Revista Brasileira de Climatologia
ISSN: 2237-8642 (Eletrônica)

DOWNWARD LONGWAVE RADIATION ESTIMATES FOR CLEAR AND ALL-SKY CONDITIONS IN CENTRAL AMAZONIA

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Submetido em: 30/03/2019
Aceito para publicação em: 14/05/2021
Publicado em: 27/05/2021
DOI: http://dx.doi.org/10.5380/abclima.v28i0.65725

ABSTRACT: Downward longwave radiation (L↓) is a component of net radiation for which it is difficult to precisely measure values. Therefore, different parameterizations have been proposed to estimate it. In this study we evaluated the performance of various parameterizations for estimated L↓ and their interaction with other measured variables as well as the interactions of air temperature and water vapor pressure with L↓ for clear and cloudy sky days in the central region of Amazonia. The datasets used in this study were measured from a micrometeorological tower managed by Large Scale Biosphere Atmosphere experiment in Amazonia (LBA) near the city of Manaus, Amazonas. The results show that precipitation and water vapor pressure exert a large influence on L↓, especially during the wet season. The models for clear-sky conditions proposed, using their original coefficients, a trend that underestimates the measured L↓ flux. The best results for clear-sky estimates were obtained with Idso & Jackson (1969), Brutsaert (1975) and Prata (1996).

KEYWORDS: Tropical forest; Fractional cloud cover; longwave fluxes.

ESTIMATIVAS DA RADIAÇÃO DE ONDA LONGA INCIDENTE PARA TODAS AS CONDIÇÕES DO CÉU NA AMAZÔNIA CENTRAL

RESUMO: A radiação de onda longa incidente (L↓) é seguramente a componente do balanço de radiação mais difícil de ser medida. Portanto, diferentes parametrizações têm sido propostas para estimá-la. Desta maneira, avaliou-se neste estudo o desempenho de várias formulações para a estimativa dos fluxos de L↓ e sua interação com outras variáveis medidas, bem como as interações da temperatura do ar e da pressão de vapor de água junto à L↓. Neste estudo se examinou o desempenho dos parâmetros de radiação de onda longa incidente para dias de céu claro e nublado, aplicados na região da Amazônia Central. Os conjuntos de dados utilizados neste estudo foram medidos a partir de torre micrometeorológica controlada pelo experimento de Grande Escala da Biosfera Atmosférica na Amazônia (LBA) em Manaus, Amazonas. Foi constatado que a precipitação e a pressão de vapor de água exercem influência suficiente sobre os L↓, principalmente na estação chuvosa. Os modelos para condições de céu claro propostos, usando seus coeficientes originais, tendem a subestimar os fluxos de L↓ medidos. Os melhores resultados para o céu claro foram obtidos com Idso & Jackson (1969), Brutsaert (1975) e Prata (1996).

PALAVRAS-CHAVE: Floresta tropical; Cobertura de nuvens fracionadas; ondas longas.

1.INTRODUCTION

The radiative energy received by the top of the atmosphere from the Sun is used to heat the Earth-Atmosphere system, and a portion is reflected by the clouds, while another is absorbed (by atmospheric gases like CO_2, O_3 and water vapor), and finally a part reaches of the earth's surface, which also absorbs it, reflects it and re-emits it, the latter in the form of longwave radiation.

The study of solar radiation is important for understanding of the various physical, chemical and biological processes that occur in the biosphere, particularly in forest ecosystems (Moura et al., 2001). Solar radiation is essential because it's a factor that determines the spatial distribution of species, forest dynamics, and biomass production among others (Vilani et al., 2007). In the forest environment solar radiation stands out as a critical factor that controls ecosystem development since it is fundamental to photosynthesis, air and surface heating and evapotranspiration. The interaction between solar radiation and the forest system is of great importance for the understanding of plant physiology processes, biomass productivity and turbulent energy and mass exchanges between the forest and the atmosphere (Moura, 2001).

Downward longwave radiation (L↓) is a component of net radiation for which it is difficult to precisely measure values, even though there are measuring instruments. The reason for this is that the instruments used for measurement also irradiate radiation of comparable wavelength and intensity to that which is being measured (Von Randow and Alvalá, 2006), thus requiring corrections made from the temperature of these instruments. The L↓ source comes from the kinetic energy of the atmospheric constituent molecules, such as water vapor, carbon dioxide and ozone, as well droplets in the clouds, and is therefore a function of their temperature (Viswanadham 1981).

Many practical situations in meteorology have occurred wherein longwave radiation is estimated through more easily measured variables used as a proxy (Brutsaert, 1982), and empirical and analytical methods have been devised to estimate this radiation from values of air temperature and vapor pressure or dew point measured at the screen-level (Prata, 1996). The main difference between analytical and empirical methods is that the former have been derived from a physical basis, while the latter are derived from empirical correlations.

Through physical-statistical models, several researchers have attempted to estimate L↓ by means of correlations of meteorological variables, since information on this variable is not always accessible either because equipment is very expensive, or cannot be used in certain circumstances, besides the frequent need for benchmarking. However, different formulations have been proposed to estimate L↓ at the terrestrial surface, and the equations that estimate it, for the most part, only have validity for clear sky conditions without cloud cover. For days with the presence of clouds, adjustments must be made to include the effects of cloudiness.

In the region of the Amazon forest few regular measurements of L↓ have been done despite its importance in the calculation the surface radiation budget, since it represents the contribution of the atmosphere that includes information on cloudiness and water vapor concentration (Vilani et al., 2010), and the use of models has become a common alternative for estimation of L↓.

Considering the importance of solar radiation and its components as the main source of energy for all physical and biological processes occurring in the biosphere, the general objective of the present work was to evaluate the performance of analytical and empirical methods used to estimate L↓ under clear and cloudy skies, as well to adjust equations using field data from central Amazonia in Brazil. The specific objectives were the following: (i) To evaluate the performance of the models proposed here for estimation of L↓ and to compare them with the data measured using statistical indices; (ii) qualify the simple models with their original coefficients and locally adjust for the estimation of L↓ under clear sky conditions; (iii) to evaluate the behavior of the models for the estimation of L↓ under cloudy conditions.

2. MATERIAL AND METHODS

2.1. DESCRIPTION OF STUDY AREA

The data in this study were measured at an experimental site managed by the Large Scale Experiment of Atmosphere Biosphere in Amazonia (LBA) in Manaus, Amazonas, Brazil (latitude 2°36'32.67''S, longitude 60°12'33.48''W, altitude 130 m), located in the Cuieiras River Biological Reserve (approximately 100 km north-west of Manaus) (Figure 1).

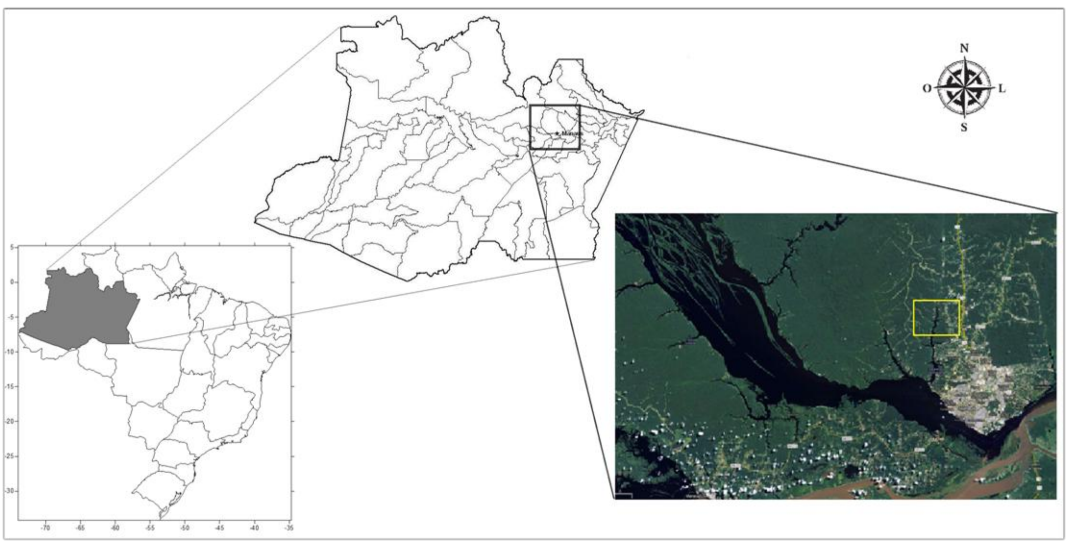

Figure 1 - Experimental site location, in the Rio Cuieiras reserve, near the city of Manaus, Amazonas.

2.2. INSTRUMENTATION AND OBSERVATIONS

The data were collected at a meteorological tower, known as K34, which is located on the plateau in central Amazonia. According to Araújo et al. (2002), the tower was erected in 1999, is composed of aluminum sections with dimensions of 1.5 m x 2.5 m, is 53 m high and rises 15 m above the canopy. For this study, measurements of incident and reflected short wavelength and downward and emitted longwave radiation were taken using a Kipp and Zonen Piranometer (CNR1), installed at a height of 44.6 m. Air temperature and humidity were measured at 51.1 m in height by a psychrometer (Vaisala HMP45C).

All sensors were connected to a datalogger (CR3000, Campbell Scientific, Utah, USA) scheduled to take measurements every 30 seconds and to record averages every 30 minutes during the period from January 1 to December 31, 2009, and data was stored on memory cards. For this study the dry and wet seasons were considered according to the definitions in Tomasella et al. (2008).

The downward longwave radiation values were maintained based on the information obtained by Bastable et al. (1993). The data presented outside this threshold are considered to be physically inconsistent and were rejected as being erroneous.

2.3. SIMPLE DOWNWARD LONGWAVE RADIATION MODELS - CLEAR SKY CONDITIONS

The Stefan-Boltzmann equation was used to estimate the density of downward longwave radiation from the atmosphere (W m^{-2}) under clear sky conditions:

$$L \downarrow = \varepsilon_a(T_a, e_a)\, \sigma\, T_a^4 \qquad (1)$$

where Ta is the temperature of the air near the Earth's surface [K], and a is the water vapor pressure (mb) and ε_a is the atmospheric emissivity under clear sky conditions, and σ is Stefan-Boltzmann's constant (5.67051×10^{-8} W m^{-2} K^{-4}).

Equation 1, derived from Stefan-Boltzmann's law, is valid for the radiation emitted by a gray body (whose emissivity is constant and always less than 1) at a uniform temperature, is a reasonable pretext that ε_a is constant, as L↓ is the result of a series of longwave emissions and absorptions in the atmosphere, where the temperature and humidity present little climatic variability (Duarte et al., 2006).

For atmospheric longwave radiation flux estimates under clear sky conditions, the following analytical and empirical methods presented in Table 1 will be used. These methods were used because they use only easily measured variables such as air temperature and relative humidity, in addition to being widely used in the literature.

Table 1 - Parameterization for the calculation of L↓, under clear sky conditions, based on air temperature, Ta (K), water vapor pressure, e_a (mb), and ξ = 46.5 (e_a/Ta). The suffix "a" indicates "atmosphere."

Parametrization		Nº
Brunt (1932)	$L\downarrow = [0{,}065(e^{0,5}) + 0{,}52]\sigma T_a^4$	(2)
Swinbank (1963)	$L\downarrow = [9{,}2 \times 10^{-6}]\sigma T_a^6$	(3)
	$L\downarrow = [1 - 0{,}261\exp(-7{,}77 \times 10^{-4}(273 - T_a)^2)]\sigma T_a^4$	(4)
Brutsaert (1975)	$L\downarrow = [1{,}24\left(\frac{e_a}{T_a}\right)^{0,1429}]\sigma T_a^4$	(5)
Idso (1981)	$L\downarrow = [0{,}70 + 5{,}95 \times 10^{-7} e_a \exp\left(\frac{1500}{T_a}\right)]\sigma T_a^4$	(6)
	$L\downarrow = [0{,}714\left(\frac{e_a}{T_a}\right)^{0,0687}]\sigma T_a^4$	(7)
Prata (1996)	$L\downarrow = \{1 - (1 + \xi)\exp[-(1{,}2 + 3\xi)^{0,5}]\}\sigma T_a^4$	(8)
Duarte et al. (2006)	$L\downarrow = [0{,}625\left(\frac{e_a}{T_a}\right)^{0,131}]\sigma T_a^4$	(9)
	$L\downarrow = [0{,}576\left(\frac{e_a}{T_a}\right)^{0,202}]\sigma T_a^4$	(10)

2.4. SIMPLE DOWNWARD LONGWAVE RADIATION MODELS - CLOUDY SKY CONDITIONS

Empirical models may work well in situations of clear sky, especially in climatic conditions similar to those for which they were obtained. However, the presence of cloudiness dramatically decreases the performance of these models, unless corrections are made.

For this reason, several authors proposed adjustments in the equations to estimate the long-wave radiation flux under cloudy conditions (Table 2), based on the solar radiation equation of clear sky.

Table 2 - Parameterizations for cloudy sky conditions for downward longwave radiation (L↓c). The fraction of cloud cover is expressed by "c".

Parametrization		Nº
Maykut e Church (1973)	$L\downarrow_c = L\downarrow(1 + 0{,}22c^{2,75})$	(11)
Jacobs (1978)	$L\downarrow_c = L\downarrow(1 + 0{,}26c)$	(12)
Sugita e Brutsaert (1993)	$L\downarrow_c = L\downarrow(1 + 0{,}0496c^{2,45})$	(13)
Konzelmann et al. (1994)	$L\downarrow_c = L\downarrow(1 - c^4) + 0{,}952c^4\sigma T_a^4$	(14)
Crawford e Duchon (1999)	$L\downarrow_c = L\downarrow(1 - c) + c\sigma T_a^4$	(15)
Duarte et al. (2006)	$L\downarrow_c = L\downarrow(1 + 0{,}242c^{0,583})$	(16)
Duarte et al. (2006)	$L\downarrow_c = L\downarrow(1 - c^{0,671}) + 0{,}990c^{0,671}\sigma T_a^4$	(17)

All the equations used in this work, for cloudy conditions, come from the following general forms:

$$L\downarrow_c = L\downarrow\left(1 + \alpha c^{\beta}\right) \tag{18}$$

$$L\downarrow_c = L\downarrow(1 - c^{\mu}) + \upsilon c^{\mu}\sigma T^4 \tag{19}$$

where α, β, μ and υ depend on cloudiness characteristics.

Under cloud conditions, estimates of downward longwave radiation are subject to empirical corrections that depend mainly on total cloud cover (Niemelä et al., 2001). Then, to determine the fraction of cloud coverage (c), the equation proposed by Crawford and Duchon (1999) is used:

$$c = 1 - \frac{Rs}{Ro} \tag{20}$$

where Rs is the downward solar radiation at the surface and Ro is the theoretical downward clear-sky solar radiation for the period, both expressed in W m^{-2}.

2.5. STATISTICAL ANALYSIS

An analysis of the models was made based on the calculation of statistical indices using a series of equations. The mean error (ME) was estimated by Equation (21), which evaluates whether the model overestimates (positive bias) or underestimates (negative bias) the observed values. The calculation of the root mean square error (RMSE) is given by Equation (22), whose objective is to elucidate the error size of a given estimate. It should be noted that the value zero indicates a perfect estimate and this value increases as the difference between the estimated and measured values increases, being more sensitive to extreme values. Willmott's index "d", also called Willmott's concordance index, (Equation 23), determines the accuracy of the method and indicates the degree of spacing of the estimated values from the observed values. This index ranges from 0, for no agreement, to 1, for perfect agreement. Values of *d* above 0.75 are considered satisfactory. Its advantage is to describe the proportional variations of two variables, distinguishing between the type and magnitude of possible covariances, unlike the correlation index (r) and the coefficient of determination (r^2) that make no distinctions.

The parameters defined in the previous paragraph are obtained by the following equations:

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i) \tag{21}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2} \tag{22}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{\sum_{i=1}^{n}\left(\left|y_i'\right| + \left|x_i'\right|\right)^2} \tag{23}$$

where *n* is the sample size, *yi* refers to estimated values, *xi* to the measured values, $x_i' = x_i - \bar{x}$, $y_i' = y_i - \bar{x}$, are deviations from the mean and the bar above the variable is equivalent to the mean variable value (Willmott, 1981, 1982).

The combined use of statistical indicators, mean error, RMSE and the adjustment index "d", is the appropriate alternative for validation of statistical models, since it allows for the simultaneous analysis of the deviation of the mean, identifying the occurrence of sub or overestimation, scattering and adjustment of the model in relation to the measures (Gomes, 2006).

3. RESULTS AND DISCUSSION

3.1. CLEAR SKY CONDITIONS MODEL PERFORMANCE

The results for the mean error showed that the estimated L↓ presented negative values, thus indicating that the proposed models underestimated the L↓ flux. It is also worth noting that RMSE informs about the actual value of the error produced by the model, i.e., the more adjusted the model, the lower its value.

When looking at the performance of each model, the same was evident, in direct contrast to a perfect straight line. It is observed that almost all the models underestimated L↓ whereas the models of Brunt (1932) and Prata (1996) approach the line (Figure 2).

Idso & Jackson (1969), Brutsaert (1975) and Prata (1996) showed the best performance in relation to the other models. These adjustments attest to the efficiency of estimating L ↓, which presents a satisfactory correlation between actual and estimated values, based on the lower RMSE and other statistical indices that indicate this tendency, exhibiting $d > 0.83$ (Table 3). In particular, the Idso and Jackson (1969) and Brutsaert (1975) models presented the highest *d*, but the models proposed by Brunt (1932) and Swinbank (1963) produced a medium concordance index (close to 0.75).

When analyzing the other models, it was noticed that those of Idso (1981), Sugita & Brutsaert (1993), Duarte et al. (2006) and Kruk et al. (2010) obtained poor performance, thus establishing that these are inefficient for estimating L↓. As already discussed, the poor performance of these models is due to the fact that the coefficients of these equations were adjusted for other regions.

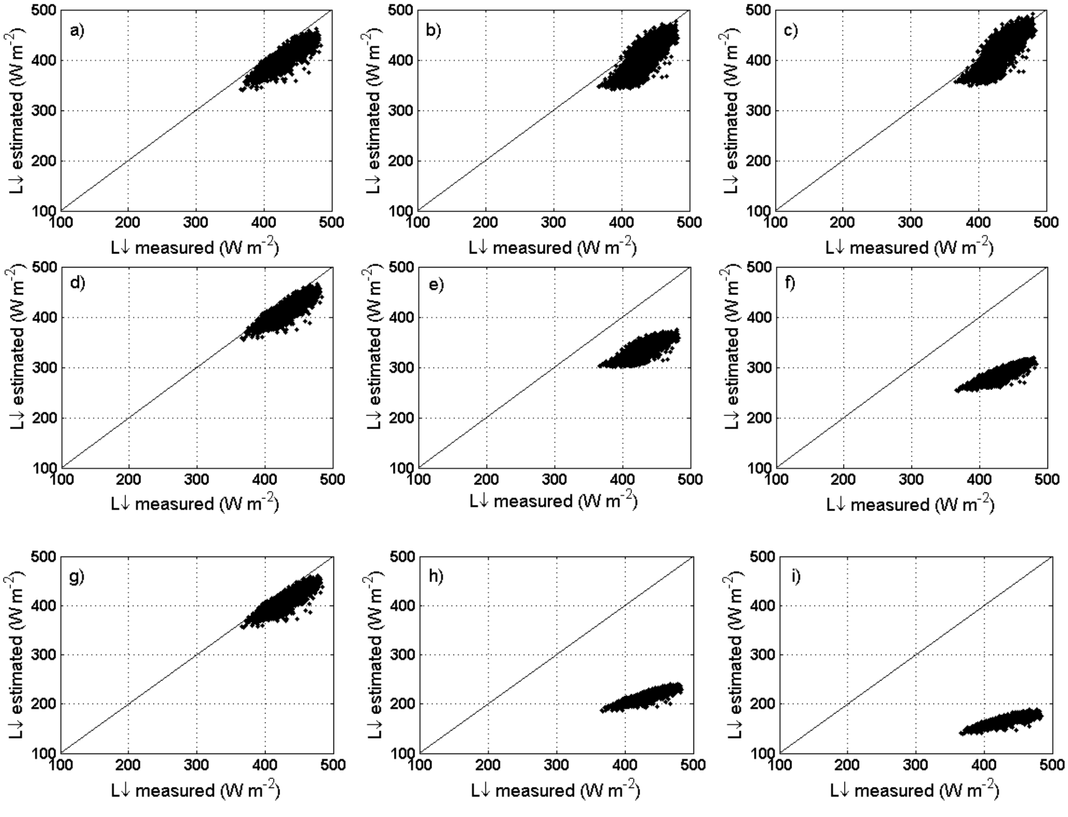

Figure 2 - Measured and estimated downward longwave radiation by models: a) Brunt (1932), b) Swinbank (1963), c) Idso & Jackson (1969), d) Brutsaert (1975), e) Idso (1981), f) Sugita & Brutsaert (1993), g) Prata (1996) h) Duarte et al. (2006) and i) Kruk et al. (2010), using the original coefficients for clear sky.

Table 3 - Statistical indexes used to evaluate the performance of parameterizations, with original coefficients, for the downward longwave radiation estimates on clear sky days, with mean error (ME), root mean square error (RMSE), Willmott's concordance index (d), angular coefficient (a) and linear coefficient (b).

Author	ME ($W\ m^{-2}$)	RMSE ($W\ m^{-2}$)	*d*	*a*	*b*
Brunt (1932)	– 27,14	32,33	0,73	0,80	60,55
Swinbank (1963)	– 27,33	34,45	0,74	1,10	-71,83
Idso e Jackson (1969)	– 15,19	26,68	0,89	1,15	-81,53
Brutsaert (1975)	– 16, 75	24,06	0,83	0,78	80,39
Idso (1981)	– 97,54	98,98	0,35	0,61	71,84
Sugita e Brutsaert (1993)	– 145,58	146,49	0,25	0,49	73,62
Prata (1996)	– 19,28	25,78	0,81	0,77	80,72
Duarte et al. (2006)	– 217,90	218,61	0,18	0,40	42,07
Kruk et al. (2010)	– 267,19	267,88	0,14	0,31	34,30

In order to obtain better model performance, the coefficients of these parametrizations were adjusted for the study region only for days under clear sky conditions or with low cloud coverage ($c < 0.5$). It is worth mentioning that the models adjusted here are the original ones, since the others used here are derived from them (Table 4), and the results attest that the adjusted coefficients show better results than the originals. When analyzing the ME, almost all the models overestimated the measured values, except that of Prata (1996).

In order to adjust the coefficients of the Prata (1996) model, the parameter ξ for Central Amazonia was determined by estimation of the rainfall (u), acquired according to the formula proposed by Hann (u = 2.5 *e*) (Vianello and Alves, 2000), and the ratio between vapor pressure and air temperature (ea/Ta), assumed to be ξ = 71.6 (e_a/Ta).

When analyzing the performance of each model, although they were adjusted, these deviate from a perfect straight line. Despite this, the adjustments make it possible to clarify the performance of each them. It can be seen that the Brunt (1932) and Prata (1996) models fit the straight line better (Figure 3).

According to the statistical indices, the best results were obtained by the Brunt (1932) and Brutsaert (1975) models, which produced the lowest ME and RMSE, and the closest to 1, indicating a good agreement between the estimated and measured values, in addition to bearing d > 0.85 (Table 5). It is noteworthy that in the literature these models, with the addition of Prata (1996), usually have good performance, independent of the climatic conditions of each region. Also, it was observed that there were smaller differences between the coefficients adjusted for the original models, and these were less than 5%. However, the Swinbank (1963), Idso & Jackson (1969) and Idso (1981) models presented the largest errors, with the greatest differences between the coefficients being superior to 15%.

Considering only Brunt's (1932) model, some authors (Iziomon et al., 2003) and Carmona et al. (2014)) showed that besides the large variation in the coefficients of this model between different geographic regions, the coefficient *b* has a strong dependence on the vapor pressure (e_a) values for atmospheric emission. Dal Pai (2014) also reports that, with the decrease of *b*, it is understood that the amount of water vapor in the atmosphere is less important than the emissivity, and that the term completes the Brunt equation (1932) and expresses the difference in the atmospheric emissivity of different locations assuming the same water vapor conditions for those locations.

In view of these results, the performance of each model was classified according to the Willmott index concordance: Brunt (1962), Brutsaert (1975), Prata (1996), Idso & Jackson (1969), Swinbank (1963) and Idso (1981).

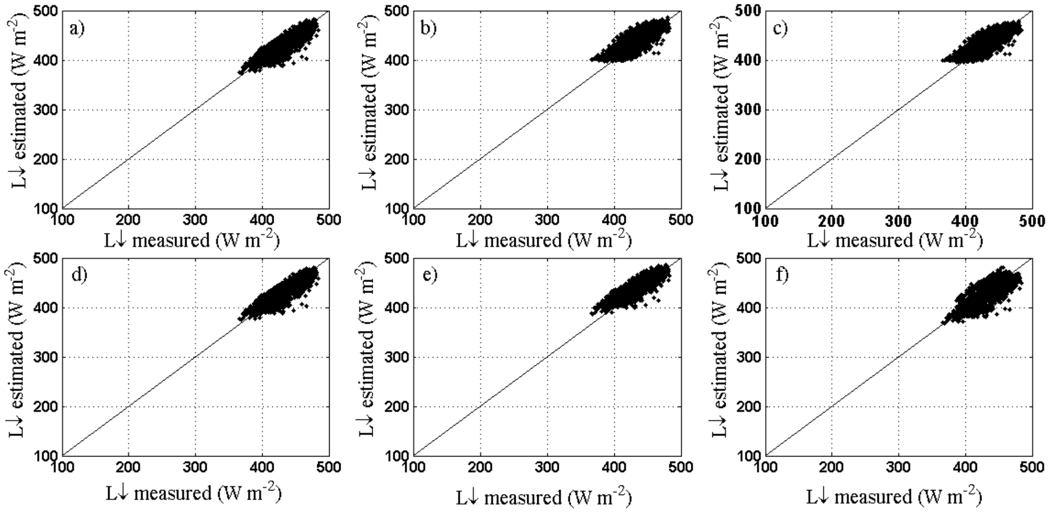

Figure 3 - Measured and estimated downward longwave radiation by the following models: a) Brunt (1932), b) Swinbank (1963), c) Idso & Jackson (1969), d) Brutsaert (1975), e) Idso (1981) and f) Prata (1996), using models with adjusted coefficients for clear sky.

Table 4 - Coefficients adjusted for the environmental conditions of the study region, under clear sky conditions.

Author	**Equations**
Brunt (1932)	$L\downarrow = [0{,}0409(e^{0,5}) + 0{,}6983]\sigma T_a^4$
Swinbank (1963)	$L\downarrow = [10^{\,(0,9395-0,3936\log(T_a))}]\sigma T_a^6$
Idso e Jackson (1969)	$L\downarrow = [1 - \exp(3{,}0\times10^{-4} * (273{,}16 - T_a)^2 - 2{,}7147)]\sigma T_a^4$
Brutsaert (1975)	$L\downarrow = [0{,}1936 + 1{,}0138\left(\frac{e_a}{T_a}\right)^{0,1429}]\sigma T_a^4$
Idso (1981)	$L\downarrow = [0{,}8146 + 3{,}0\times10^{-5}\left(e_a \exp\left({}^{1500}/_{T_a}\right)\right)]\sigma T_a^4$
Prata (1996)	$L\downarrow = \{1 - (1+\xi)\exp[-(2{,}23 + 3{,}44\xi)^{0,5}]\}\sigma T_a^4$

Table 5 - Statistical indices applied to evaluate the performance of parameterizations, with adjusted coefficients of downward longwave radiation on clear sky days with the mean error (ME), root mean square error (RMSE), Willmott's concordance index (d), angular coefficient (a) and linear coefficient (b).

Author	ME (W m^{-2})	RMSE (W m^{-2})	*d*	*a*	*b*
Brunt (1932)	0,42	17,58	0,86	0,83	75,72
Swinbank (1963)	6,26	19,47	0,81	0,72	126,86
Idso e Jackson (1969)	3,72	18,80	0,81	0,70	135,93
Brutsaert (1975)	0,43	17,53	0,85	0,80	85,35
Idso (1981)	8,91	19,74	0,80	0,73	126,66
Prata (1996)	-9,52	19,33	0,83	0,78	84,21

By analyzing the variations of the measured and estimated L↓ by fitting models, box plots show that these variations tend to be homogeneous, that is, the values are concentrated around the 440 W m^{-2} average (Figure 4). It should be noted that this behavior is due to the small microclimatic variations in this region with respect to L↓, air temperature and relative humidity. It was also observed that the range of variation of the results is between 370 and 490 W m^{-2}, and that the adjusted models presented a similar behavior to the measured records, thus attesting to their satisfactory performance (see Table 5).

The measured and estimated records by Brunt (1932) and Prata (1996) present the highest dispersions (> 100 W m^{-2}). Outliers in the measured values, in relation to the groups, as well as in the adjusted Brunt (1932), Brutsaert (1975), Idso (1981) and Prata (1996) models are associated with the extreme values caused by low concentrations of water vapor present in the atmosphere, which strongly influences the emissivity of the atmosphere in the early hours of the morning. On the other hand, the lack of outliers in the Swinbank (1963) and Idso & Jackson (1969) models is due to large variations in estimated values.

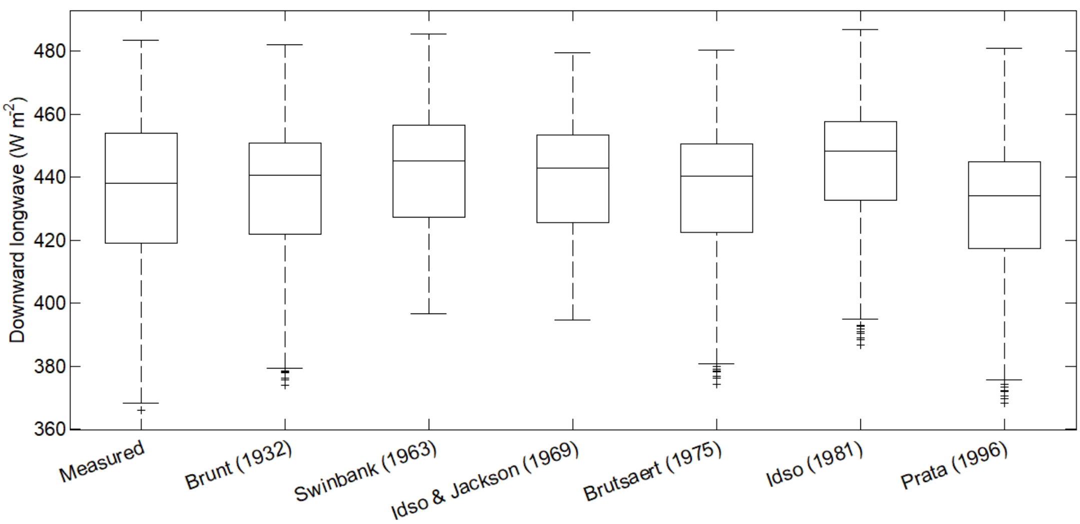

Figure 4 - Box-plot for the measured and estimated downward longwave radiation by fitted models for the study region.

3.2. PERFORMANCE OF EQUATIONS FOR CLOUDY CONDITIONS

In several studies, estimation calculations for cloudy sky downward longwave radiation (L↓c) were performed using data for all cloud conditions (which ranges from 0 to 1). In the current analysis, only data in cloudy conditions ($c \geq 0.65$) was included in order to describe the actual performance of each model under cloudy conditions (Carmona et al., 2014). It is emphasized that for this analysis, the use of Brunt (1932)'s adjusted parameterization for clear skies was chosen because it presented better performance.

The representations of the estimation models of L↓c exhibited unsatisfactory performance, and some models showed a categorical tendency to underestimate the measured data (Figure 5). These models have the same structure, similar to Eq. (18), and this result can be considered slightly anomalous since the model adjustment still did not provide more information.

However, despite some dispersion in the model estimates, it was noted that some tended to adjust to the straight line.

The analysis of the statistical indices revealed that Jacobs (1978) and Duarte et al. (2006) [Eq. (16) models had the worst performance, with $d < 0.35$, thus confirming that the original coefficients of these parametrizations are dissonant in places with high humidity, according to the region of study (Table 6). It should be noted that the Willmott's agreement method establishes the type and magnitude of the differences between a measured value and a value predicted by estimation models.

However, the model developed by Sugita & Brutsaert (1993) provided satisfactory performance ($d = 0.75$), even though it was made in a dry climate in the central-western region of the USA. In the same way the performance of the two adjusted models, in the 95% confidence interval, whose coefficients were $\alpha = 0.075 \pm 0.02$, $\beta = 3.05 \pm 0.157$, $\upsilon = 0.986 \pm 0.002$ and $\mu = 3.49 \pm 0.175$, also presented the best concordance indices ($d > 0.89$), in relation to those tested here. It was also observed that, after the adjustments, statistical errors were significantly reduced, which had ME close to zero and RMSE less than 1.0 W m^{-2}.

The least squares linear regression obtained between the observed and calculated data from Eq. (18) resulted in an angular coefficient (a) equal to 0.620 and an interception (b) analogous to 162.58, with d approximately equal to 0.90. It should be noted that Eq. (18) has the same structure as the model proposed by Sugita & Brutsaert (1993), and with the adjustments for local conditions, it obtained a slight improvement on the original coefficients of the proposed model. In addition, Eq. (19) also showed similar behavior, despite having a distinct structure, showing $a \approx 0.6$ and $b \approx 181.0$, and still presented satisfactory d (= 0.90).

Considering these results in general, the parameterizations for cloudy sky tend to overestimate the flow of measured $L\downarrow c$ and its errors, even using a locally calibrated formula, and the above mentioned parameterizations generate higher results than those developed for clear sky. Duarte et al. (2006) explain that in part this is attributed to its simplicity since they do not take into account more specific information, such as cloud type (Sugita & Brutsaert, 1993), and height of the base and thickness of the cloud. However, this simplicity becomes useful and makes this method easier to apply.

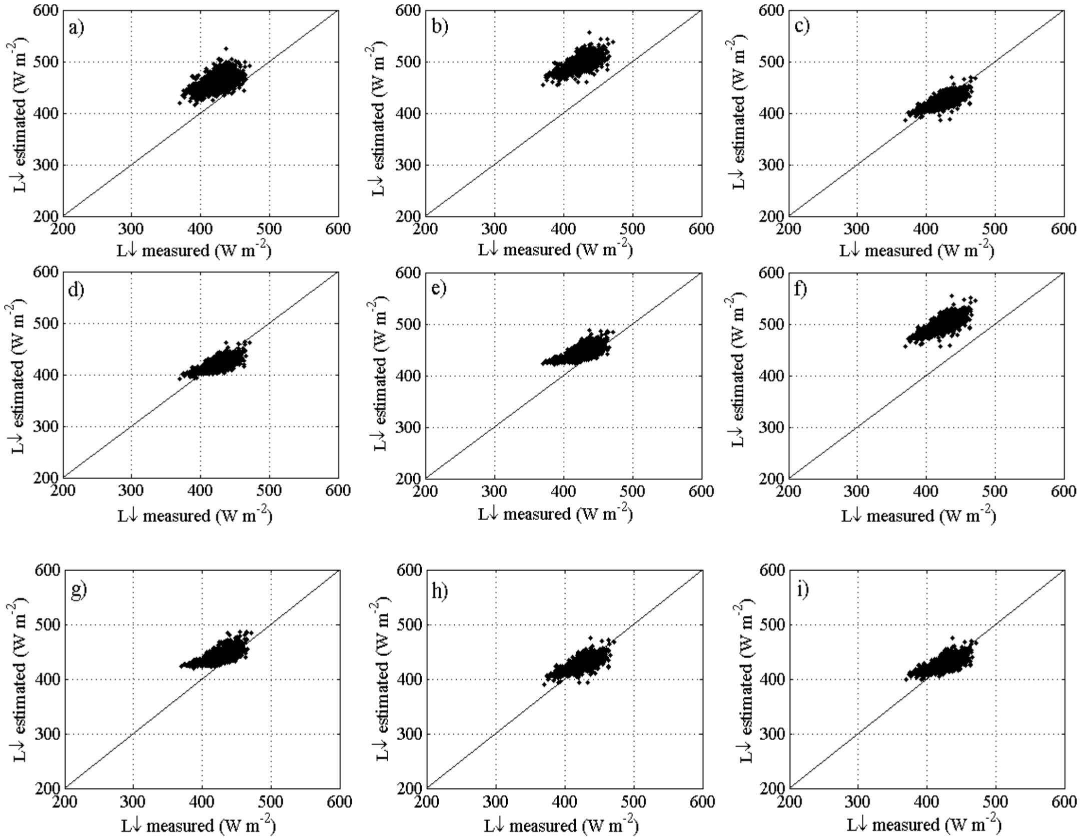

Figure 5 - Measured and estimated downward longwave radiation by the following models: a) Maykut & Church (1973), b) Jacobs (1978), c) Sugita & Brutsaert (1993), d) Konzelmann et al. (1994), e) Crawford & Duchon (1999), f) Duarte et al. (2006) [Eq. (16)], g) Duarte et al. (18) Adjusted and h) Eq. (19) Adjusted, using models for cloudy days.

Table 6 - Statistical indices used to evaluate the parameterizations of cloudy downward longwave radiation, with the mean error (ME), root mean square error (RMSE), Willmott's concordance index (*d*), angular coefficient (*a*) and linear coefficient (*b*).

Author	ME ($W m^{-2}$)	RMSE ($W m^{-2}$)	*d*	*a*	*b*
Maykut e Church (1973)	28,358	32,127	0,47	0,65	179,44
Jacobs (1978)	66, 456	67,937	0,27	0,72	190,39
Sugita e Brutsaert (1993)	– 5, 628	13,860	0,75	0,62	160,15
Konzelmann et al. (1994)	– 10,873	16,573	0, 68	0,58	173,77
Crawford e Duchon (1999)	12,084	17, 543	0, 65	0,59	203,99
Duarte et al. (2006) Eq. (16)	69,767	71,132	0,27	0,72	189,43
Duarte et al. (2006) Eq. (17)	10,896	16,860	0, 66	0,55	206,12
Eq. (18) Adjusted	– 0,005	0,260	0,90	0,62	162,58
Eq. (19) Adjusted	– 0,005	0,255	0,90	0,58	180,76

In an exploratory analysis of L↓c, it was found that the highest averages and their respective outliers were found in the models of Jacobs (1978) and Eq. (16) by Duarte et al. (2006), and this value was approximately 500 W m^{-2} (Figure 6). It was also observed that the model proposed by Maykut & Church

(1973) showed a relatively high average (≈ 460 W m^{-2}). The curious aspect among these models is that they all exhibit the same structure. The opposite was seen in Eq. (18), although having the same structure, behaved differently than the equations previously cited. This can be explained by the fact that it presents coefficients adjusted for this environment, thus expressing values close to those measured. The same was observed in Eq. (19), although it had a distinct structure, in which it obtained a behavior analogous to the previous equation and, therefore, to the observed measurements.

We also observed a higher frequency of outliers in the measured and estimated groups. These lower atypical values were concentrated at dawn and late afternoon, while the maximum outliers occurred near the local noon, more specifically, between 11:00 to 14:00. These high values (over 460 W m^{-2}) were also observed by Correia (2000) in Central Amazonia. The highest occurrence of the estimated values happened in the afternoon period, where cloud cover was more active, which is is common in this region.

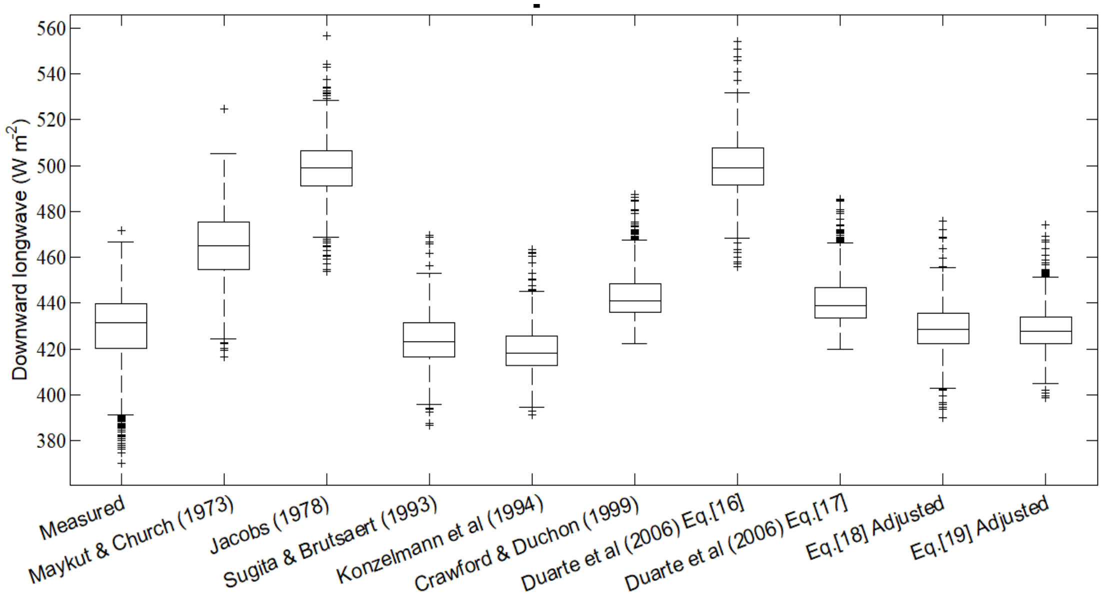

Figure 6 - Box plot for measured and estimated downward longwave radiation on cloudy days for Central Amazonia.

4. CONCLUSIONS

Based on what has been reported in this work and the discussions carried out regarding the analysis of measured and estimated downward longwave radiation (L ↓) in the central Amazon forest region, the following conclusions can be drawn:

• The models proposed for clear sky conditions, using their original coefficients, showed a tendency to underestimate the measured L↓. The Idso & Jackson (1969), Brutsaert (1975) and Prata (1996) models presented the best performance, establishing a satisfactory agreement for the Willmott index. However, the Sugita & Brutsaert (1993), Duarte et al. (2006) and Kruk et al. (2010) models generated the worst performance.

• The adjustments of the coefficients, according to the environmental conditions of the study area, lead to an improvement in the model estimates of L↓, and the adjusted models of Brunt (1932) and Brutsaert (1975) generated the best results. It should be noted that the adjusted Prata (1996) model also performed well. Therefore, these three models can be used in Central Amazonia;

• The models proposed for cloudy conditions had mediocre performance, but the exception was the model determined by Sugita & Brutsaert (1993) which exhibit excellent statistical results, along with the adjusted equations (18) and (19).

5. ACKNOWLEDGEMENTS

The authors are grateful for the Coordenação de Aperfeicoamento de Pessoal de Nível Superior (CAPES) and thank the anonymous reviewers whose suggestions were helpful for improving the quality of this paper.

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