PATTERNS OF LONGWAVE RADIATION AT THE SURFACE IN THE MEGACITY OF SÃO PAULO, BRAZIL – PART I: DATA VALIDATION AND MODELING

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RESUMO: Este trabalho avalia a consistência e a qualidade das séries temporais médias de 5 minutos de radiação de onda longa atmosférica, radiação de onda curta, temperatura e umidade relativa de maneira objetiva. Os dados neste trabalho foram observados simultaneamente e de forma contínua de 1997 a 2006 na plataforma micrometeorológica do IAG, localizada no topo do prédio do IAG-USP. O efeito de emissão do domo do pirgeômetro foi removido através da técnica de Redes Neurais reduzindo o erro dos valores de radiação de onda longa atmosférica para 3,5%. A comparação entre os valores médios mensais de radiação de onda longa atmosférica observada em São Paulo com as estimativas de satélite do projeto SRB-NASA, indica excelente concordância. Além disso, neste trabalho é avaliada a qualidade de 10 modelos empíricos de estimativa de radiação de onda longa atmosférica, para dias de céu claro, na cidade de São Paulo. A comparação entre os modelos empíricos indicou que o proposto por Brunt apresenta os melhores resultados, com menores "Mean Bias Error" e "Root Mean Square Error" e maior coeficiente de concordância de Wilmott, sendo assim o mais indicado para estimar a radiação de onda longa emitida pela atmosfera na superfície em dias de céu claro para a cidade de São Paulo.

ABSTRACT: This work evaluates objectively the consistency and quality of a 9 years dataset based on 5 minutes average values of downward longwave atmospheric (LW) emission, shortwave radiation, temperature and relative humidity. All these parameters were observed simultaneously and continuously from 1997 to 2006 in the IAG micrometeorological platform, located at the top of the IAG-USP building. The pyrgeometer dome emission effect was removed using neural network technique reducing the downward long wave atmospheric emission error to 3.5%. The comparison, between the monthly average values of LW emission observed in São Paulo and satellite estimates from SRB-NASA project, indicated a very good agreement. Furthermore, this work investigates the performance of 10 empirical expressions to estimate the LW emission at the surface. The comparison between the models indicates that Brunt's one presents the better results, with smallest "MBE", "RMSE" and biggest "d" index of agreement, therefore Brunt is the most indicated model to estimate LW emission under clear sky conditions in the city of São Paulo.

Key Words: Long Wave Radiation, Neural Network, São Paulo City, Empirical Models.

1. INTRODUCTION

The city of São Paulo, with about 11 millions inhabitants, together with 38 other smaller cities, form the Metropolitan Region of São Paulo (MRSP). It is located about 60 km far from the Atlantic Ocean, is occupied by 20.5 millions of habitants and has approximately 7 millions vehicles. The MRSP has an area of 8,051 km^2 and it is the largest urban area in South America and one of the 10 largest in the world (Codato *et al.,* 2008). There are also evidences that pollution in São Paulo has even altered the local climate by affecting the diurnal evolution of diffuse, direct and global solar irradiance components at the surface locally (Oliveira *et al.*, 2002) and in regional scale (Codato *et al.,* 2008).

The downward long wave atmospheric emission at the surface (LW) plays an important role in the air-surface interaction. It can be estimated using radiative transfer models, empirical expressions, satellite estimates and from *in situ* observations (Oliveira *et al.*, 2006). The LW is one of the key terms in the surface energy budget and is vitally important for climate studies and many other applications such as agricultural meteorology (e.g. prediction of frost) and air-sea-ice interaction studies (Niemelä *et al.,* 2001). Even though LW observations provide reference values for radiative transfer models, empirical expressions and satellite estimates they are not available in Brazil in regular basis, because pyrgeometer is an expensive sensor and LW observations require especial care (Fairall *et al.* 1998).

LW has been regularly measured in São Paulo city, Brazil, since September 1997. These measurements are taken on a platform located at the top of the IAG-USP building ($23^0 33'35''$S; $46^0 43'55''$W).

The platform altitude is 744 m above MSL and the measurements are taken regularly with a sampling frequency of 0.2 Hz and stored at 5 minutes intervals. Simultaneous measurements of global solar radiation, air temperature and relative humidity are also taken at the platform. The LW has been measured using a pyrgeometer model PIR from Eppley Lab Inc. This instrument performs hemispherical, broadband, infrared radiative flux measurements, using thermopile temperature difference. The model PIR pyrgeometer comes with a battery-powered resistance circuitry that provides a voltage that expresses the radiative flux contribution due to the case temperature. Extra channels for measuring case and dome temperatures became available only in October 2003.

The main objective of this work is twofold. First, it will be carried out a characterization of the seasonal evolution of LW in the City of São Paulo. Secondly, it will be evaluate the performance of the empirical expressions available in the literature to estimate LW in São Paulo for clear sky condition. To accomplish that it will be used LW measurements of and other meteorological parameters carried out at the micrometeorological platform located at the University of São Paulo campus in the West side of São Paulo city from 1997 to 2006. In this work, a pyranometer model 8-48, built also by Eppley Lab. Inc, measures the global solar irradiance (SW). The air temperature and relative humidity were estimated using a pair of thermistor and capacitive sensors from Vaisalla. All data measured at the platform was checked and questionable data was removed (Oliveira *et al.* 2002).

2. DATA INSPECTION

Initially it was performed a visual inspection of the entire raw data set. Figure 1a shows raw data from 1997 to 2006, and shortwave radiation, air temperature and LW glitches are easily identified as large incursion of these signals. These problems are related to missing connection between sensor and datalloger, battery failure and rain or dust accumulated over the sensors. In the case of LW it was removed data when $LW < 0$ and $LW > 1000 Wm^{-2}$. This interval was chosen because LW, physically, can not be smaller than zero or higher than 1000 Wm^{-2}. To make the data set consistent it was removed simultaneously all three parameters even when the glitches happened only in one of them.

Even tough the above procedure removed most of the problems there were periods of time when the pyrgeometer was not totally functioning. This problems were caused by battery malfunctioning and the effect on the LW data were more difficult to identify, because the pyrgeometer is not totally shut down. To attenuate the contamination of these more difficult to identify glitches from dataset, a second step was applied to the data inspection procedure. This second step consists in removing LW values located out of the two standard deviation interval centered in the mean value (362.37 ± 64.17 Wm^{-2}). As in the previous step it was also removed from observation of SW and temperature, when LW was not good. To guarantee representativeness for the diurnal cycle it was considered as a valid days with 100% of observations. Here, 100% included days with less than 4 missing values (5 minutes each). The final data set is indicated in Figure 1b. Comparatively to the raw data (Fig. 1a) the final series (Fig. 1b) correspond to 602,134 values or about 64 % of the original series.

3. DOME EMISSION EFFECT CORRECTION USING NEURAL NETWORK TECHNIQUE

According to Fairall *et al.* (1998), considering case (Tc) and dome (Td) temperatures in the estimates of LW using a pyrgeometer model PIR from Eppley, reduces the error below 5 %. In the case of São Paulo simultaneous measurements of LW, T_C and T_D were only available after October 15, 2003.

To correct LW measurements carried out prior that, it was used a neural network technique developed by Oliveira *et al.* (2006). The training set (learning and optimization dataset) employs data measured during years 2004 (7 days) and 2005 (2 days), corresponding to 2,578 observations.
These 9 days were chosen based on heuristic method, from patterns defined as dry, wet, cold, cloudy and clear sky days. As carried out in the previous works (Oliveira *et al.,* 2006), the standard back propagation algorithm with a learning rate 0.3 and momentum 0.5 provided a quick and effective learning of the chosen neural network type – multilayer Perceptron neural network (MLP). The first layer contains 4 neurons, second layer 50 neurons and third layer 1 neuron.

The time evolution of the correction ($LW_{CORRECTED}$ - $LW_{NOT\ CORRECTED}$) are indicated in the Fig. 2a. There, one can see that there is no apparent discontinuity in the series after the NN correction and most of the correction was negative. Negative correction confirms the uncorrected pyrgeometer measurements are due to daytime solar radiation heating of the dome. The correlation between LW corrected by neural network and by $LW_{Fairall}$ is indicated in Figure 2b. The correlation coefficient 0.991 indicated a very good matching between synthetic and real LW series. The data used in the training of the neural net work (7 days) in 2004 was not included in the dispersion diagram of figure 2b.
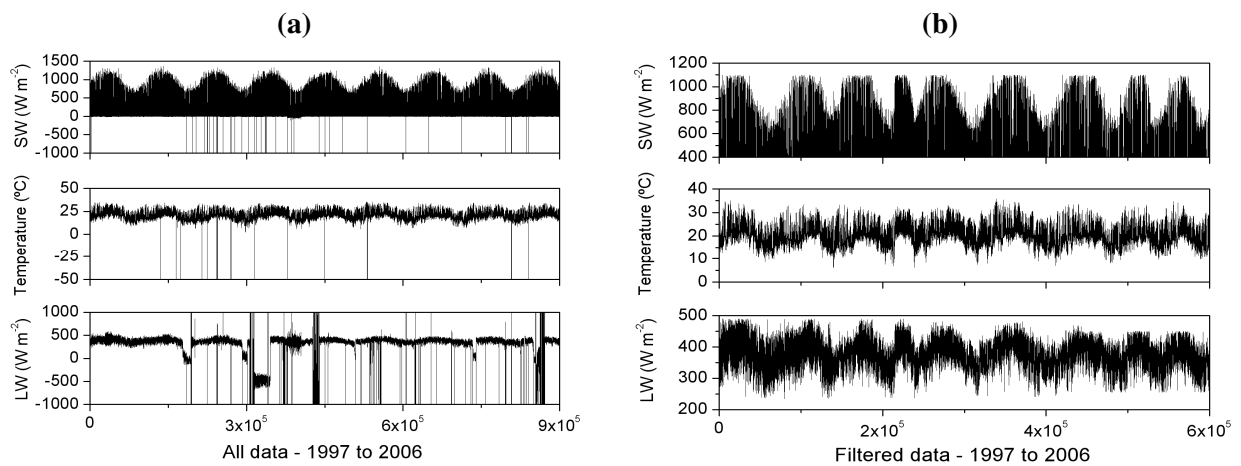
(a)

(b)

All data - 1997 to 2006

Filtered data - 1997 to 2006

Figure 1. (a) Time series of global solar radiation (SW), air temperature (Temperature) and atmospheric downward long wave radiation (LW). **(b)** Filtered data set.
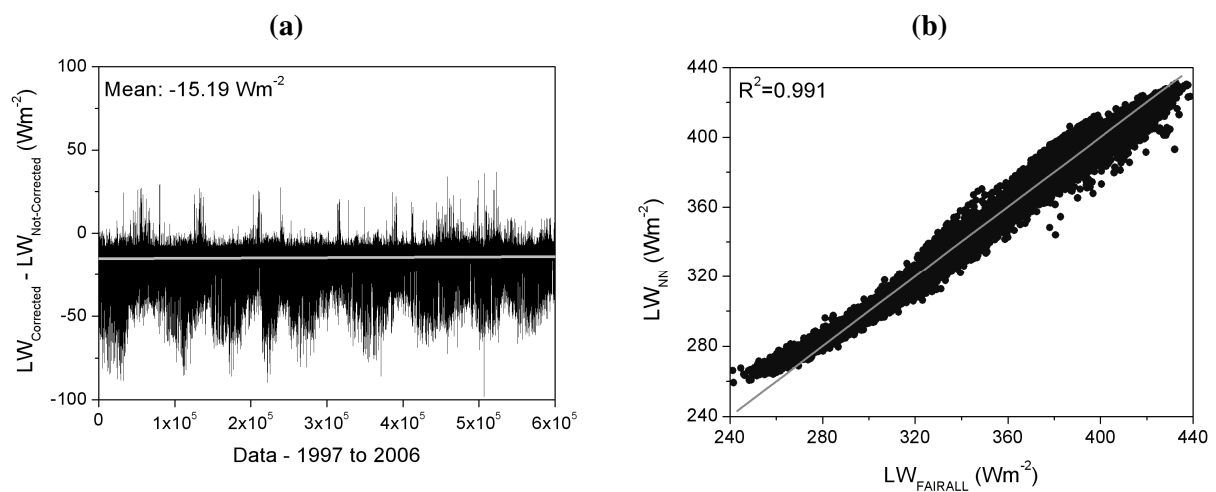
(a)

Mean: -15.19 Wm^{-2}

Data - 1997 to 2006

(b)

R^2=0.991

Figure 2: (a) Time evolution of the correction carried out by NN. **(b)** Dispersion diagram of LW obtained from neural network versus LW corrected by Fairall observed during 2004.

4. PERFORMANCE OF LW MEASUREMENTS

In order to evaluate the performance of LW measurements after the application of 2-steps data inspection and NN corrections it was carried a comparison between LW observed and estimated from satellite data by Project SRB (Surface Radiation Budget) from the National Aeronautics and Space Administration, NASA.

The SRB program was developed by the Langley Research Center for computing LW and SW at the surface using Television Infrared Observational Satellite (TIROS) Operational Vertical Sounder (TOVS) (Gupta *et al.*, 1999). The LW model uses a 1° equal-area global grid and 3-hourly time resolution.

The seasonal evolution of LW observed in São Paulo, considering filtering and NN corrections matches well the daily values estimated from SRB, fig 3. The corrected values systematically underestimate the SRB data, indicating that the SRB has not considered all the parameters required to estimative LW in São Paulo.

It is known that particulate matter in suspension in the urban atmosphere attenuates the solar radiation by scattering it back to space (Oliveira *et al.*, 2002, Codato *et al.*, 2008). This effect may be contributing to reduce the LW emission of the local atmosphere in the case of São Paulo.
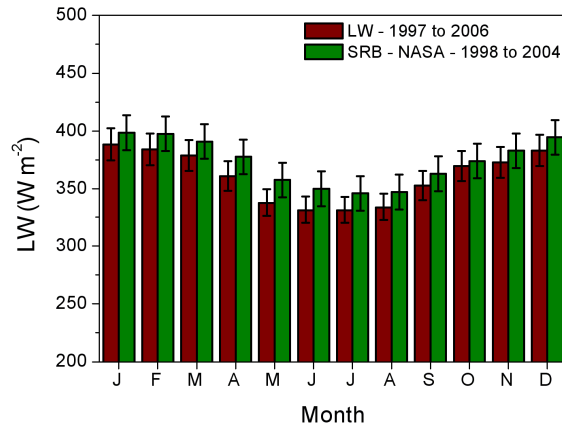
Figure 3. Seasonal evolution of daily value of LW estimated from SRB and based on observations carried out in São Paulo from 1997-2006.

5. MODELING

In this work the performance of 10 empirical expressions will be evaluated to estimate LW in the City of São Paulo for clear sky days (Prata, 1996; Niemelä, 2002). To evaluate the performance of the models it was used three statistical parameters: MBE (Mean bias error), RMSE (Root mean square error) and d (index of agreement; Willmott, 1981).

The frequency distribution of clear sky days, between 1997 and 2006, is indicated in Fig. 4. The seasonal distribution indicates a maximum in the winter and minimum during summer. As expected, the largest number of clear sky days occurs in August, the driest month of the year. Here, a clear sky day was considered when the curves of the diurnal evolution of global and diffuse solar irradiances are simultaneously smooth and have a distinct separation early in the morning and come together only at the end of the day.
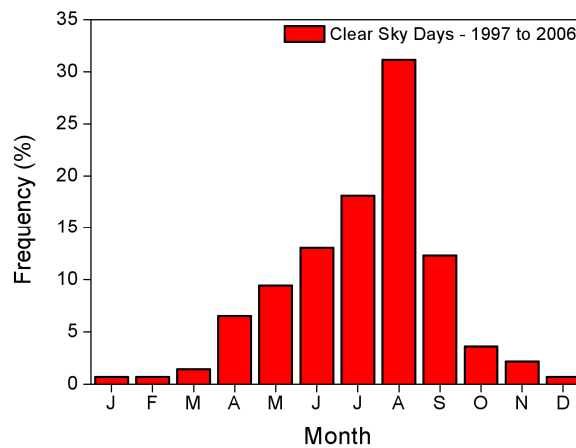

Figure 4. Seasonal evolution of the monthly-average frequency of clear sky days in São Paulo, between 1997 – 2006.

The performance of all 10 empirical expressions can be visualized by comparing the MBE, RMSE and the index of agreement as indicated in figure 5.

All models used in this work overestimate the LW values because they present a positive MBE. The Brunt's model presents the better result, with the smallest MBE, RMSE and the biggest index of agreement, d (fig 5a). In addition, all the models perform better in the nighttime (fig 5b) because all of them are very sensible to air temperature and vapor pressure fluctuations, which are more intense during daytime due to the shortwave radiation.
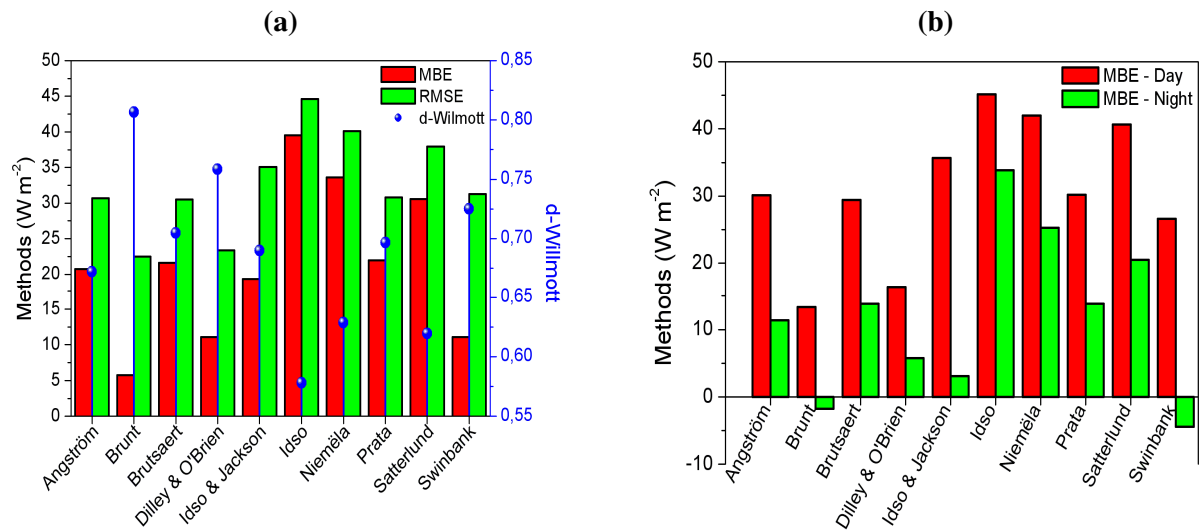
Figure 5. (a) Performance of the model in terms of MBE, RMSE and d; (b) MBE for day and nighttime periods.

6. CONCLUSION

The main objective of this work is to evaluate the LW data consistency and the performance of the empirical expressions available in the literature to estimate LW in São Paulo. The methodology to evaluate data consistency objectively for LW using solar radiation, temperature and relative humidity data was developed and performed satisfactorily. The pyrgeometer dome emission effect was removed using neural network technique reducing the LW emission error to 3.5%. Comparison between the monthly average values of LW emission observed in São Paulo and satellite estimates from SRB-NASA project indicated a very good agreement. The comparison between the models indicates that Brunt's model presents the better results, with smallest "MBE", "RMSE" and biggest "d-index of agreement", therefore this is indicated to estimate the LW, in clear sky conditions, in the city of São Paulo.

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