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# SIMPLIFIED MODELING OF DOWNWELLING LONG-WAVE RADIATION OVER BRAZILIAN SEMI-ARID UNDER IRRIGATION CONDITIONS

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**ABSTRACT.** Data collected in a micrometeorological campaign conducted in a banana orchard in a semi-arid land of Brazil in the period from 2005 to 2006 were used for a long-wave radiation (LWR) study. The objective of the study was the calibration and determination of a long-wave radiation models. In this sense, two established models were used for estimating apparent emissivity of the atmosphere locally calibrated. The percentage and root square errors obtained by calibrated equations were equal to 3.28% and 16.10 $Wm^{-2}$ for the model of Brutsaert and 2.46% and 12.68 $Wm^{-2}$ for the model Bastiaanssen. It was found that the errors obtained with the calibrations performed substantially decreased and that estimates of the radiation incident wave with the same produce results far more accurate than those made with the calibrations proposed originally. This shows the variability of the coefficients in the regions studied and the importance of local calibration.

**Keywords**: radiation, calibration, long-wave, emissivity.

**RESUMO.** Foram utilizados dados de uma campanha micrometeorológica realizada em um pomar de bananeiras na região do semiárido brasileiro, no período de 2005 a 2006, com o objetivo de calibração de modelo de quantificação da radiação de onda longa incidente. Para tanto, foram utilizados dois modelos consagrados de estimativa da emissividade aparente da atmosfera que tiveram os seus coeficientes calibrados localmente. Os erros percentuais e erros médios quadráticos obtidos por meio das equações calibradas foram respectivamente iguais a 3,28% e 16,10 $Wm^{-2}$ para o modelo de Brutsaert e de 2,46% e 12,68 $Wm^{-2}$ para o modelo de Bastiaanssen. Constatou-se que os erros obtidos com as calibrações realizadas diminuíram substancialmente e que as estimativas da radiação de onda incidente com as mesmas produzem resultados bem mais precisos do que aquelas realizadas com as calibrações propostas originalmente. Isto evidencia a variabilidade dos coeficientes com as regiões de estudo e a importância da calibração local.

**Palavras-chave**: radiação, calibração, onda longa, emissividade.

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## INTRODUCTION

The Brazilian semi-arid region is characterized on the climate point of view by its spatial and temporal rainfall irregularity, which produces a lack of water for the population in general. In this region, the commercial agricultural production is almost totally obtained through irrigation. With this, the monitoring of the use of water based on the evapotranspiration (ET), obtained through remote sensing techniques, is being always more used in the last years (Bezerra et al., 2008; Santos & Silva, 2008).

The radiation balance, the main source of energy available for the physical and biological processes, is the essential component of the energy balance on the surface. The understanding of the factors which control the ascending and descending flows in the atmosphere is essential to improve the models used in the various environmental applications. The precise determination of the incident long-wave radiation (LWR) is essential for a good estimate of the radiation balance and, consequently, of the radiation and energy balances (Duarte et al., 2006).

The radiation of the incident long-wave, which represents the thermal flow originated in the atmosphere, is traditionally obtained by the use of the Stefan-Boltzmann Law using the direct measurement of the air temperature, when the apparent emissivity of the atmosphere is known. Various parameterizations to estimate the atmospheric emissivity are found in the literature for different climatic conditions (Flerchinger et al., 2009).

Under the proposed parameterizations for various parts of the globe, two of them stand out in relation to the others. Initially the Brutsaert (1975) model must be mentioned, who in its original form is well adjusted to the majority of the regions in which it is applied, generating determination coefficients above 0.80 in the great majority (Sridhar & Elliott, 2002; Duarte et al., 2006; Choi et al., 2008; Sedlar & Hock, 2009; Kruk et al., 2010; Santos et al., 2011). The second model that stands out is that proposed by Bastiaanssen (1995), which, although having been initially calibrated for Egypt (Bastiaanssen et al., 1998) and later for Idaho – USA (Allen et al., 2000) is being often used in various studies made in various places on the world, including United States, France, China, Turkey, Egypt and other African, European and Asian countries (Bastiaanssen et al., 2005) and more recently in Brazil (Silva & Bezerra, 2006).

Various works are using the calibration proposed by Allen et al. (2000) in the semi-arid region of Brazil (Silva et al., 2005; Santos et al., 2007; Di Pace et al., 2008) due to the lack of a more specific regional calibration. Thus, this work aims the calibration of models proposed by Brutsaert (1975) and Bastiaanssen (1995) for the Brazilian semi-arid with base on the data observed in the region and, consequently, the estimate of the long-wave radiation in a more precise form.

## MATERIAL AND METHODS

### Study area

The study was performed in the Ceará State, located in the Northeast Region in Brazil. The experiment was set up in the area of the Frutacor Farm, emphasized on Figure 1. This region is situated over the Chapada do Apodi and the main agricultural activity is tropical fruit growing. The experiment was installed in an irrigated banana orchard on the farm (5°4′35″S; 37°51′54″O; 131 m), located in the Quixeré County – CE. The region presents a warm and semi-arid climate, and the average annual temperature of 28.5°C, and the maximum and minimum annual temperatures are 36°C and 22°C, respectively. The average annual rainfall in the region is 772 mm and the average annual relative humidity is 62%.

The Ceará State has about 93% of its territory inserted in the semi-arid region of Brazil, becoming vulnerable to the dry season, to the rain irregularity and shortage phenomena. The predominant climate in the State is the hot semi-arid tropical, occurring in an extension of 101,001 km$^2$, this means, about 68% of the total State area. It should also be stressed that the hot semi-arid tropical climate occurs in 98 counties of Ceará. According to the Köppen classification the hot semi-arid climate (BSw'h') predominates in the State in the region of the "sertão" and the rainy tropical climate (Aw') predominates in the coastal region (IPECE, 2011).

In relation to the occurrence of soil types, the State has three preponderant types of soils, and the greatest occurrence are the "Neossolos" occupying an area of approximately 53,000 km$^2$ or 36% of the State area. The second soil type with greatest occurrence is the "Argilossolos", including 36,720.6 km$^2$ or 24.67% and the third refers to the "Luvissolos" with 16.72% of the total State area, or 24,885.6 km$^2$. The type of vegetation with greatest occurrence in the State is the "Caatinga" forest, which occupies about 46% of the Ceará territory. Nevertheless, other types of vegetation are found in Ceará, such as humid forests, the dry forests, the riparian forests with a type of palm tree "carnaúba"), the savanna ("cerrado") and the vegetation complex of the coastal zone (IPECE, 2011).

### Experiment data

The data were obtained in the experimental campaign in Frutacor Farm through instruments installed in a micrometeorological tower in the center of the area. The instruments were installed at 8.0 meters height, and where: a net-radiometer CNR1 (Kipp & Zonen BV, Delft, Holland), to measure the four components of the

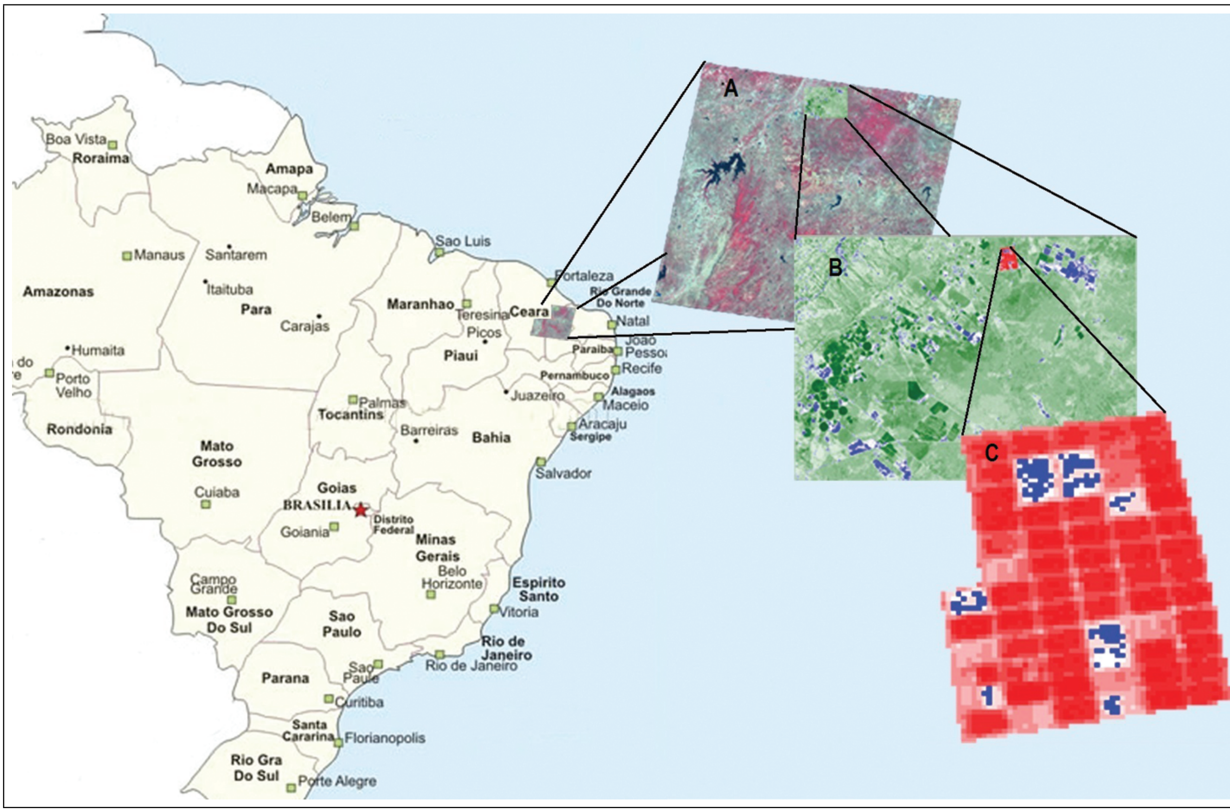



**Figure 1** – Representation of the study area, enhancing the Ceará State (A), area of interest (B) and Frutacor Farm (C).

radiation balance; and one analogical thermo-hygrometer model HMP45C (Vaissala, Finland), to measure the relative humidity and air temperature. For data storage was used a data acquisition system (Data logger) CR23X (Campbell Scientific Inc., Logan, USA), programmed to collect data at every 5 seconds and extract averages at every 20 minutes during the period between September 2, 2005 and September 19, 2006.

## Modeling of the long-wave radiation

The radiation of the incident long-wave ($R_{L\downarrow}$), obtained through the Stefan-Boltzmann Law, is a function of the atmospheric temperature and emissivity. Various studies suggest parameterizations based on air temperature and/or vapor pressure measurements near the surface (Sridhar & Elliott, 2002). In accordance with Duarte et al. (2006) the value of the atmospheric emissivity ($\varepsilon$) is not necessarily constant and $R_{L\downarrow}$ is the balance resulting from a series of emissions and absorptions in long-waves in the atmosphere where the temperature is not uniform.

$$R_{L\downarrow} = \varepsilon\sigma T^4 \tag{1}$$

with $\sigma = 5{,}67051.10^{-8}$ Wm$^{-2}$K$^{-4}$ is the Stefan-Boltzmann constant; $T =$ air temperature near the surface (K).

Brutsaert (1975) obtained analytically a parameterization for the estimate of $\varepsilon$ and, consequently, compute the $R_{L\downarrow}$ at surface under conditions of clear sky and considering an almost standard atmosphere. His relation depends only on the air temperature and the vapor pressure, given as follows by:

$$\varepsilon = a\left(\frac{10e_d}{T}\right)^b \tag{2}$$

where $e_d =$ vapor pressure (kPa); $a$ and $b =$ calibration coefficients. The calibration values found by Brutsaert (1975) were $a = 1.24$ and $b = 0.143$.

Bastiaanssen (1995) suggests a parameterization for the estimate of $\varepsilon$ in daily scale for any cloudiness conditions as only function of the atmospheric transmissibility ($\tau_{sw}$), given by:

$$\varepsilon = a(-\ln\tau_{sw})^b \tag{3}$$

with $a$ and $b =$ calibration coefficients. The original values found for Egypt (Bastiaanssen, 1995) were $a = 1.08$ and $b = 0.26$. Allen et al. (2000) obtained values of $a = 0.85$ and $b = 0.09$

for Idaho, which are used by METRIC (Allen et al., 2007). The values of $\tau_{sw}$ were obtained by measured data in the experiment dividing the incident solar radiation by the solar radiation on the top of the atmosphere.

The estimate of the regression coefficients $a$ and $b$ from Equations (2) and (3) was made beginning with linear and exponential regressions based on data observed on the surface. The linear regression tries to maintain the original exponent of the equations and tries to calibrate only the angular coefficient (zero intercept), while the exponential regression allows to obtain both coefficients.

For comparison purposes, two nebulosity criteria were adopted. The first criterion adopts a condition of clear sky defined by Escobedo et al. (2009), where only the values of $\tau_{sw} > 0.65$ are considered. The second criterion adopts all values of $\tau_{sw}$ obtained in the experiment to obtain the coefficients.

Next will be described the models compared in this study and their respective associated regressions:

- Model 1 (M1): exponential regression from certain hours for the clear sky condition ($\tau_{sw} > 0.65$). Both regression coefficients were obtained.

- Model 2 (M2): simple linear regression from certain hours for the clear sky condition ($\tau_{sw} > 0.65$). The original Brutsaert (1975) exponent was maintained ($b = 0.143$) and only the angular coefficient was calibrated.

- Model 3 (M3): exponential regression from certain hours for any nebulosity condition. Both regression coefficients were obtained.

- Model 4 (M4): simple linear regression from certain hours for any nebulosity condition. The original Brutsaert (1975) exponent was maintained ($b = 0.143$) and only the angular coefficient was calibrated.

- Model 5 (M5): exponential regression from daily data. Both regression coefficients were obtained.

- Model 6 (M6): simple linear regression from daily data. The original Bastiaanssen (1995) exponent was maintained ($b = 0.26$) and only the angular coefficient was calibrated.

- Model 7 (M7): simple linear regression from daily data. The original exponent from Allen et al. (2000) was maintained ($b = 0.09$) and only the angular coefficient was calibrated.

To evaluate the performance of the models the regression analysis was used to obtain the determination coefficients ($R^2$), the correlation coefficients $r$, the average percentage error (APE), the root mean square error (RMSE), the Willmott index $(d)$ (Willmott, 1981) and the performance index $c$ (Camargo & Sentelhas, 1997).

Considering that $X$ represents the observed value, $X'$ represents the estimated value from the models and $N$ represents the number of values, we find that APE and RMSE are given by:

$$APE = \frac{100}{N} \sum_{i=1}^{N} \left| \frac{X_i - X'_i}{X_i} \right| \tag{4}$$

$$RQAE = \sqrt{\frac{\left[\sum_{i=1}^{N} (X_i - X'_i)^2\right]}{N}} \tag{5}$$

The index $d$ quantifies numerically the exactness, being a concordance coefficient (Willmott, 1981). It also shows how the model simulates the values observed, reflecting, in a scale between 0 and 1, the degree of deviation from the 1:1 line in a graphic, on how much the regression line differs from 1 and the interception line from zero, such as:

$$d = 1 - \frac{\sum_i^N (X_i - X'_i)^2}{\sum_i^N (|X'_i - \overline{X}| + |X_i - \overline{X}|)} \tag{6}$$

with $\overline{X}$ = average of values observed.

The performance index $c$ is given by the product of the correlation coefficient and the Willmott index (Camargo & Sentelhas, 1997), this is:

$$c = r \cdot d \tag{7}$$

The Table 1 presents the classification of the regression in accordance with the performance index obtained.

**Table 1** – Values of the performance coefficient ($c$) according to Camargo & Sentelhas (1997).

| Value of $c$ | Performance |
|---|---|
| $> 0.90$ | Excellent |
| 0.81–0.90 | Very Good |
| 0.71–0.80 | Good |
| 0.51–0.70 | Median |
| 0.41–0.50 | Fair |
| 0.31–0.40 | Bad |
| $\leq 0.30$ | Very bad |

## RESULTS AND DISCUSSION

The Equations (2) and (3) were calibrated from data observed in the experiment by the exponential regression and simple linear regression methods (intercept equal to zero). The Tables 2 and 3 present the adjustments found for the Brutsaert (1975) and Bastiaanssen (1995) models, respectively, from the methods previously described. The respective associated determination coefficients are also presented.

**Table 2** – Regression coefficients found for the proposed calibrations for the Brutsaert (1975) model.

| Model | Coefficients | | |
|---|---|---|---|
| | $a$ | $b$ | $R^2$ |
| M1 | 1.3525 | 0.1813 | 0.3326 |
| M2 | 1.2205 | 0.1429 | 0.6099 |
| M3 | 1.6832 | 0.2543 | 0.4945 |
| M4 | 1.2590 | 0.1429 | 0.5032 |

**Table 3** – Regression coefficients found for the proposed calibrations for the Bastiaanssen (1995) model.

| Model | Coefficients | | |
|---|---|---|---|
| | $a$ | $b$ | $R^2$ |
| M5 | 0.9565 | 0.1362 | 0.6149 |
| M6 | 1.0316 | 0.2600 | 0.5532 |
| M7 | 0.9299 | 0.0900 | 0.4403 |

The adjustments evidence that the original exponent from Brutsaert (1975) promotes a better adjustment when maintained fixed in the regression. This is observed due to the dependence of this coefficient in relation to the conditions of an almost standard atmosphere (Duarte et al., 2006). The adjustment for the clear sky condition (M2) represented better the behavior of the variables, followed by the adjustment (M4), which represents all nebulosity conditions. Sridhar & Elliott (2002) found a value of 1.31 for the coefficient $a$ from the linear adjustment. Brutsaert (1975) found a value of 1.24 for the same coefficient.

The adjustment of the Bastiaanssen (1995) model which best represented the behavior of the variables was the exponential (M5), where both coefficients were determined. The independence of the coefficients in relation to the standard atmospheric conditions evidences a local variation of the calibration. The coefficients obtained stayed between the values found for Idaho ($a = 0.85$ and $b = 0.09$; Allen et al. (2000)) and for Egypt ($a = 1.08$ and $b = 0.26$; Bastiaanssen (1995)). Teixeira et al. (2008) found similar values ($a = 0.94$ and $b = 0.11$) for the region of Petrolina – PE, Brazil.

The Table 4 indicates that all adjustments obtained high performances and correlation and a median $c$ value. The RMSE associated to models M1, M2 and M3 were in the order of 16 $Wm^{-2}$, while the model M4 generated an error in the order of 18 $Wm^{-2}$. The APE associated to all models were in the order of 3%. The difference among models M1, M2 and M4 and the data observed was not statistically meaningful when checked through the t-student tests and Tukey at a confidence level of 95%. The model M3 presented a significant difference.

**Table 4** – Comparison among the calibrations proposed for the Brutsaert (1975) model for observed hourly data.

| Model | RMSE ($Wm^{-2}$) | APE (%) | $d$ | $r$ | $c$ |
|---|---|---|---|---|---|
| M1 | 15.89 | 3.21 | 0.83 | 0.85 | 0.70 |
| M2 | 16.10 | 3.28 | 0.83 | 0.84 | 0.69 |
| M3 | 16.65 | 3.23 | 0.84 | 0.76 | 0.65 |
| M4 | 18.15 | 3.43 | 0.81 | 0.71 | 0.57 |

Considering the results obtained, it is found that the model which best fitted to the data was M2 (clear sky) which explains the behavior of 61% of data observed. It is then evidenced that this model stands out in relation to the others.

Table 5 evidences that the performance of models M5 and M6 was similar. The model M7 presented a performance below to all others. The difference between the models and data observed was not statistically significant at a confidence level of 95%, in accordance with the t-student and Tukey tests.

**Table 5** – Comparison among the calibrations proposed for the Bastiaanssen (1995) model for observed hourly data.

| Model | RMSE ($Wm^{-2}$) | APE (%) | $d$ | $r$ | $c$ |
|---|---|---|---|---|---|
| M5 | 12.68 | 2.46 | 0.84 | 0.73 | 0.61 |
| M6 | 19.87 | 3.69 | 0.81 | 0.76 | 0.62 |
| M7 | 13.73 | 2.82 | 0.74 | 0.67 | 0.50 |

The adjustment-performance set which had the best presentation was model M5, which explains the behavior of approximately 61% of the data. The RMSE and APE associated were in the order of 12 $Wm^{-2}$ and 2.5%, respectively.

Figure 2 presents the adjustment of the models described with relation to data observed.

The errors presented in this study correspond to less than 10% of the observations of the incident long-wave and may be considered insignificant when compared to the total radiation of the surface.

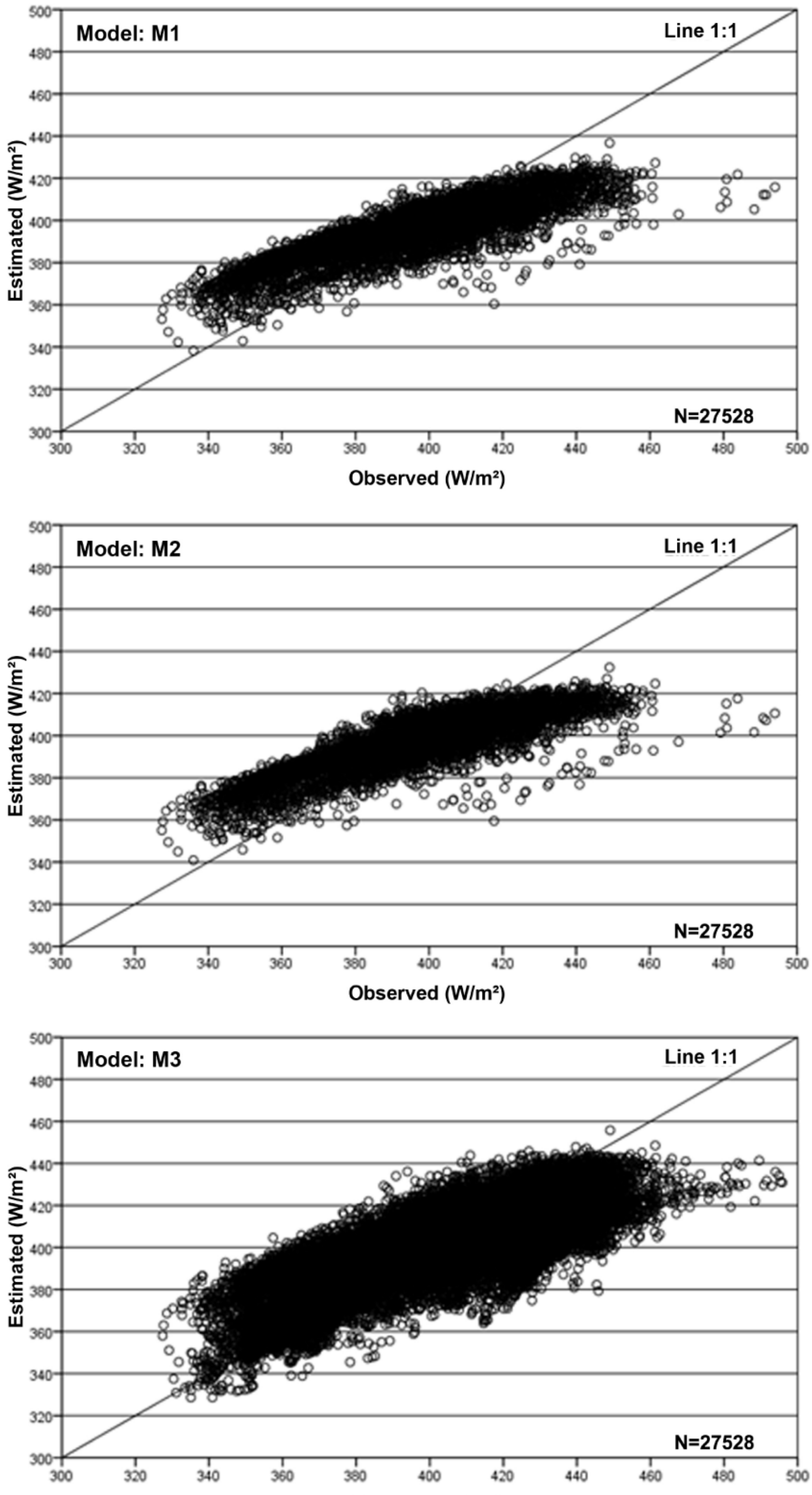
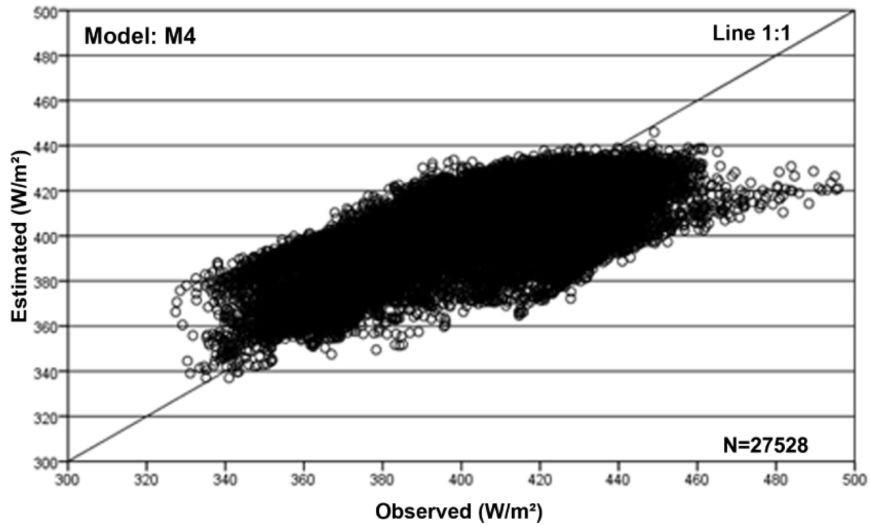
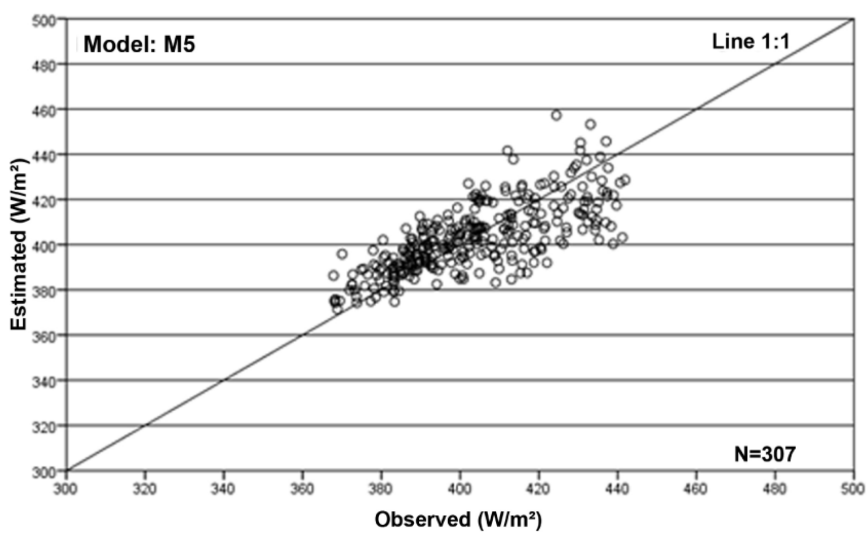



**Figure 2** – Comparison among incident long-wave radiation observed and estimated data from certain hours for the models M1 to M4, and daily for the models M5 to M7.



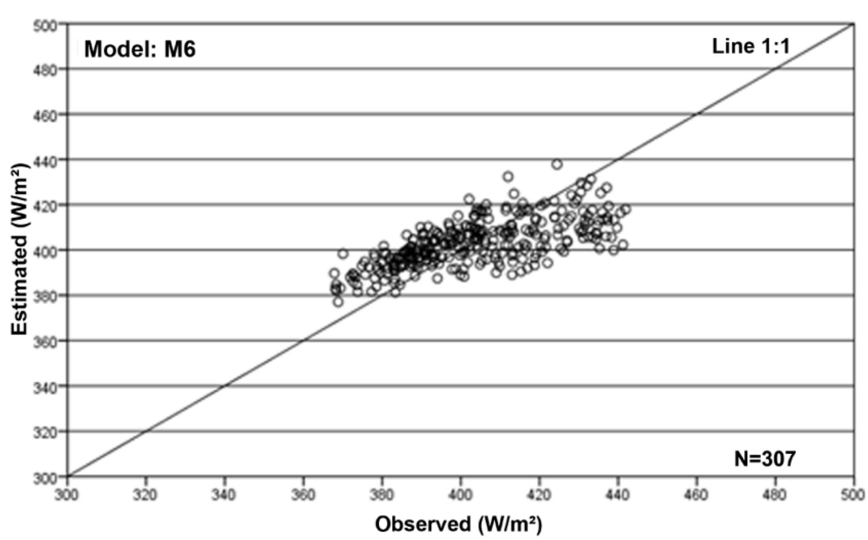




**Figure 2** (continuation) – Comparison among incident long-wave radiation observed and estimated data from certain hours for the models M1 to M4, and daily for the models M5 to M7.

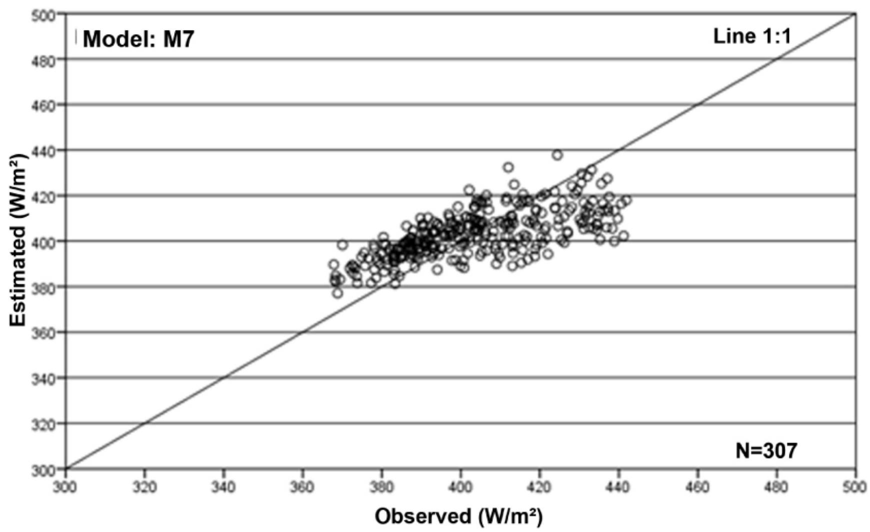



**Figure 2** (continuation) – Comparison among incident long-wave radiation observed and estimated data from certain hours for the models M1 to M4, and daily for the models M5 to M7.

## CONCLUSION

The calibrations suggested in this study evidence significant improvements in the estimation of the radiation of the incident long-wave in the region. The calibrations of the Brutsaert model suggest that the exponent, which depends from the almost standard atmospheric characteristics, must be maintained constant and the geographic variability is represented by the linear adjustment of the equation. The calibrations of the Bastiaanssen model indicate that both coefficients vary considerably from one region to another. The exponential adjustment, in this case, comes out as the best alternative for the proposed models.

The results suggest a good agreement between the estimated and observed values in the region studied. The Brutsaert model requires only temperature and vapor pressure measurements, while the Bastiaanssen model requires incident solar radiation measurements to estimate the atmospheric transmissibility. Both expressions may be applied in regions with a similar climate when measurements of the incident long-wave radiation are not available, but local calibrations suggest a better adjustment of data.

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