PADRÕES DE EMISSÃO DE RADIAÇÃO DE ONDA LONGA ATMOSFÉRICA NUMA MEGACIDADE: SÃO PAULO, BRASIL

PATTERNS OF LONGWAVE RADIATION EMISSION FROM THE ATMOSPHERE IN A MEGACITY: SÃO PAULO, BRAZIL

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RESUMO

Este trabalho avalia de maneira objetiva a consistência e a qualidade das séries temporais médias de 5 minutos de radiação de onda longa atmosférica (OL), radiação de onda curta, temperatura e umidade relativa. Também, descreve a caracterização sazonal da evolução diurna da OL na cidade de São Paulo. 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 OL para 3,5%. A comparação entre os valores médios mensais de OL observada em São Paulo com as estimativas de satélite do projeto SRB-NASA, indica excelente concordância. A OL apresenta uma variação sazonal do ciclo diurno determinada pela temperatura e umidade na superfície, e, a presença de nuvens aumenta a emissividade da atmosfera em cerca de 8 %. Durante o inverno, o índice AI indica que o aerossol em São Paulo absorve mais do que espalha radiação. Além disso, neste trabalho é avaliada a qualidade de 10 modelos empíricos de estimativa de OL, 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 "MBE" e "RMSE" e maior coeficiente de concordância de Wilmott, sendo assim o mais indicado para estimar a OL para dias de céu claro na 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. The LW and respective atmospheric emissivity diurnal cycle shows a seasonal variation that is determined by temperature and relative humidity evolution at the surface. The Presence of clouds intensifies the monthly-average atmospheric emissivity at the surface in about 8 %. During winter the AI index indicates that aerosol in RMSP absorbs more than scatters radiation. 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, São Paulo City, Particulate Matter, Empirical Models.

1. INTRODUCTION

The city of São Paulo, with about 11 millions habitants, together with 38 other smaller cities, forms the Metropolitan Region of São Paulo (MRSP). This region, located about 60 km far from the Atlantic Ocean, is occupied by 20.5 millions of habitants and has approximately 7 millions of 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 become 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. It will be given special emphasis on the assessment of the impact caused by air pollution, especially by aerosol. 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 micro-meteorological 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 > 1000Wm^{-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 cause 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 into to remove 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 in 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 602134 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 15 October 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 year 2004 (7 days) and 2005 (2 days), corresponding to 2578 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 contain 4 neurons, second layer 50 neurons and third layer 1 neuron.

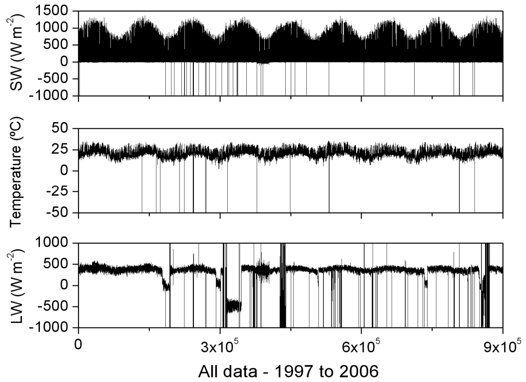

Figure 1. (a) *Time series of global solar radiation (SW), air temperature (Temperature) and atmospheric downward long wave radiation (LW).*

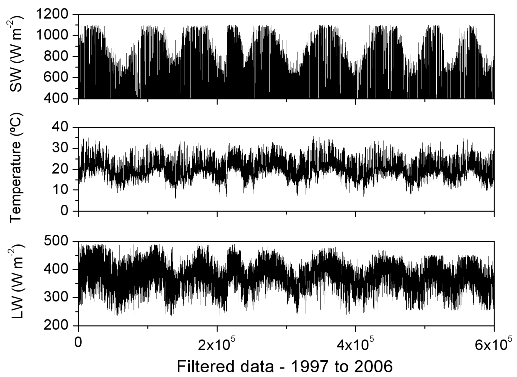

Figure 1. (b) *Filtered data set*

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 that 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.

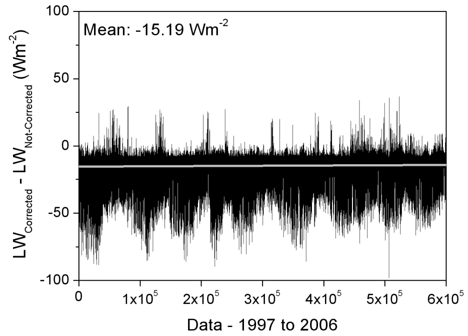

Figure 2.(a) *Time evolution of the correction carried out by NN.*

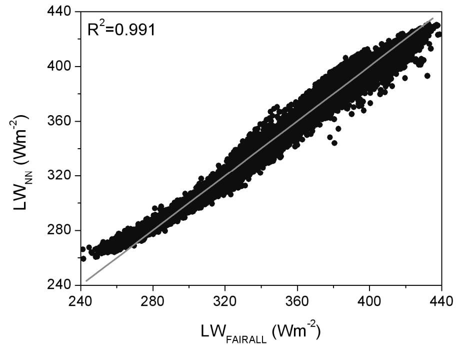

Figure 2.(b)*Dispersion diagram of LW obtained from neural net work versus LW corrected by Fairall observed during 2004.*

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.

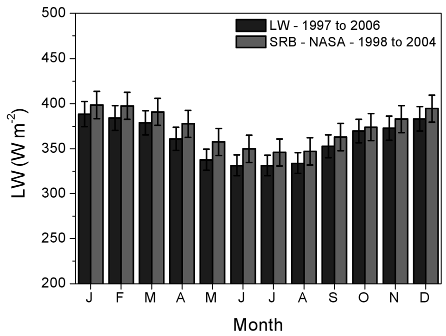

Figure 3. *Seasonal evolution of daily value of LW estimated from SRB and base on observations carried out in São Paulo from 1997-2006*

5. LW SEASONAL EVOLUTION

The seasonal evolution of monthly average hourly values of LW in MRSP is displayed in Figure 4. There, the LW observed in São Paulo shows a maximum during daytime and during summer. This pattern reflects the local climate of temperature, moisture, cloud and pollution.

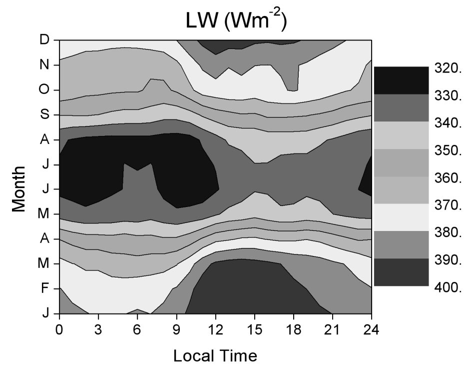

Figure 4. *Seasonal variation of the diurnal evolution of LW in MRSP. Observations carried out in the micrometeorological platform of the IAG-USP.*

6. IMPACT OF POLLUTION

To investigate the impact of air pollution on the seasonal evolution of LW in the MRSP, it will be analyzed in this section the seasonal evolution of the particulate matter (PM_{10}). The São Paulo State Environmental Agency (CETESB), using Beta Attenuator Method (CETESB, 2004), measures hourly values of PM_{10} at the surface.

In this work it was selected two stations C. César and Lapa. These stations are located respectively at 6 and 4 km far from micrometeorological platform of IAG USP where LW measurements are carried out. The data used to evaluate the monthly-average values of PM_{10}, corresponds to 9 years of continuous observation from 1997 to 2005. The seasonal evolutions of monthly averaged daily values of PM_{10} are indicated in Figure 5.

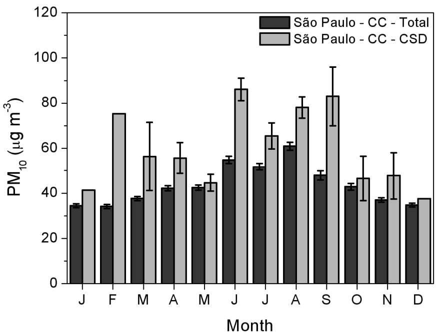

Figure 5.(a) C. César (CC)

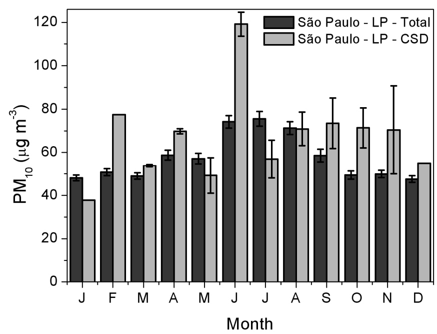

Figure 5.(b) Lapa (LP)

Seasonal evolution of monthly average daily values of PM_{10} observed at the surface in the city of São Paulo at CETESB monitoring network stations. Monthly-average values based on entire dataset (1997-2005) are indicated by **Total**. Monthly-average values based only clear sky are indicated by **CSD**.

The seasonal evolutions of PM_{10} in these two stations are correlated, indicating that the high level of this pollutant is a regional feature of the MRSP during all months of the year.

One way to characterize the radiometric properties of the aerosol in the MRSP is by using the aerosol index (AI) estimated from satellite measurements (Torres *et al.*, 1998). This technique has been used to show that the dust from Sahara is correlated with negative anomalies of sea surface temperature (Lau and Kim, 2007). In Figure 6 is showed the time evolution of daily values of PM_{10} in Cerqueira Cesar and Lapa, accumulated rain and AI index, observed during summer (Fig. 6a) and winter (Fig. 6b). Rain cleans the atmosphere and reduces the concentration of PM_{10}, therefore the aerosol present in the atmosphere must reflect the local sources. However, there is no clear pattern relating AI and PM_{10} concentration, principally in the summer time. Some times AI is positive, indicating that the aerosol is scattering radiation. Other times, AI is negative, indicating that the aerosol present in RMSP is absorbing radiation.

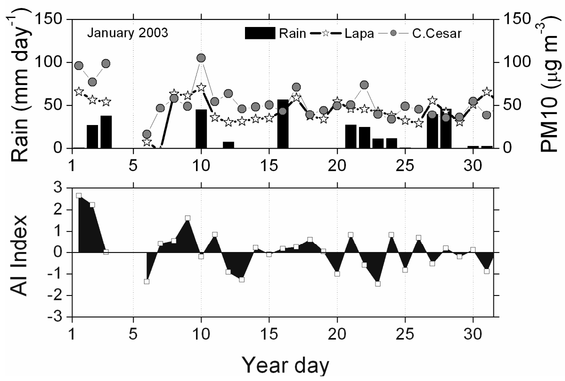

Figure 6.(a) *Summer (January)*

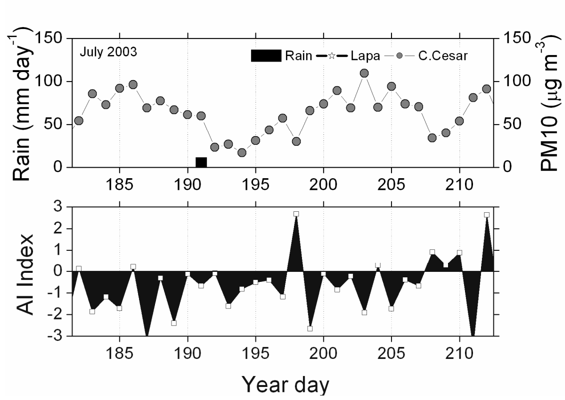

Figure 6.(b) *Winter (July)*

Time evolution of PM, accumulated rain and AI index

The histogram of AI index for summer (Fig. 7a) and winter (Fig. 7b) indicates that during winter the aerosol in the MRSP absorbs more than scatter radiation. During summer, the aerosol present in the atmosphere both absorbs and scatters radiation.

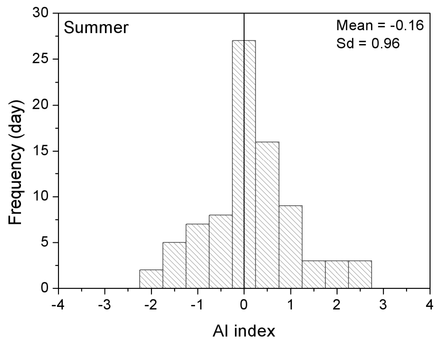

Figure 7.(a) *Summer (January)*

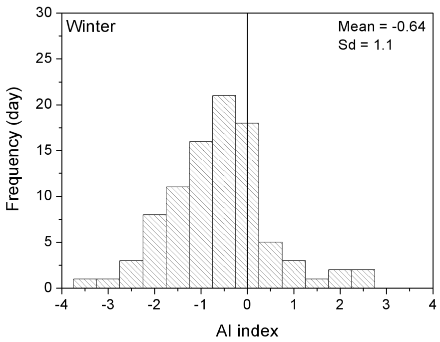

Figure 7.(b) *Winter (July)*

Histogram of AI index for MRSP

7. 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 distributions of clear sky days, between 1997 and 2006, are indicated in Fig. 8. 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.

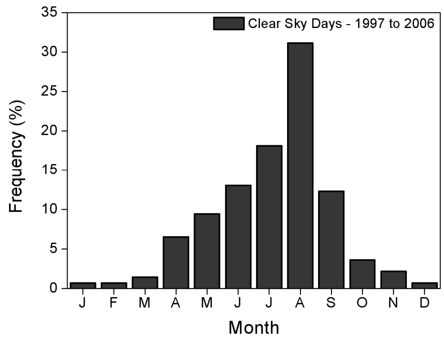

Figure 8. *Seasonal evolution of the monthly-averaged frequency of clear sky days in São Paulo. Period: 1997 – 2006.*

The performance of all 10 empirical expressions can be visualized by comparing the MBE, RMSE and the index of agreement as indicated in figure 9.

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 9a). In addition, all the models perform better in the nighttime (fig 9b) because all of them are very sensible to air temperature and vapour pressure fluctuations, which are more intense during daytime due to the shortwave radiation.

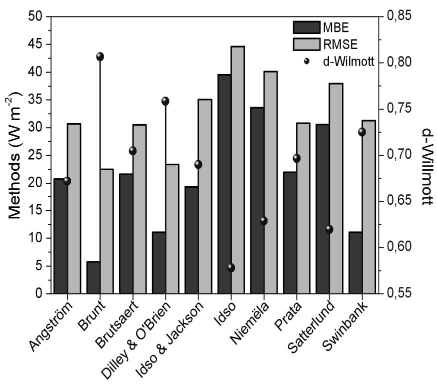

Figure 9. *(a) Performance of the models in terms of MBE, RMSE and d*

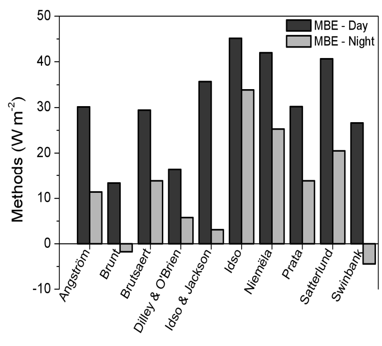

Figure 9.*(b) MBE for day and nighttime periods*

8. CONCLUSION

The main objectives of this work are to evaluate the LW data consistency and the performance of the empirical expressions available in the literature to estimate LW in São Paulo, and to characterization of the seasonal evolution of LW in the city of 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 averaged values of LW emission observed in São Paulo and satellite estimates from SRB-NASA project indicated a very good agreement. During summer and daytime, the LW observed shows a maximum. This pattern reflects the local climate of temperature, moisture, cloud and pollution. The impact of pollution was analyzed, indicating that the PM_{10} daily values are high during all the year, even when only clear sky days are considered. The AI index indicates that during the winter the aerosol in the MRSP absorbs more than scatter radiation. 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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