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Evaluation of the atmospheric longwave radiation models estimated in Brasília – DF

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Abstract

The atmospheric longwave radiation has considerable importance in meteorological studies, as well in the global warming. Because it is connected to atmospheric gases and air temperature. This paper has a purpose to evaluate the performance of twelve models for the estimation of atmospheric longwave radiation in Brasília-DF. The meteorological data used in this study were acquired from the data network of the Environmental Data Organization System - SONDA. In this study, the data of air temperature, relative humidity, global radiation and long-wave atmospheric radiation, were used for the models evaluated. The calculations were processed using hourly and daily averages. The evaluation of the models and the comparison of the estimated and measured results of atmospheric longwave radiation was performed by using the statistical methods of the Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and Percent Mean Relative Error (PMRE). The Pearson correlation coefficient (r) and the coefficient of determination (R^2) were also applied. The models that had an excellent results were Brunt (1932), Prata (1996), Berdahl and Martin (1984), Idso (1982) and Berger et al.(1984), since they presented good performance, due the lowest values of RMSE, MAE and PMRE.
Keywords**:** Long wave equations, statistical indices, estimate.

1. Introduction

Atmospheric Longwave Radiation - ROL is essential in meteorological studies and as well as those that involve global warming, because it is linked to the atmospheric gases and thus air temperature. Its flow is fundamental element in the radiative exchanges at the surface level, therefore it is decisive for climatological studies.

ROL is the radiant energy flux, that is resulting from the emission of atmospheric gases, liquid and solid surfaces of the Earth (Galvão and Fisch, 2000). All materials, on the Earth, have the lower temperature than the Sun, such as the radiation that they emit has wavelengths greater than the global solar radiation.

The water vapor is main absorber of the ROL, according to Radel et al. (2015), that is determinant for the radiative balance due to its abundance in the atmosphere and its sensitivity to temperature changes. The ROL is fundamental for the understanding of the surface energy balance and for the heat exchanges at the surface-atmosphere interface, since it is necessary to calculate the available energy for the environment (Aguiar et al., 2011).

Sobrinho (2011) evidences that for measuring and identifying the effects that the anthropogenic activities could cause in time and in the climate, they are used studies of radiative exchanges at the surface level, in what refers to regions whom cover important biomes, such as the Cerrado. Studies which involve solar radiation are important because this is the main source of energy for the physical and biological processes, that occur in the biosphere and, in particular, in the forest (Leitão, 1994).

The determination of its magnitude, its temporal variability and modeling are important for studies those involve climate change. According to the Querino (2016), ROL is a critical component in the global energy flux, the alterations in its average behavior on different biomes may be linked to climate changes.

According to Vilani et al. (2010), surface flows and ROL estimates can aid in the calibration of General Circulation Atmospheric Models (MCGAs), since these require realistic parameterizations of many surface processes, such as energy partitioning.

The firsts equations developed for long wavelength irradiance were made in function of the air temperature and the water vapor pressure. The ROL estimation is a result of the Stefan-Boltzmann equation which considers the emissivity (ε) and surface temperature of a body, for example, of the atmosphere, where the temperature and vapor pressure of the water are not constant.

Kjaersgaard et al. (2007) point out that the ROL measure is normally used in studies of agriculture, engineering, and for its determination in studies that involve weather and climate forecasting, plant growth, and water resource planning, through empirical models.

Accurate estimates of the surface radiation balance, which modulates the amplitude of surface energy balance components (including latent heat flux), depend on good estimates of atmospheric ROL. The instrument that directly measures ROL is the pygometer, that is expensive and sensitive, compared to the pyranometer used to measure shortwave radiation (Duarte et al., 2006).

According to Aguilar et al. (2015) there is an increasing need in several areas of research to have continuous measures of ROL. Thus, it is necessary to search for alternatives to estimate this component with precision. For this, work has been developed in the area of modeling in order to generate equations that estimate this component. According to Silver (1996) empirical and analytical methods estimate ROL from values of air temperature and vapor pressure or dew point, measured at the shelter level.

Santos et al. (2011) shows that minimum and maximum temperature and rainfall daily records are available for many locations, but precise measurements of solar radiation are only available for some locations, a situation that probably reflects not only the cost of the required instrumentation but also the maintenance problems and the calibration of radiation sensors.

In this context, the objective of this paper was to evaluate the performance of twelve models for the estimation of atmospheric longwave radiation for the Brasília SONDA station.

2. Materials and methods

2.1 Location and climate and geographic characteristics

This research was performed by the SONDA station of Brasilia, which belongs to the central western region of Brazil. It has as geographical coordinates: latutude 15° 50 '16' 'S, longitude 47° 42' 48 " O and altitude of 1023 m. Its population of 2 977 216 inhabitants (IBGE, 2016).

According to the information from the SONDA network, the local climatology of Brasília has a tropical climate of altitude. The region has a well defined precipitation regime. The rainy season starts in October and extends until March. The dry season happens the rest of the year, from April to September.

The rainy season is caused by the strong warming of the atmosphere in the Amazon, which favors the development of a quasi-stationary system at high levels, the Alta of Bolivia. As a result of this circulation, a low pressure region, called Baixa do Chaco, is observed at low levels. This region, with low pressure and the convergence of air, is the main factors that cause the precipitation in this period, responsible for 70% of the annual average total. The average annual rainfall in Brasília is approximately 1700 mm. The relative humidity of the air, in the period of drought, falls from values greater than 70% to 20%. Coinciding with the warmer period, in August and September, relative air humidity can reach 12%, typical desert value. The average temperature reaches values around 22ºC and the annual peak occurs in the spring months. The months of June and July are those with the lowest temperatures of the year, averaging 18 ºC.

2.2 Meteorological data

The meteorological data used in this study were acquired from the data network of the Environmental Data Organization System (SONDA). This network was born from a project of the National Institute of Space Research (INPE) for the implementation of physical infrastructure and human resources to raise and to improve the database of solar and wind energy resources in Brazil.

The sensors in each station determine which variables are measured in each case. First, the data of the SONDA stations go through a validation process in order to endorse its reliability. The validation indicates where there is or may not be a suspected error with 4-digit numeric codes stored in the files. Each data has a flag code that qualifies it and each data file has its corresponding validation file, the data itself is not modified.

The meteorological data are available minute by minute, in this study the data of air temperature, relative humidity, global radiation and atmospheric longwave radiation are being used in the atmospheric longwave radiation models. The hourly and daily averages have been used for the calculation of ROL for the year 2014.

2.3 Sky Coverage

Clarity Index (Kt)

In order to achieve the best result in the evaluation of longwave atmospheric radiation models, since most of the models developed are only valid for clear sky conditions. The periods with days of clear sky, partly cloudy and cloudy were selected through the clarity index.

The sky cover can be expressed in terms of the atmospheric transmissivity index (Nkemdirim, 1972),it determined by the clarity index (kT), that defined as the ratio of incident global solar radiation

(Rg) in $MJ.m^{-2}$. day^{-1} and the irradiation at the top of the atmosphere (R0) given in $MJ.m^{-2}.day^{-1}$. The equation used was that of Iquibal (1983) that takes the form:

$$Kt = \frac{Rg}{Ro} \quad (1)$$

The classification of the sky cover (KT) was made according to the research developed by Dallacor et al. (2004), which in the range of $0 \leq KT \leq 0.3$ was defined as cloudy, between $0.3 \leq KT \leq 0.65$ and partly cloudy sky and between $0.65 \leq KT \leq 1$ as clear sky.

The incident global radiation (Ro) at the top of the atmosphere at ($MJ.m^{-2}.dia^{-1}$) was calculated by equation (2). It depends on the latitude (φ), the correction of the eccentricity of the Earth orbit (Eq.3), the solar declination (δ) (Eq.4) and the hour angle (Eq. 5).

$$Ro = \frac{1367}{\pi} * 86400 * dr * \left(\frac{\pi}{180} * h * sin\varphi * sin\delta + cos\varphi * cos\delta * senh\right) \quad (2)$$

$$dr = 1 + 0.033 * \left(\frac{360*dn}{365}\right) \quad (3)$$

$$\delta = 23.45 * sin\left(\frac{360}{365} * (dn + 284)\right) \quad (4)$$

$$h = cos^{-1}(-tg\varphi * tg\delta) \quad (5)$$

where dn is the order day of the year according to the Julian calendar.

2.4 Estimation of Micrometeorological Parameters

Water vapor pressure

The water vapor pressure used in some of the models to estimate atmospheric longwave radiation was calculated in function of humidity and saturation vapor pressure (Figure 1).

Figure 1 - Sensors of diffuse, direct and long wave radiation. Source: SONDA.

According to Radel et al. (2015) atmosphere is a complex and at the same time dynamic system, water vapor, which is considered one of the main absorber gases and emitters of atmospheric longwave radiation, it becomes a fundamental part of Earth's radiative balance.

The water vapor pressure (mb) and the saturation pressure of the water vapor (mb) are expressed by the equations developed by Wright (1982) with the temperature in ° C.

$$es = A + B * Ta + C * Ta^2 + D * Ta^3 + E * Ta^4 + F * Ta^5 \quad (6)$$

on what A = 6.105, B = $4.44*10^{-1}$, C = $1.434*10^{-2}$, D = $2.623*10^{-4}$, E = $2.953*10^{-6}$ and F = $2.559*10^{-8}$

$$ea = \frac{UR*es}{100} \quad (7)$$

Where UR is the air relative humidity.

2.5 Estimation of Atmospheric Long Wave Radiation

The general equation for the calculation of atmospheric longwave radiation is given by the Stefan-Boltzann equation which considers the emissivity and the absolute temperature:

$$\varepsilon = \sigma * \epsilon * Ta^4 \quad (8)$$

Where $\sigma = 5.67 * 10^{-8}$ Wm^{-2} K^{-4} is the Stefan-Boltzann constant and ε is the air emissivity.

In this study twelve models were evaluated for estimating of atmospheric longwave radiation, as explained in (Table 1).

Table 1 - Models for estimating Atmospheric longwave radiation and their respective authors

Model	Author
$\varepsilon = 9 * 10^{-6} * Ta^6$	Swinbank 1963
$\varepsilon = 0.065 * \sqrt{ea} + 0.52 * 5.67 * 10^{-8} * Ta^4$	Brunt 1932
$\varepsilon = 1.24 * \frac{ea^{\frac{1}{7}}}{Ta} * 5.67 * 10^{-8} * Ta^4$	Brutsaert 1975
$\varepsilon = (1 - 0.26 * exp(-7.77 * 10^{-4} * (273 - Ta)^2 * 5.67 * 10^{-8} * Ta)$	Idso and jacson 1969
$\varepsilon = 0.7 + 5.95 * 10^{-5} * \left(ea * \exp\left(\frac{1500}{Ta}\right)\right) * 5.67 * 10^{-8} * Ta^4$	Idso 1981
$\varepsilon = (1 - (1 + \xi) * exp\left[-(1.2 + 3 * \xi)^{\frac{1}{2}}\right])$	Prata 1996
$\varepsilon = 9.2 * 10^{-6} * Ta^2 * 5.67 * 10^{-8} * Ta^4$	Zillman 1972
$\varepsilon = 0.56 + 0.059 * ea^{\frac{1}{2}} * 5.67 * 10^{-8} * Ta^4$	Berdahl and Martin 1984
$\varepsilon = (0.746 + 0.0066 * ea) * 5.67 * 10^{-8} * Ta^4$	Efimosa 1961
$\varepsilon = 1.18 * \left(\frac{ea^{\frac{1}{7}}}{Ta}\right) 5.67 * 10^{-8} * Ta^4$	Lommer et al. 2007
$\varepsilon = 0.66 + 0.04 * ea^{\frac{1}{2}} * 5.67 * 10^{-8} * Ta^4$	Berger et al.1984
$\varepsilon = (0.82 - (0.25 * 10^{-0.168 * ea}) * 5.67 * 10^{-8} * Ta^4$	Angstrom 1918

2.6 Statistical Analysis of Data

The evaluation of the models for the analysis and comparison of the estimated and measured results of atmospheric longwave radiation were performed by statistical methods of the Mean Square Error (EQM) equations, the Mean Absolute Error (EMA) equation and the Percent Error Relative Mean (EPRM). The Pearson correlation coefficient (r) and the coefficient of determination (R^2) were also applied, those indicate the degree of correlation between the measured and estimated values (Table 2).

Table 2 - Statistical criteria for performance evaluation of the atmospheric longwave radiation models analyzed. Where the suffixes Pi and Oi represent respectively the estimate and measurement of radiation.

Descrition	Sigla	Equation
Erro Quadrático Médio	EQM	$\sqrt{\frac{\sum(Pi - Oi)^2}{n}}$
Erro Médio Absoluto	EMA	$\frac{\sum\lvert Pi - 0i\rvert}{n}$
Erro Percentual Relativo Médio	EPRM	$\frac{100}{n}\sum\left\lvert\frac{Pi - Oi}{Oi}\right\rvert$

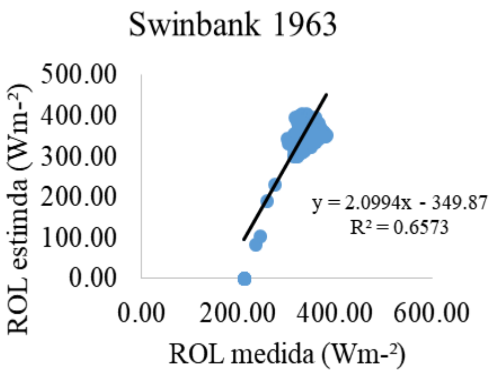
3. Results and Discussion

The data required for the calculation of the atmospheric longwave radiation in the twelve evaluated models included the air temperature near the surface and the water vapor pressure. With this it is possible to evaluate the performance of the proposed equations by means of the statistical parameters, the calculations were done with daily and hourly averages.

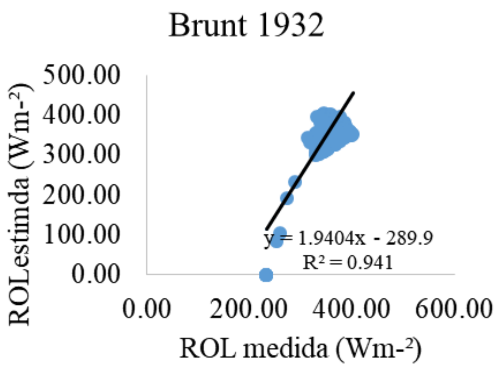
The equations of Swinbank (1963), Idso and Jacson (1969) and Zillman (1972) used only air temperature, they were not use vapor pressure as a measure of the effect of moisture in the atmosphere.

The calculation of the clarity index was done to characterize the sky coverage conditions, which are directly related to the precipitation due to the formation of clouds, those influence the reflectance and transmittance of the atmosphere. For the evaluated period, the conditions of sky cover were: days with cloudy skies (46%), days with clear skies (35%), and days with partly cloudy skies (19%).

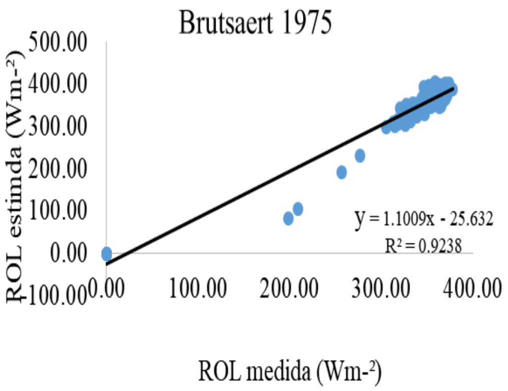
The linear regression and the correlation coefficient obtained between estimated atmospheric longwave radiation fluxes and measured fluxes for clear, partly cloudy and cloudy conditions are presented in Figure 2. The best models for measuring atmospheric longwave radiation were Brunt (1932), Brutsaert (1975), Silver (1996), Idso (1982), Berdahl and Martin (1984), Lhommer et al. (2007) and Berger et al. (1984).



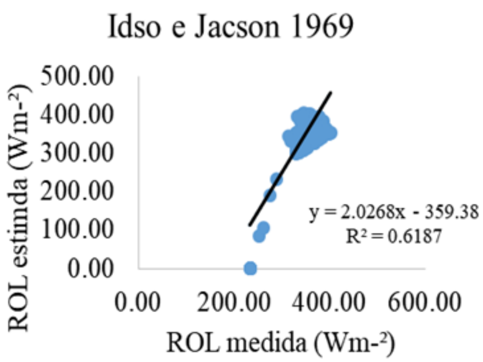
a)



b)



c)



d)

Figure 2 - Comparisons between estimated and measured fluxes of atmospheric longwave radiation, averages daily. The results of the different formulas are given in panels a to l. (Continue…)

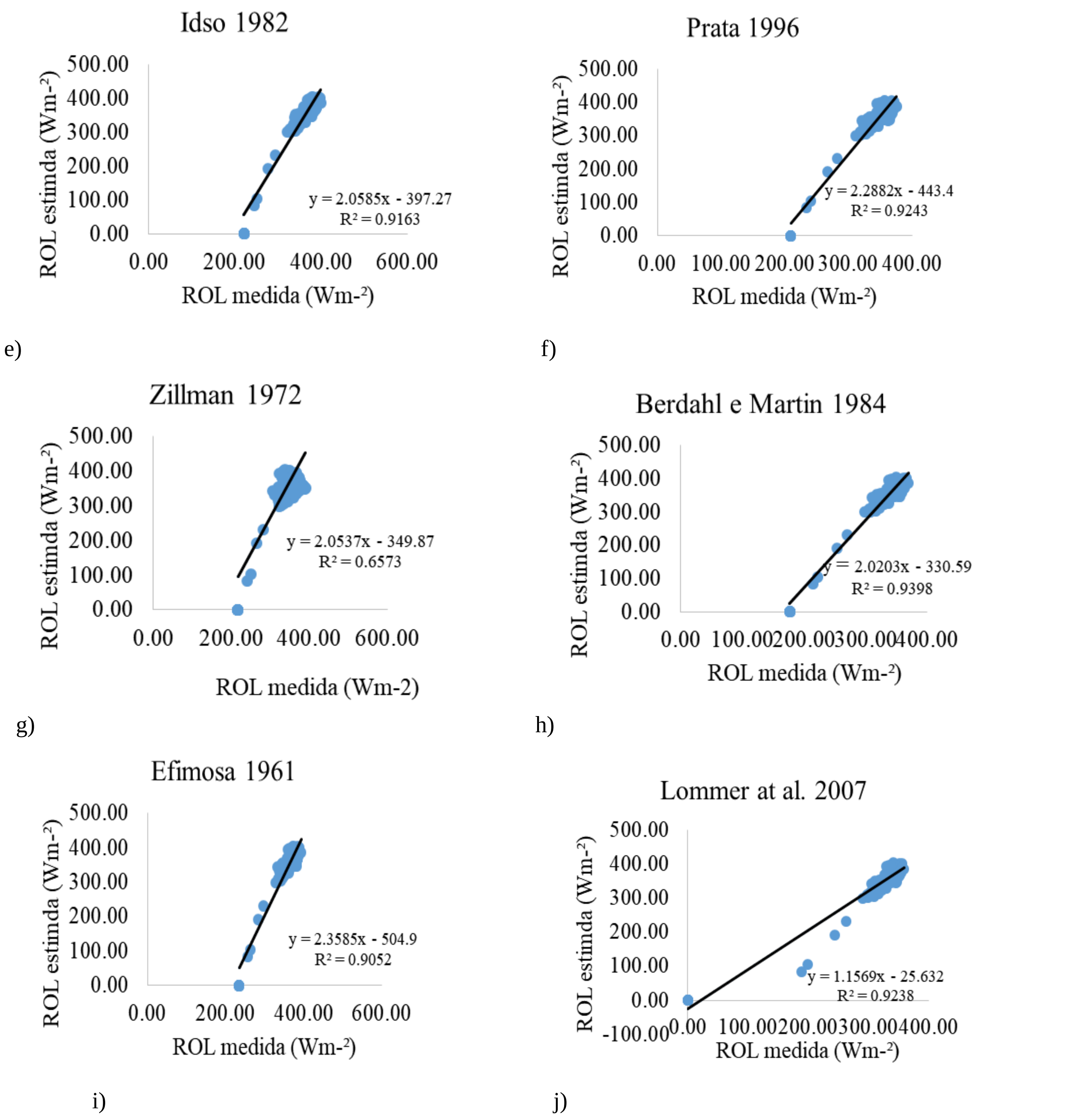
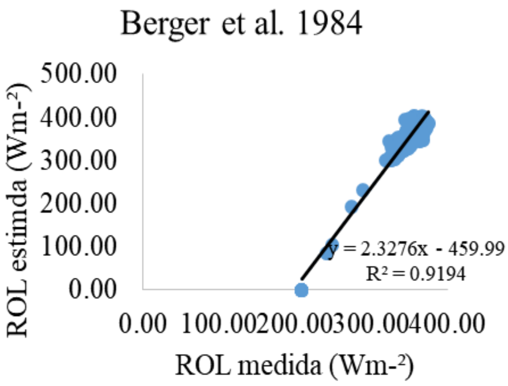
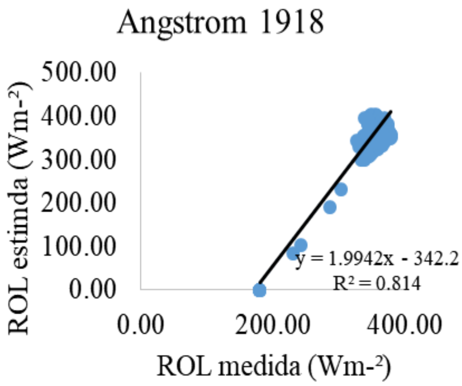


Figure 2 - Comparisons between estimated and measured fluxes of atmospheric longwave radiation, averages daily. The results of the different formulas are given in panels a to l. (Continue…)





k) l)

Figure 2 - Comparisons between estimated and measured fluxes of atmospheric longwave radiation, averages daily. The results of the different formulas are given in panels a to l. (Conclusion)

The table 3 shows the comparative statistics for models performance. In general, these parametrizations, which use vapor pressure and air temperature to obtain atmospheric emissivity, have the best scores during the day.

The models that obtained the best results, with lowest RMSE, MAE, and PMRE, for the hourly mean, were the Brunt (1932), Idso (1982), Prata (1996), Berdahl and Martin (1984), Efimosa 1961), Berger et al. (1984) and Angstrom (1918).

The table 4 shows the comparative statistics for the calculations with daily mean for the evaluation of the models. The equations nearest to the real conditions of longwave irradiance measured were Brutsaert (1975), Brunt (1932), Idso (1982), Prata (1996), Berdahl and Martin (1984), Berger et al. (1984) and Lommer et al. (2007).

Swinbank (1963) and Zillman (1972), respectively presented the results with the highest RMSE, MAE and PMRE. The equations of Brunt (1932), Idso (1982), Silver (1996), Berdahl and Martin (1984), Efimosa (1961), Brutsaert (1975), Lommer et al. (2007), and Berger et al. (1984) presented a correlation coefficients higher than (r = 0.94), those show the strong correlation between the calculated and measured values.

Table 3 - Comparative statistics for the performance of the twelve models of the calculation of the atmospheric longwave radiation in comparison with the data measured in Brasilia, average hourly.

Model	**RMSE (Wm-²)**	**MAE (Wm-²)**	**PMRE (%)**	**r**
SWINBANK 1963	39.56	30.97	8.34	0.77
BRUNT 1932	33.58	27.43	7.37	0.92
BRUTSAERT 1975	40.39	33.23	9.41	0.76
IDSO e JACSON 1969	34.25	27.72	7.64	0.76
IDSO 1981	19.01	16.18	4.61	0.93
PRATA 1996	23.77	17.91	4.83	0.91
ZILLMAN 1972	36.23	28.46	7.71	0.77
BERDAHL e MARTIN 1984	28.58	21.69	5.79	0.92
EFIMOSA 1961	22.14	18.95	5.36	0.90
LOMMER et al. 2007	34.95	28.48	7.87	0.76
BERGER et al. 1984	24.57	18.98	5.15	0.89
ANGSTROM 1918	29.84	24.06	6.58	0.82

Table 4 - Comparative statistics for performancing of the twelve models of the calculation of the atmospheric longwave radiation in comparison to the data measured in Brasília, daily average.

Model	RMSE (Wm-2)	MAE (Wm-2)	PMRE (%)	r
SWINBANK 1963	48.27	33.18	8.27	0.81
BRUNT 1932	38.90	29.39	7.44	0.97
BRUTSAERT 1975	20.17	14.68	4.46	0.96
IDSO e JACSON 1969	45.97	28.70	7.21	0.79
IDSO 1981	37.94	18.07	4.49	0.96
PRATA 1996	38.14	20.19	4.88	0.96
ZILLMAN 1972	45.90	30.08	7.51	0.81
BERDAHL e MARTIN 1984	36.76	23.70	5.85	0.97
EFIMOSA 1961	41.18	21.13	5.31	0.95
LOMMER et al. 2007	31.76	26.99	7.68	0.96
BERGER et al. 1984	38.61	21.33	5.26	0.96
ANGSTROM 1918	39.10	26.44	6.83	0.90

The results found in this research will contribute to a better understanding of the budget for surface energy for Brasilia, and may result in a better characterization of evapotranspiration for many applications in agriculture, biology, ecology, climatology and hydrology (CHOI et al., 2008).

These equations can be used as research tools for helping to improve current understanding of the basic physiology of crop growth and development, and also as decision support tools for helping to optimize crop and soil management strategies. These equations are of fundamental importance to improve and manage the agricultural activities, developed in Brasilia.

4. Conclusions

Twelve models were tested for ROL estimation for Brasilia, all of them were well adapted to micrometeorological characteristics with satisfactory results.

However, the models that stood out with excellent results from the statistical analysis for atmospheric longwave radiation measurements were Brda (1932), Prata (1996), Idso (1982) Berdahl, Berger et al. (1984) and Martin (1984), they showed good performance with lower values of RMSE, MAE and PMRE for daily and hourly averages.

The models presented better performance for calculations performed with hourly averages, as well as for the daytime period.

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