0.665
11	0.2171	0.3681	0.9748	0.6563	0.0794	0.0846	0.3203	1.25	0.6658
12	0.2159	0.4893	0.7101	0.8452	0.1109	0.0687	0.4474	0.7844	0.852
13	0.197	0.494	0.6848	0.8221	0.1327	0.041	0.4448	0.6997	0.8263
14	0.2113	0.494	0.6286	0.887	0.1042	0.0718	0.4294	0.6683	0.8954
15	0.2355	0.4382	0.6629	0.8081	0.0935	0.0862	0.36	0.6808	0.8256
16	0.2055	0.5173	0.6947	0.9029	0.1331	0.0499	0.4823	0.7233	0.9068
17	0.1968	0.4229	0.7587	0.794	0.0487	0.0876	0.3483	0.8363	0.8065
18	0.278	0.4029	0.6001	0.8422	0.2053	0.045	0.4053	0.6424	0.8477
19	0.2549	0.3692	0.778	0.6905	0.123	0.0836	0.3203	0.9069	0.7108
20	0.2453	0.4656	0.7138	0.8429	0.1176	0.0766	0.4036	0.7679	0.8503

Met.	Model 45					
Stations	a	b	c	d	e	R^2
1	7.1	-0.413	-13.02	6.47	0.3146	0.6513
2	18.05	-1.06	-32.94	16.11	1.08	0.7264
3	6.68	-0.3971	-13.03	6.39	1.04	0.7197
4	4.56	-0.2595	-8.59	4.26	0.4144	0.6825
5	12.48	-0.7875	-23.28	11.62	0.7932	0.7007
6	10.72	-0.5403	-18.54	8.83	0.3082	0.6095
7	14.57	-0.8666	-26.66	13.08	0.8747	0.6124
8	13.14	-0.9469	-25.69	13.19	1.17	0.7341
9	1.52	-0.0997	-3.45	1.84	0.4104	0.8
10	7.33	-0.3692	-12.76	6.12	0.2696	0.4998
11	13.04	-0.6702	-22.98	10.87	0.8086	0.4661
12	-	-	-	-	-	-
13	2.93	-0.2	-6.02	3.16	0.3889	0.629
14	13.7	-0.8282	-25.04	12.42	0.5538	0.6981
15	5.06	-0.3339	-9.95	5.1	0.4996	0.6639
16	27.61	-1.71	-50.07	24.76	1.09	0.6741
17	13.64	-0.6925	-23.86	11.31	0.5745	0.6767
18	-33.41	1.81	55.84	-26.79	1.72	0.3738
19	-	-	-	-	-	-
20	11.07	-0.5971	-20.36	9.72	1.17	0.7435

4. Discussion

The results found in this study provide details of the local calibration and statistical significance of the coefficients of 87 models for daily estimation of global radiation in tropical climate regions, having as input variables meteorological data that can be easily made available by routine measurements at meteorological stations. Determining the significance of the coefficients of each model is relevant information in the modeling since the lower P-value of the t-test at the α significance level (5%) indicates that in the region evaluated, the meteorological and environmental conditions may be complex and cause greater uncertainties in the Hg estimate [30]. This can be observed by the large number of models with locally calibrated NS coefficients. As observed in Figures 2 to 4, insolation (S) and global radiation (Hg) incidents in the Amazon biome are significantly influenced by atmospheric components, such as the emission of aerosols into the atmosphere through the burning of vegetation in the dry season of the Amazon basin [14] or the presence of clouds due to high rainfall in the rainy season [56,66].

These conditions are the main factor in attenuating Hg and the increase in uncertainty in insolation values due to the sensitivity to heliograph burning and maintenance. According to the results (Figure 5), the best statistical performance was obtained by modifying the Angstrom-Prescott linear model to a model that uses power in its explanatory variable [$Hg/Ho = a + b (S/So)^c$]. According to Almorox & Hontoria [29] and Bakirci [30], depending on the atmospheric transmissivity conditions, the relationship between S and Hg can be better represented by linear, polynomial, logarithmic, exponential or hybrid correlations. For Santos et al. [25], even in conditions of absence of cloudiness (open sky), elements present in the Earth's atmosphere can attenuate solar radiation by diffusion (scattering) and influence Hg.

When evaluating the different models of group I under the climatic conditions of Turkey, Bakirci [30] did not observe significant differences in the statistical performances of the linear, exponential and logarithmic models, obtaining coefficients of determination (R^2) greater than 0.96 and MBE values ranging from 0.20 to 0.24 MJ m^{-2} d^{-1} and RMSE from 1.31 to 1.35 MJ m^{-2} d^{-1}. Almorox & Hontoria [29], in sixteen cities in Spain, evaluated linear and polynomial models of the second and third-degree, logarithmic and exponential based on insolation (S) and concluded that all statistical models could be used to estimate Hg with good precision, however, they recommend the linear model due to its simplicity and because it presents better statistical performance.

It was observed that the performance of models 8, 9 and 11, which do not have a linear coefficient (a), was lower in all cities. According to Prieto & García [6], this coefficient represents the minimum transmissivity of the region's atmosphere and is associated with diffuse radiation. In the Amazon, this condition represents a considerable part of global radiation due to the seasonality of rainfall and changes in the composition of the atmosphere [10], and, therefore, models that do not present coefficients that characterize days with low atmospheric transmissivity, can generate larger errors for adjustments in annual or seasonal groupings; in cases of monthly adjustments, these models can potentially present good estimates for dry months (absence of cloudiness) in some regions of the Amazon.

Still regarding interference, in some regions, climate change can increase precipitation, which results in a reduction in atmospheric transmissivity and consequently in the adjustment of models, as is the case in the city of Boa Vista, which, according to Araújo et al. [66], analyzing the period of meteorological data from 1961 to 2020, there was an increase in precipitation from 1,420.4 to 1,761.8 mm $year^{-1}$ and in the average air temperature from 27.4 to 28.2 ºC, after analyzing the period of meteorological data from 1961 and 2020 and the variations between the two climatological normal.

For group II models (based on air temperature), the best estimates of daily global radiation were obtained with the model insert model number here [$Hg/Ho = a + b (Tmax - Tmin) + c (Tmax - Tmin)^{0.25} + d (Tmax - Tmin)^{0.50} + e (Tmed/Ho)$], corroborating the results found by Qiu et al. [1]. These authors evaluated 78 models based on air temperature for 105 meteorological stations in China and concluded that models that relate thermal amplitude ($\Delta T = Tmax - Tmin$), maximum, mean and minimum temperatures (Tmax, Tmed and Tmin) present better estimates. In models based on air temperature, ΔT is related to several local factors that directly influence the radiation and energy balance, such as latitude, rainfall, current water vapor pressure, atmospheric transmissivity (cloudiness), proximity to large free water surfaces, among other factors [25]. This is an essential parameter in models based only on air temperature when the aim is to improve predictive capacity since ΔT has a good correlation with Hg [1].

It is also worth noting that the statistical performance of the empirical models of groups I and II in estimating Hg in the Amazon can be considered satisfactory. Sometimes, depending on the study

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region and the input variables, an empirical model may present variable performance depending on the climatic conditions of the region; for example, in this study under tropical conditions, model 37 [Hg/Ho = a + b Ho Tm^c] presented the worst performance in group II with coefficients of determination ranging from 0.2765 to 0.4000. In these cases, the adjusted coefficients were insignificant in 55% of the meteorological stations evaluated. However, for the Cairo region (Egypt) - dry and desert climate, Hassan et al. (2016), evaluating 20 models based on air temperature, found that this same model (37) presented the best statistical performance in daily Hg estimates, with RMSE of 0.5813 MJ m^{-2} d^{-1} and R^2 of 0.9897.

The significance of regionally calibrated empirical models can be considered the combination of two factors: the first related to the input meteorological variables representing the location's environmental conditions, and the second due to the empirical model's structure. The lowest performances in the estimation of Hg were obtained with the empirical models based on relative humidity (group III). Group III models generally presented good estimates in arid regions with low annual rainfall totals, such as Nigeria [24,44], Bahrain [34] and Turkey [50].

The five models in group IV were NS for all 20 meteorological stations evaluated. Astronomical input variables, such as solar declination, photoperiod and Julian day, are variables that do not consider local factors related to atmospheric and geographic conditions, which can directly interfere with global radiation incidents on the surface, where the use of radiometric fractions aims to minimize these effects [10,65]. Group IV models are used in countries with arid regions, low rainfall and high atmospheric transmissivity, such as Saudi Arabia [45] and Jordan [51]. Although the statistical performances of hybrid models (group V) were better when compared to simple models with air temperature (group II) and relative humidity (group III), these differences are reduced when compared to models based on insolation (group I) (Figure 6). Several studies report considerable differences in the performance of simple models compared to hybrid models in different climatic regions [2,4–6,16,25].

When analyzing the variations in estimates at meteorological stations at different latitudes in the Amazon (Figure 7), it is again observed that, in general, the models have greater difficulty in estimating days and times of the year with intermediate atmospheric transmissivity (partly cloudy or partially clear skies). According to Santos et al. [25], different combinations of cloud cover can result in the same ΔT value, but each combination of cloud cover results in a single Hg value.

Another point to be highlighted is that using models based on air temperature generally leads to overestimations of Hg [2,5,18,25]. This behavior occurs because air temperature depends on surface heating processes, energy balance, and heat transport, which in turn can reflect levels of sensible heat higher than those that would potentially be generated exclusively by incident Hg.

Models 10, 45 and 62 presented consistencies in Hg estimates, each with its input variables (groups). Due to the spatial distribution of the 20 meteorological stations evaluated, they can be used in the Brazilian Amazon. Despite the good adjustments of empirical models found in this work, according to Prieto & García [6], after reviewing articles published in the last 100 years on this topic, they found that none of the 165 empirical models with different input variables were consistent and presented good performances in the different climatic regions. This becomes more worrying with climate change scenarios, which predict rising air temperatures, changes in rainfall patterns and gas concentrations, which will directly interfere with the radiation balance [2,13]. This climate change scenario has also been observed in the Amazon biome region, with increased rainfall and air temperature [66,67]. Therefore, it is essential to understand and make available as many models for estimating meteorological variables as possible, allowing regional calibrations and applications in large databases to fill gaps and generate long and consistent databases.

Finally, the empirical models must be recalibrated when these climate change conditions materialize. New studies, mainly in smaller data groups (seasonal and monthly), must be conducted to update the coefficients and maintain the predictive capacity of the different empirical models.

5. Conclusions

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The most accurate empirical models for estimating global radiation (Hg) for the Brazilian Amazon biome were first the hybrid model based on insolation and air temperature, represented by $[\mathrm{Hg/Ho = a + b\,ln\Delta T + c\,S/So^{d}}]$, followed by the model based on insolation $[\mathrm{Hg/Ho = a + b\,S/So^{c}}]$, and finally the model based on air temperature $[\mathrm{Hg/Ho = a + b\Delta T + c\Delta T^{0,25} + d\Delta T^{0,5} + e\,Tmed/Ho}]$ in the Brazilian Amazon biome.

It is not recommended to use simplified models based solely on relative humidity or astronomical variables to estimate Hg in the Amazon, in annual data groupings; these models may present better statistical performances if they are locally calibrated for meteorological stations with well-defined dry and rainy seasons.

Cloudiness and rainfall seasonality affect atmospheric transmissivity and estimates of global radiation. In this case, future updates of these analyses should consider the models that generated the best estimates and seek analyses in seasonal (year or water seasons) and monthly database groupings. The recommendation of simplified models that produce good Hg estimates will also allow comparisons with other methodologies, such as machine learning and reanalysis.

Therefore, generating conditions that allow knowledge of global radiation will contribute to numerous agricultural and environmental applications, providing a comprehensive context for applying these estimates on larger spatial and temporal scales.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Tables 8 to 94 - adjusted coefficients for each simplified model and statistical performance indicators in the 20 meteorological stations evaluated.

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