

SEASONAL EVOLUTION OF THE SURFACE RADIATION BALANCE IN THE CITY OF SÃO PAULO

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Abstract: The seasonal evolution radiation balance at the surface in the City of São Paulo, Brazil, is estimated. The atmospheric long wave emission and global solar radiation at the surface are based on measurements carried out at surface in the University of São Paulo campus (CUASO). The surface long wave emission was based on the surface temperature measured at the IAG meteorological station (PEFI) and by considering the surface emissivity equal to 0.95. The surface reflected solar radiation was estimated from the global solar radiation observed in the CUASO and an albedo equal to 0.15.

Keywords: Radiation balance; São Paulo; Global solar radiation; Longwave radiation; pyrgeometer.

Resumo: A variação sazonal das componentes do balanço de radiação na superfície da Cidade de São Paulo, Brasil, é estimada. A radiação de onda longa emitida pela atmosfera e a radiação solar global na superfície são baseadas em medidas efetuadas na superfície sobre o campus da Universidade de São Paulo (CUASO). As estimativas da emissão de onda longa da superfície estão baseadas na temperatura da superfície observada na estação meteorológica do IAG (PEFI). A radiação solar refletida pela superfície é estimada a partir da radiação solar global observada no CUASO e considerando o albedo da superfície constante e igual a 0.15.

Palavras-chave: Balanço de radiação; São Paulo; Radiação global; Radiação de onda longa; pirgeômetro.

INTRODUCTION

The characterization of the climate in city is a very complex task due to the large heterogeneity of the land use and topography (Oke, 1982; Oke *et al.*, 1999, Gambi, et al., 2000) by the effects of pollution (Longuetto et al., 1992). Despite of these complexities, several works have described the seasonal patterns of solar radiation components and wind velocity at the surface in the

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city of São Paulo (Pereira *et al.*, 1996; Oliveira, *et al.*, 1996; Pereira *et al.*, 1998; Oliveira e Machado, 1999; Oliveira *et al.*, 2000; Oliveira e Machado, 2001; Oliveira *et al.*, 2002a; Oliveira *et al.*, 2003).

This work describes the seasonal evolution of the radiation balance at the surface of São Paulo city considering atmospheric long wave radiation and global solar radiation measurements taken on a platform located at the top of the building of the IAG-USP (“Instituto de Astronomia, Geofísica e Ciências Atmosféricas da Universidade de São Paulo”) at the "Cidade Universitária Campus", in the west side of the São Paulo city, hereafter referred as CUASO.

The surface long wave radiation is estimated from the monthly average surface temperature observed in the climatological station located in the east side of São Paulo city, at 780 m amsl ($23^{\circ}39' S$, $46^{\circ}37' W$), hereafter referred as PEFI.

These two sites are located in similarly vegetated areas of São Paulo, at basically the same altitude (Figure 1).

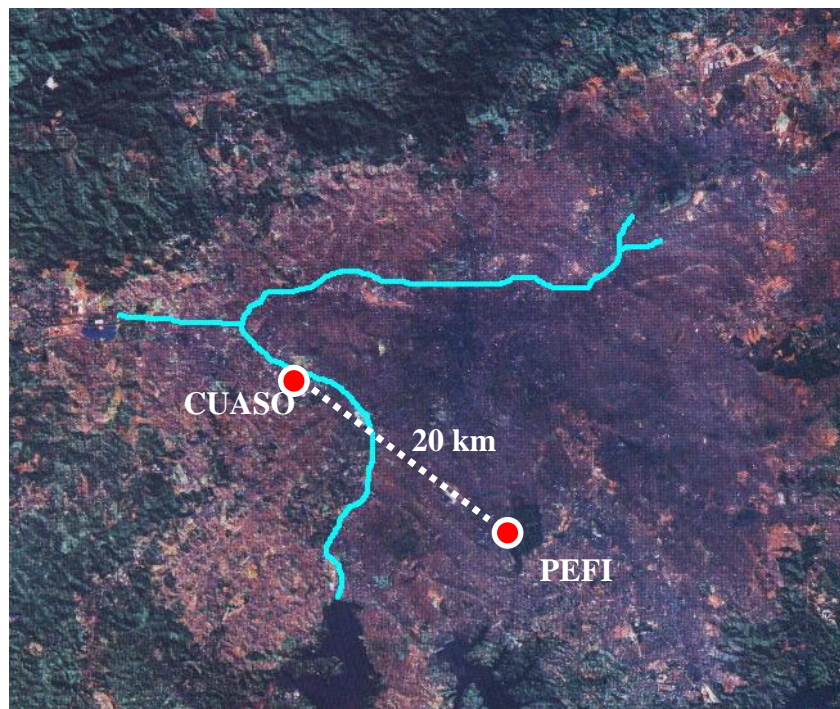


Figure 1: Satellite image of the São Paulo urban area. The CUASO and PEFI geographical localizations are indicated. The blue lines are the Tiete and Pinheiros rivers.

SITE AND MEASUREMENTS

Most of the measurements used here were taken on a platform located at the top of the building of the IAG-USP (Institute of Astronomy, Geophysics and Atmospheric Sciences of the University of São Paulo) at the "Cidade Universitária Campus", in the west side of São Paulo, at 744 m above the mean sea level (23°33' S, 46°43' W). This site hereafter will be called CUASO (Figure 1).

The surface long wave radiation is estimated from the monthly average surface temperature observed in the climatological station located in the east side of São Paulo city, at 780 m amsl (23°39' S, 46°37' W), hereafter referred as PEFI.

These two sites are located in similarly vegetated areas of São Paulo, at basically the same altitude (Figure 1).

The data used in this work is described in Table 1.

CUASO			
	Variable	Sensor	Period of observation
I _{DW}	Global solar radiation	Pyranometer - Eppley	Apr/1994-Sep/2003
L _{DW}	Atmospheric longwave emission	Pyrgeometer - Eppley	Sep/1997-Sep/2003
T _{AIR}	Air Temperature	Thermistor - Vaisala	Sep/1997-Sep/2003
UR	Relative humidity	Thermistor - Vaisala	Sep/1997-Sep/2003
I _{UP}	Reflected solar radiation	Pyranometer - Kipp-Zonen	November 10, 2003
L _{UP}	Surface longwave emission	Pyrgeometer - Kipp-Zonen	November 10, 2003
I _{DW}	Global solar radiation	Pyranometer - Kipp-Zonen	November 10, 2003
L _{DW}	Atmospheric longwave emission	Pyrgeometer - Kipp-Zonen	November 10, 2003
V	Wind speed	Cup anemometer -RM Young	November 10, 2003
	Wind direction	Wind direction sensor -RM Young	November 10, 2003
PEFI			
T _{AIR}	Air Temperature	Termographer - Fuess	Jan/1998-Dec/2002
T _G	Surface Temperature	Geothermometer -Fuess	Jan/1998-Dec/2002
V	Wind velocity	Anomegrapher - Fuess	November 10, 2003
-	Wind direction	Anomegrapher - Fuess	November 10, 2003
CETESB			
V	Wind velocity	Oliveira <i>et al.</i> 2003	Jan/1988-Dec/1988
-	Wind direction	Oliveira <i>et al.</i> 2003	Jan/1988-Dec/1988

Table 1: Sensors, localization and period of observation.

LONGWAVE RADIATION EMISSION FROM THE ATMOSPHERE

Pyrgeometer performance

To test the performance of the pyrgeometer used at the CUASO site (PIR from Eppley), it was compared with another pyrgeometer used as reference (Kipp-Zonen model CNR1). These two pyrgeometers were run side by side between August 17 and September 15 of 2000 in the country city of Botucatu (Assunção *et al.*, 2003).

To avoid problems related to solar heating effects (discussed in details later), the dispersion diagram displayed in Figure 2 was built considering only nighttime values of longwave radiation measured by the pyrgeometer PIR and the reference pyrgeometer. As can be seen in Figure 2 there is a good agreement between the observations carried out by both radiometers.

Calibration constant obtained from the linear regression coefficient of the adjusted line in Figure 2 indicated a value of $3.99 \mu\text{V W}^{-1} \text{m}^{-2}$. This value corresponds to a positive deviation of $0.21 \mu\text{V W}^{-1} \text{m}^{-2}$, about 6% larger than the original value proposed by the manufacture ($3.63 \mu\text{V W}^{-1} \text{m}^{-2}$). Considering the age sensor at the calibration time (10 years old), this variation is not consistent with the expected decreases with time, observed in radiometers based on thermopiles.

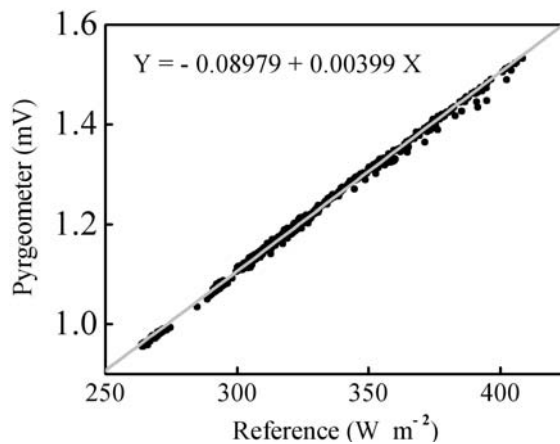


Figure 2: Nighttime longwave radiation dispersion diagram for the pyrgeometer Eppley used to measure long wave radiation in CUASO. The reference is a pyrgeometer from Kipp-Zonen model CNR1.

A possible explanation for this discrepancy in the pyrgeometer calibration constant is that the reference pyrgeometer (Kipp-Zonen model CNR1) has a flat dome, while pyrgeometer model PIR from Eppley has a hemispherical dome. Despite this apparent inconsistency the Eppley pyrgeometer output shows a very good matching with the reference pyrgeometer. Therefore, it was used the calibration constant proposed by the manufacturer, $3.63 \mu\text{V W}^{-1} \text{m}^{-2}$, to estimate longwave radiation measured by the PIR pyrgeometer.

Solar heating effects on longwave radiation measurements

To describe the diurnal evolution of radiation balance at the surface is necessary to address solar heating effects (dome and case of the pyrgeometer) on daytime measurements. To take into consideration the heating effects on the pyrgeometer performance is necessary to estimate the heat balance on the sensor.

According to Fairall *et al.* (1998) the atmospheric long wave emission measured by a model PIR pyrgeometer, manufactured by Eppley, can be estimated considering the heat balance given by:

$$L_{DW}^1 = \frac{\Delta V}{s_0} + \sigma T_c^4 + B\sigma(T_c^4 - T_D^4) \quad (1)$$

Where L_{DW}^1 is the corrected value of longwave radiation, ΔV is the thermopile voltage, T_c and T_D are, respectively, the case and dome temperatures, s_0 and B are calibration factors which depend of the sensor direct calibration. According to Fairall *et al.* (1998), taking into consideration the third term of expression (1) reduces the error below 5 %.

Even though the expression (1) being highly recommended it may not be easily applied, mainly because the manufacturer does not provide s_0 and B and the calibration factors have to be estimated indirectly (Payne *et al.*, 1999). Besides, as pointed by Fairall *et al.* (1998), the T_c and T_D are seldom observed due to the restrictions in the channel numbers of the data acquisition system.

In the case of CUASO, extra channels for measuring T_c and T_D become available only in October 2003. Therefore, measurements of longwave radiation with the PIR pyrgeometer before that date followed only the manufacturer recommendations, that considers a calibration factor, s_1 , applied to the temperature to compensate the voltage output, ΔV_c . The manufacturer correction is:

$$L_{DW} = \frac{\Delta V_c}{s_1} = \frac{\Delta V}{s_0} + \sigma T_c^4 \quad (2)$$

The value of s_1^{-1} provided by the manufacturer is $3.63 \pm 0.04 \mu V W^{-1} m^{-2}$.

The long wave radiation measured by the PIR pyrgeometer, from Eppley, can also be corrected using the expression proposed by Pérez and Allados-Arboledas (1999):

$$L_{DW}^2 = L_{DW} + 0.099 \frac{I_{DW}}{\sqrt{V+1}} \quad (3)$$

Where L_{DW}^2 is the corrected long wave radiation in Wm^{-2} , L_{DW} is the long wave radiation obtained using expression (2) in Wm^{-2} , I_{DW} is the global solar radiation in Wm^{-2} and V is the wind intensity in ms^{-1} .

Table 2 resumes the corrections performed on the PIR pyrgeometer measurements.

Correction	Period
Manufacturer	September 1997 to September 2003
Perez and Allados-Arboledos (1999)	September 1997 to September 2003 using monthly averaged wind velocity from CETESB and monthly averaged global solar radiation observed in CUASO
Perez and Allados-Arboledos (1999)	November 10, 2003, using hourly values of wind velocity and global solar radiation observed in CUASO (Figures 5 and 6)
Fairall et al. (1998)	November 10, 2003, using hourly values of dome and case temperatures (Figure 4)

Table 2: PIR pyrgeometer corrections.

The hourly values of atmospheric longwave emission measured in São Paulo (CUASO) on November 10, 2003 (year day 314) are indicated in Figure 3. The atmospheric emission in CUASO was corrected by the manufacturer method (L_{DW} , expression 2), Fairall method (L_{DW}^1 , expression 1) and by Allados-Arboledas method (L_{DW}^2 , expression 3) as described above.

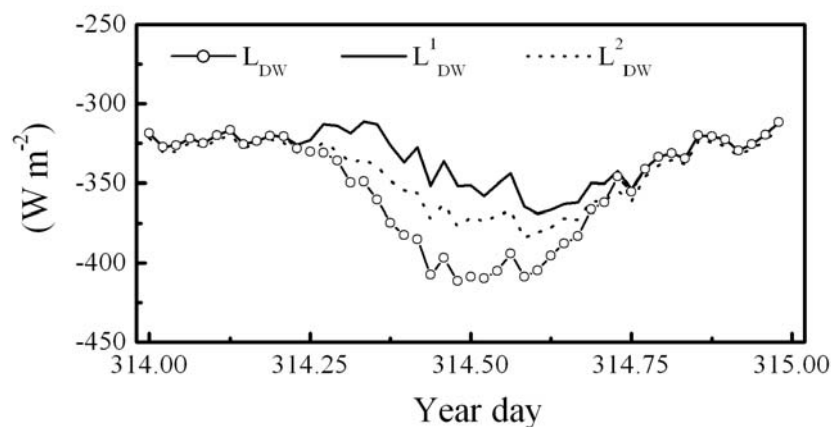


Figure 3: Longwave atmospheric emission estimated by the pyrgeometer Eppley using expression (2), L_{DW} , using expression (1), L_{DW}^1 , and using expression (3), L_{DW}^2 . Observed in São Paulo (CUASO) on November 10, 2003.

The case and dome temperatures used in the Fairall correction are indicated in Figure 4. The case and dome temperatures are warmer (slightly colder) than the air temperature during daytime (nighttime).

The case temperature was smaller than the dome temperature, during daytime, indicating a significant dome emission. The discrepancies between the not corrected and corrected longwave emission from the atmosphere reach about 25 W m^{-2} for Fairall correction and 40 W m^{-2} for Perez and Allados-Arboledas, during daytime.

During nighttime the case was slightly warmer than the dome (Figure 4) and there is no significant difference between the not corrected longwave atmospheric emission (L_{DW}) and the corrected by Fairall (L_{DW}^1) and Perez and Allados-Arboledas (L_{DW}^2).

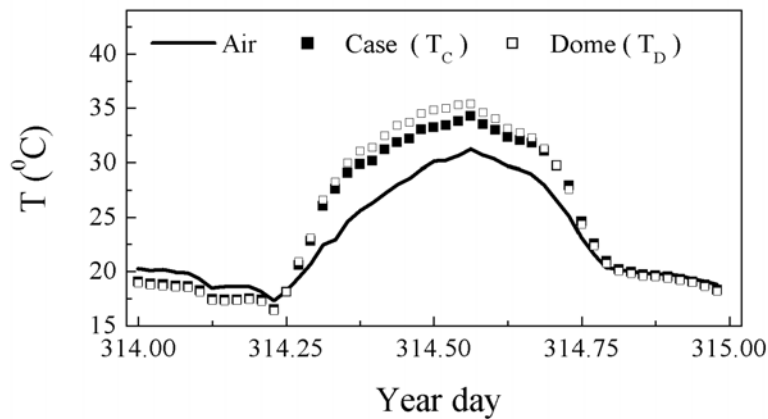


Figure 4: Diurnal evolution of air, case and dome temperatures on November 10, 2003 in São Paulo (CUASO).

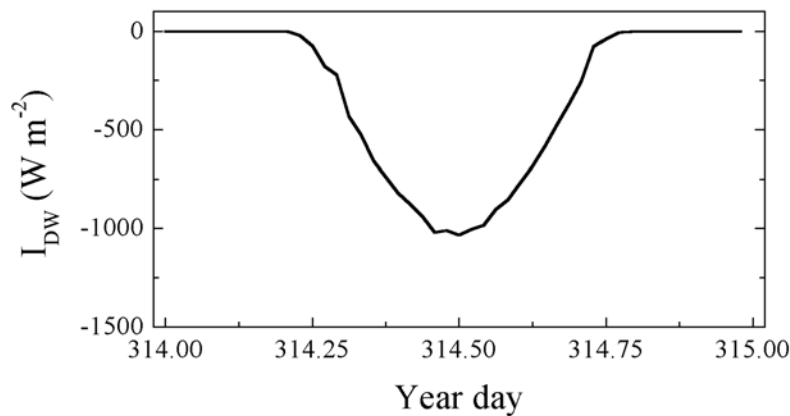


Figure 5: Diurnal evolution of the global solar radiation at the surface at CUASO on November 10, 2003.

The long wave emission corrected using Perez and Allados-Arboledas method (L_{DW}^2) was evaluated using global solar radiation (I_{DW}) and the wind velocity observed in CUASO (Figs. 5 and 6).

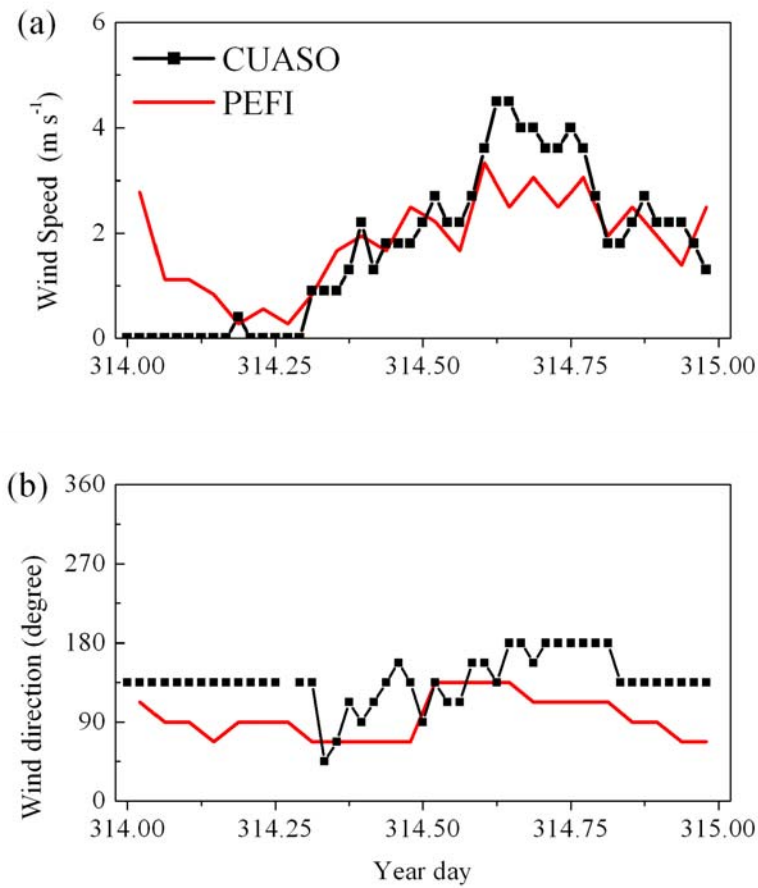


Figure 6: Diurnal evolution of the (a) wind velocity and (b) direction observed in CUASO and PEFI stations on November 10, 2003.

The case and dome temperatures were not available prior October 7, 2003 and therefore, it was applied Perez e Allados-Arboledas method to correct the effects on the long wave emission measured at the surface at CUASO by the pyrgeometer Eppley.

Unfortunately, wind velocity is not available at CUASO prior October 7, 2003, therefore, expression (3) was applied only to correct hourly monthly averaged values of longwave radiation. In this case it was used hourly monthly averaged values of wind observed by CETESB (Oliveira et al, 2003) and hourly monthly averaged values global solar radiation measured at CUASO.

LONGWAVE EMISSION AND REFLECTED SOLAR RADIATIONS FROM THE SURFACE

The long wave radiation emitted by the surface and the surface temperature are not routinely measured at CUASO. The surface temperatures observed at PEFI were used to estimate the long wave emission, at CUASO, considering a surface emissivity of 0.95 (Voogt and Grimmond, 2000).

The surface temperature observations at PEFI were carried out every hour from 7:00 to 24:00 LT. Between 0:00 and 7:00 LT there is no observation available and, therefore, the surface temperatures between 0:00 and 07:00 were obtained considering the air temperature, at PEFI, equal to the surface temperature at PEFI (Voogt and Grimmond, 2000)

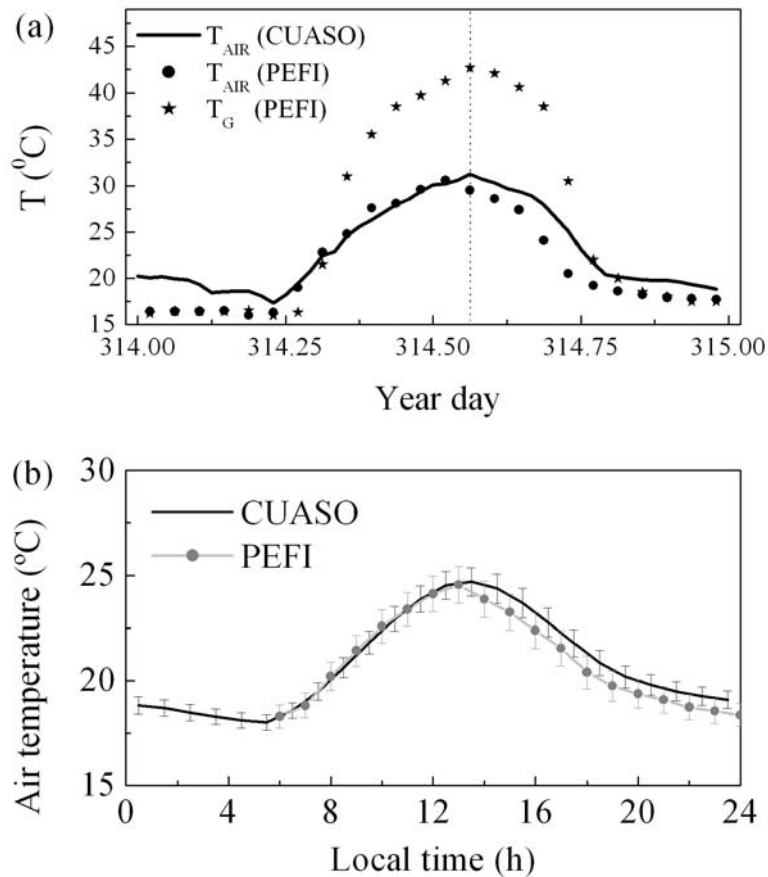


Figure 7: Diurnal evolution of (a) air temperature in CUASO and PEFI and surface temperature in PEFI on November 10, 2003.(b) monthly average air temperature measured in CUASO and PEFI during november.

The air temperatures at CUASO and PEFI during the morning period are similar (Figure 7a). The difference in the afternoon is due to the sea breeze that penetrates in CUASO later (vertical dashed line in Figure 7a) than it penetrates at PEFI. During nighttime, the CUASO is warmer than PEFI. The monthly average values of air temperature in PEFI and CUASO confirmed the fact that air temperatures in CUASO and PEFI show a similar diurnal evolution, modified only by the

cooling associated to the sea breeze penetration early in PEFI. Therefore it seems reasonable to estimate the emission in CUASO base on the surface temperature measured in PEFI.

In order to measure the net radiation flux, a net radiometer model CNR1, manufactured by Kipp and Zonen was set up in November 2003, at the micrometeorological platform in CUASO site. This sensor is composed by two pyranometers (model CM3), two pyrgeometers (model CG3) and one thermistor (Pt100). The thermistor provides the sensor temperature used to compensate the solar heating effects on the radiation measurements. The accuracy is around 2.5 % for intensities smaller than 1000 W m^{-2} . It was selected the observations carried out on November 10, 2003 because during that day there was no cloud activity.

The diurnal evolution of the surface longwave emission estimated from the surface temperature measured at PEFI is compared with the measurement using Kipp-Zonen pyrgeometer at CUASO (Figure 8). The surface emission estimated from PEFI surface temperature is systematically smaller (around 10 %) than the emission estimate at CUASO.

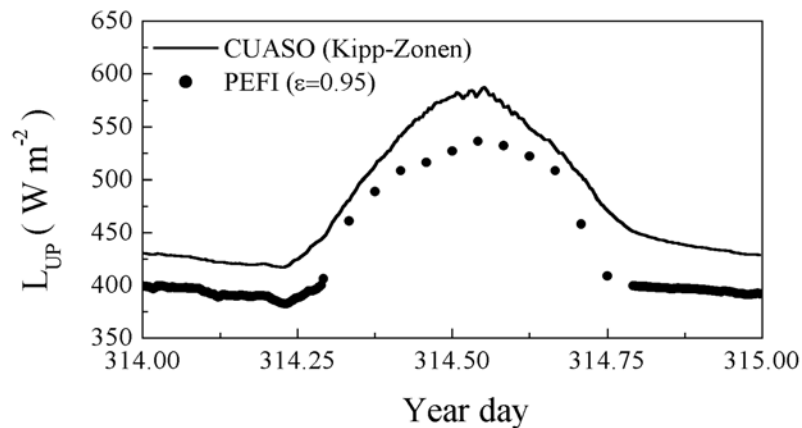


Figure 8: Diurnal evolution of surface long wave emission observed in CUASO and estimated from the surface temperature observed at PEFI site, on November 10, 2003.

The surface atmospheric long wave emission measured at CUASO using the pyrgeometer (Kipp Zonen) is compared with the emission also observed at CUASO using the pyrgeometer (Eppley). As illustrated in Figure 9, the matching is good.

The global solar radiation at the surface observed from the Kipp-Zonen and Eppley pyranometers are indicated in Figure 10. The reflected solar radiation at the surface (I_{UP}) observed from the Kipp-Zonen pyranometer and estimated considering the observed global solar radiation and the surface albedo equal to 0.15 is indicated in Figure 11.

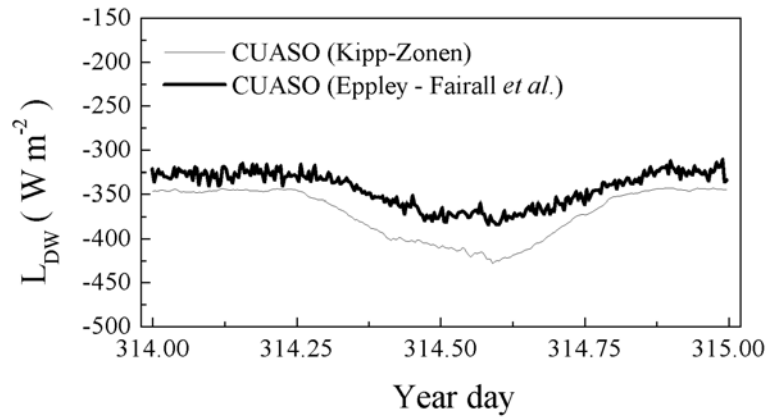


Figure 9: Diurnal evolution of atmospheric long wave emission observed in CUASO site using the pyrgometers Kipp-Zonen and Eppley, on November 10, 2003.

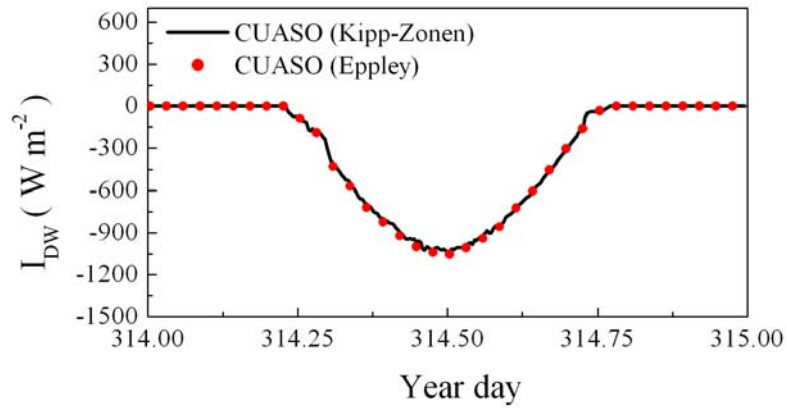


Figure 10: Diurnal evolution of global solar radiation observed in CUASO site using Kipp-Zonen and Eppley pyranometers, on November 10, 2003.

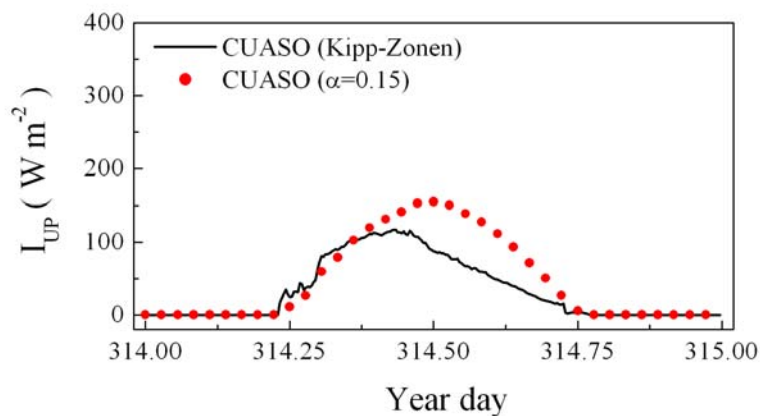


Figure 11: Diurnal evolution of solar radiation reflected at the surface observed in CUASO site using the Kipp-Zonen pyrgometer and estimated from global solar radiation (Figure 10) considering the albedo equal to 0.15, on November 10, 2003.

The variation in I_{UP} , after 10:00 LT, is caused by the fact that the reflected solar radiation was measured in the top of the building. This shows how difficult is to use a simple albedo to characterize urban areas.

SEASONAL VARIATION OF THE RADIATION FLUX COMPONENTS

The diurnal evolutions of the global and reflected solar radiations at the surface are indicated for December and June in figure 12. For the City of São Paulo the amplitude of solar radiation at the top of the atmosphere in December (Figure 12a) corresponds to approximately twice the amplitude in June (Figure 12b).

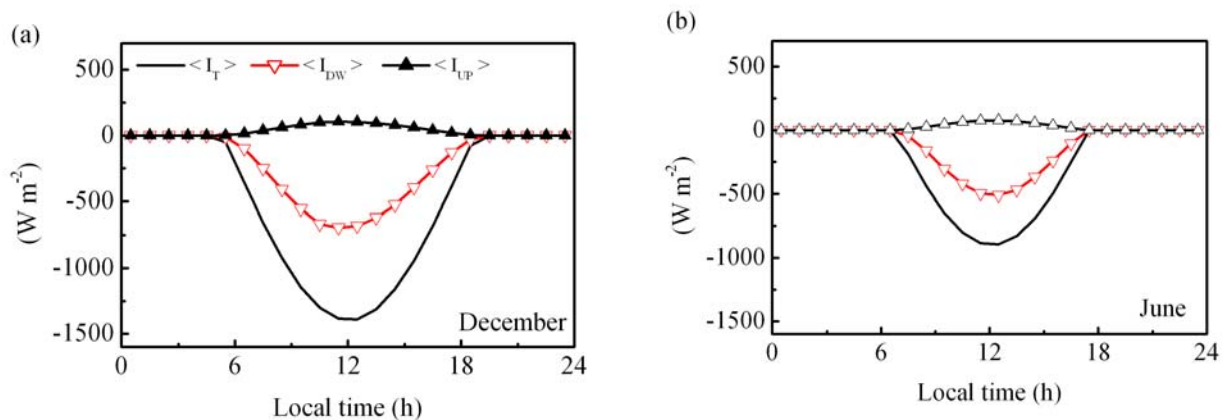


Figure 12: Diurnal evolution of monthly averaged solar radiation components at the CUASO site.

Monthly average hourly values of longwave radiation emitted from the atmosphere have similar amplitudes during December (Figure 13a) and June (Figure 13b). The longwave radiation from the atmosphere is correlated with the diurnal evolution of the air temperature. It is interesting to observed that relative humidity have a very well defined diurnal cycle either during December and June (Figure 14). However this diurnal evolution is not caused by the variation in the moisture content of the atmosphere, because the monthly average values of water vapor pressure at CUASO does not show any significant diurnal pattern (Figure 14).

The amplitude of the longwave emission from the surface follows, as expected, the diurnal evolution of the surface temperature (Figure 15).

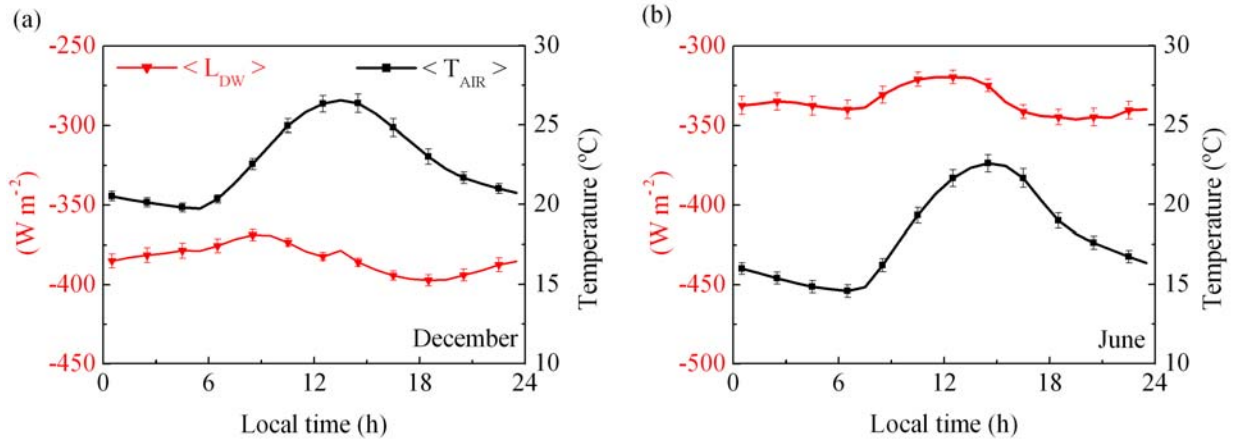


Figure 13: Diurnal evolution of monthly averaged atmospheric longwave radiation and air temperature at the CUASO site.

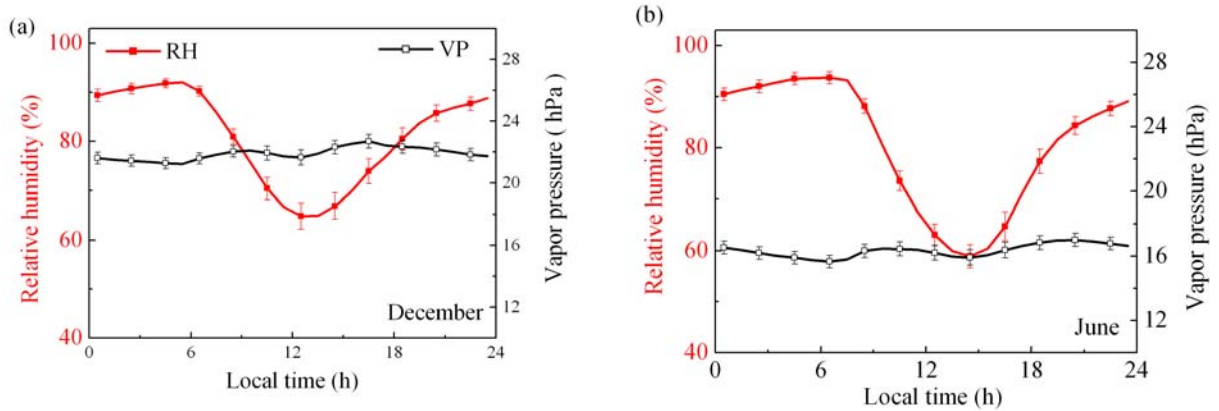


Figure 14: Diurnal evolution of monthly average relative humidity and water vapor pressure at the CUASO site.

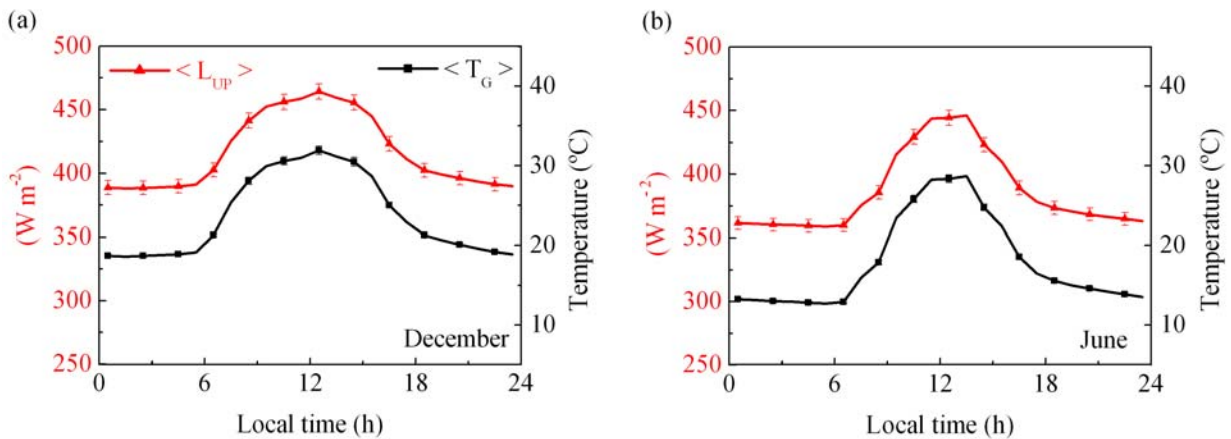


Figure 15: Diurnal evolution of monthly average surface long wave emission and temperature at the CUASO site.

The monthly averaged hourly values of radiation balance components are indicated in Figure 16. The long wave components have a similar trend in both months. However, in December (Fig. 17a) the net radiation at the surface indicated a very small positive values during the nighttime,

comparatively to June (Fig. 17b). The seasonal evolution of net radiation in São Paulo are indicated in Figure (18).

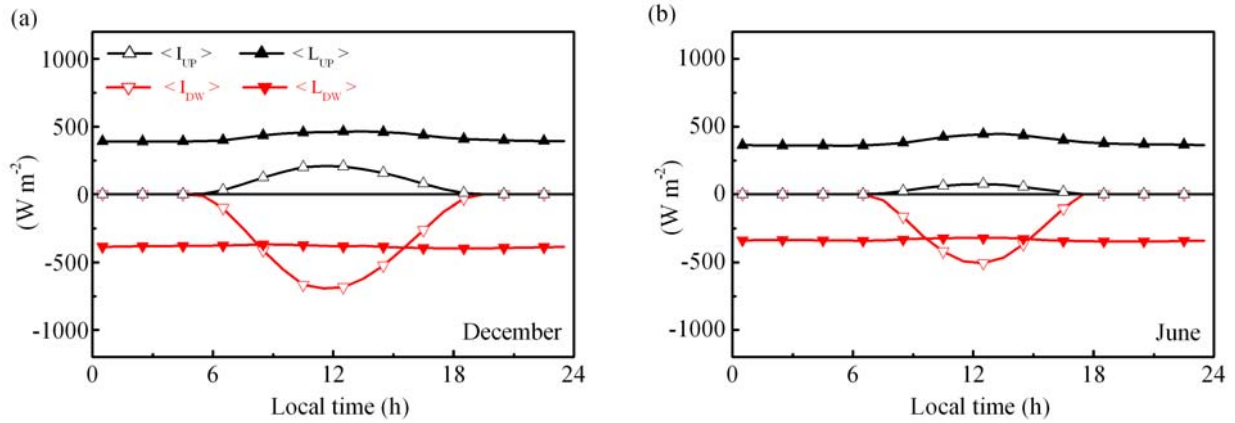


Figure 16: Diurnal evolution of monthly average radiation balance components at the surface at the CUASO site..

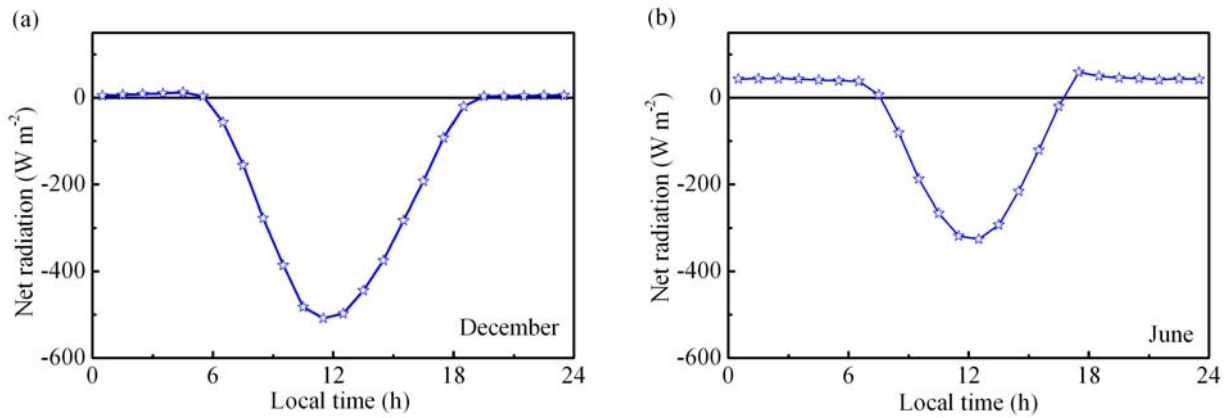


Figure 17: Diurnal evolution of monthly averaged net radiation at the surface at the CUASO site.

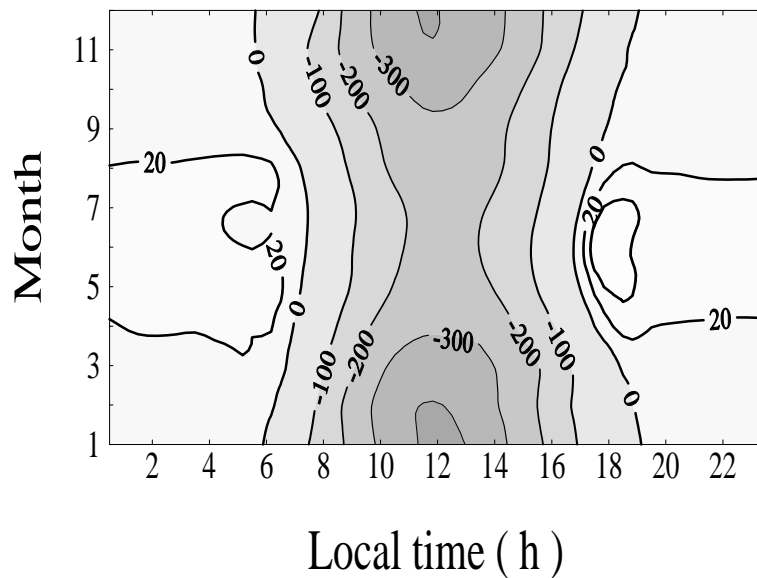


Figure 18: Diurnal evolution of monthly averaged hourly values of net radiation at the surface at the CUASO site.

CONCLUSION

The main goal of this work is to describe the temporal evolution of radiation balance at the surface in São Paulo city. The analysis was carried out using atmospheric global solar radiation and longwave radiation measured at CUASO, located and the University of São Paulo campus. The longwave radiation emitted by the surface was estimated from the observations of surface temperature carried out at the climatological station from IAG, labeled PEFI, located about 20 km eastward from CUASO.

The pyrgeometer Eppley was calibrated using as reference a pyrgeometer Kipp-Zonen. The calibration constant estimated from calibration was about 6 % larger than the manufacturer values. It was decided to keep the original manufacturer constant. Solar heating effects were taken into consideration in the evaluation of the longwave atmospheric emission considering the Perez and Allados-Arboledas methodology. In this case the global solar radiation used was measured in CUASO and the wind velocity was estimated from the monthly averaged hourly values obtained from the CETESB network (Oliveira *et al.*, 2003).

Longwave surface emission at CUASO site was estimated from the surface temperature observed at PEFI site and by considering the emissivity equal to 0.95. Comparison between this estimate and observations indicated a very good matching.

Reflected solar radiation at CUASO site was obtained from the hourly values of global solar radiation and by considering the albedo of the surface equal to 0.15. Comparison between this estimates and observations in CUASO indicated deviations after 10:00 LT.

The diurnal evolution of monthly averaged values of net radiation at the surface at CUASO site indicates large positive values (50 W m^{-2}) during winter months at nighttime and large negative values during daytime in the summer (-500 W m^{-2}).

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