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Diurnal Evolution of Surface Radiation Budget Components in the Cities of São Paulo and Botucatu

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***Abstract**: Seasonal variation of diurnal evolution of the global, diffuse and direct solar radiations at surface are described in details for the cities of São Paulo and Botucatu. The description is based on measurements of (i) global and diffuse solar radiation carried out in São Paulo (7.5 years) and in Botucatu (5 years). This description includes also continuous measurements of long wave downward atmospheric emission, air temperature and humidity carried in São Paulo (3.5 years). The diurnal cycle of the diffuse and direct components of solar radiation at the surface have a distinct evolution in these two cities. In July, arrives in Botucatu about 24 % more global radiation and 45 % more direct beam solar radiation than in São Paulo. The amplitude of the diurnal cycle of long wave downward atmospheric emission has maximum amplitude of 420 W m^{-2}, in the summer around noontime, and a minimum of 300 W m^{-2}, in the winter between 2:00 and 3:00 LT. Under clear sky conditions, simultaneous observations indicated a large contrast of long wave downward atmospheric emission, air moisture and temperature between São Paulo and Botucatu. The pollution effect combined with the distance from the Atlantic Ocean may be responsible for the discrepancy found between São Paulo and Botucatu..*

***Keywords:** Solar Radiation; Atmospheric Radiation; Urban Climate; São Paulo City; Botucatu City.*

1. Introduction

The radiation budget at the horizontal and homogeneous surface can be express as:

$$Rn = I\downarrow + I\uparrow + L\downarrow + L\uparrow \qquad (1)$$

where Rn is the net radiation, $I\downarrow$ ($I\uparrow$) and $L\downarrow$($L\uparrow$) are the incoming (outgoing) solar and atmospheric radiation components. The incoming solar radiation component that reaches the surface can also be decomposed in direct (I_{BEAM}) and diffuse ($I_{DIFFUSE}$) components. In general the incoming solar radiation is also called global solar radiation (I_{GLOBAL}). The knowledge of the time and spatial evolution of the radiation budget components at the surface is important to quantify local and global climate change processes (Wainer *et al*, 2002), to understand the air pollution impact on the local atmospheric and climate process (Longuetto, *et al.* 1992), to support a more significant urban management from the thermal and air quality point of view (Oke, 1980), to improve the remote sensing skill (Gambi, *et al.* 2000), to make a more rational energy use (Colle *et al.*, 2001). Unfortunately, there is no information available in the literature about the spatial distribution of the radiation budget components in Brazil. Most of the available information has been concentrated on solar radiation components (Pereira, *et al.*, 1996, 1998). Therefore the main goal of this work is to describe the temporal and spatial evolution of the components of radiation budget at the surface using the observations of solar radiation components and long wave downward atmospheric emission in the Cities of São Paulo and Botucatu.

The City of São Paulo, with 10 millions habitants, together with 38 other smaller cities, form the Metropolitan Region of São Paulo (MRSP). This region is occupied by 16.5 millions habitants distributed over an area of 8051 km^2 and it is the largest urban area in South America and one of the 10 largest in the world. The MRSP, with more than 4 million of motor vehicles (CETESB, 1999), is characterized as having moderate degree of contamination by particulate matter and other pollutants (Kretzschmar, 1994). The seasonal distribution of surface wind speed indicated the MRSP area is characterized by light winds throughout the year, with intensity varying between 1 ms^{-1} and 2.5 ms^{1}, from N-NE direction (Oliveira, *et al.*, 2001). The analysis of 5 days of continuous observations of solar radiation in São Paulo indicated a systematic reduction in the direct solar beam associated to a progressive increase in the concentration of particulate matter (Oliveira *et al.*, 1996). The long-term effects caused by particulate matter on the solar radiation field in São Paulo has indicated also a systematic reduction in the direct solar beam at the surface (Oliveira *et al.*, 2002a). However, this reduction was not followed by a proportional increase in the diffuse component of the solar radiation.

Therefore, if the global solar radiation at the surface has a tendency to decrease (as the concentration of particulate matter in São Paulo increases) and the diffuse radiation does not increase proportionally, some questions remain to be answered:

(a) Where is the depleted solar radiation going?

(b) Are the observed reductions absorbed by the polluted atmosphere in São Paulo?

(c) How much of this effect is related to the expected larger values of air humidity and cloud cover of São Paulo due to its Atlantic Ocean proximity?

(d) Is this absorption increasing the temperature in the Planetary Boundary Layer and contributing to the Heat Island Effect in São Paulo?

One way to address these effects on the solar radiation field in the City of São Paulo is comparing the radiometric properties of its atmosphere with another place geographically similar to São Paulo, but not so polluted. Besides, this reference place must have observations of solar radiation matching, in terms of quantity and quality, the ones carried out in the City of São Paulo.

The City of Botucatu, used in this work as the reference place, satisfies most of these conditions. Botucatu is located at 786 m above the mean sea level, which is close to the height of São Paulo (770 m). Besides, the latitude of Botucatu (22^{o}51'S) is very similar to the latitude of São Paulo (23^{o}33´S). Another important condition - also satisfied by Botucatu - is that its urban area is occupied by about 100,000 habitants, which is about 100 times smaller than São Paulo. Therefore, one can expect to find much less air pollution contamination in the atmosphere of Botucatu. Moreover, the radiometric station located in State University of São Paulo campus, and maintained by the Laboratory of Solar Radiation in the Department of Environmental Science, UNESP, has measured global and diffuse components of solar radiation, at surface, since 1994.

2. Site and Measurements

Global and diffuse components of solar radiation, at surface, have been regularly measured in the Cities of São Paulo and Botucatu, since 1994. In both sites, the diffuse component has been measured directly using a shadow-band device (Escobedo *et al.*, 1997; Oliveira *et al.*, 2002c)

In São Paulo, the measurements were 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 City of São Paulo (Table 1). Hereafter this measurement site will be called *IAG site* (Figure 1a). In the IAG site, the global solar irradiance and its diffuse component were measured by two pyranometers, model 8-48 and model 2; both built by Eppley Lab. Inc. The beam solar radiation was measured using pyrheliometer, model NIP (coupled to a solar tracker device) and the long wave radiation downward atmospheric emission was measured using infrared radiometer. They are also, manufactured by Eppley. These sensors are periodically calibrated, using as secondary standard another spectral precision pyranometer model 2 (Oliveira and Machado, 1999 and 2001). Measurements of air temperature and relative humidity were accomplished using probe manufactured by Campbell Inc (model HMP35C). The mixing ratio was estimated using atmospheric pressure measurements carried out in IAG site with barometric pressure sensor manufactured by Campbell Inc (model SETRA).

In Botucatu, the equivalent measurements were taken in a rural area of Botucatu City (Figure 1b). This site, referred hereafter as UNESP site, is located in the Campus of the State University of São Paulo, and maintained by the Solar Radiation Laboratory of the Department of Environmental Sciences. It is located at 786 m above the mean sea level and at geographic coordinates 22°51'S and 48°26'W (Table 1). The UNESP site corresponds to a rural area characterized by an homogeneous horizontally distributed green short grass surrounded by spots of deciduous forest at South (Figure 1b). The radiometers used in Botucatu are similar to the ones used in Sao Paulo and they were also calibrated periodically (Frisina, 1998, Galvani, 2001). The atmospheric long wave downward emission at the surface has been measured in IAG site since September of 1997, and in UNESP site since 2000. Recently, the calibration procedure of these radiometers has been carried by an absolute radiometer, as reference, in the UNESP Laboratory of Solar Radiation.

Figure 1a: The *IAG site* in the University of São Paulo Campus, São Paulo (23°32'S). The shadow-band device has 40 cm of diameter. The picture reports the Southeast sector of the University Campus, with the Oceanographic Institute behind.

Figure 1b: The *UNESP site* in the State University of São Paulo, Botucatu, SP (22°51'S). Both shadow-band devices have 40 cm of diameter. The solar tracker in the up front has a shadow disk coupled in it. The picture reports the Southeast sector the State University of São Paulo campus located at left side of the Department of Environmental Sciences building.

2.1. Climate of São Paulo

The City of São Paulo (Figure 2) is located in the State of São Paulo, Brazil, at approximately 770-m above the mean sea level and 60-km westward from the Atlantic Ocean. Its climate - typical of subtropical regions of Brazil - is characterized by a dry winter during June-August and a wet summer during December-March. The minimum values of daily monthly-averaged temperature and relative humidity occur in July and August (16^{o}C and 74%, respectively), and the minimum monthly-accumulated precipitation occurs in August (35 mm). The maximum value of daily monthly-averaged temperature occurs in February (22.5^{o}C) and the maximum value of daily monthly-averaged relative humidity occurs from December through January and from March through April (80%). The maximum value of monthly-accumulated precipitation occurs in February (255 mm). The shortest and the longest day light durations are, respectively, 10.6 hours (June) and 13.4 hours (December) when the sun reaches the maximum elevation of 54º and 89^o. The maximum value of monthly accumulated period of sunshine occurs in July (183 hours) and the minimum in September (149 hours). The maximum daily monthly-averaged cloudiness occurs in December (8.2 tenths) and the minimum in July (6.1 tenths).

2.2 Climate of Botucatu

Botucatu City (Figure 2) is located in the countryside of Brazil, at 786 m above the mean sea level, and approximately 240 km far from the Atlantic Ocean. It is characterized by mild cold and dry winter (June to August) and warm and wet summer (December to February). The averaged air temperature varies from a minimum of 16.5^{o}C in the winter to a maximum of 23.9^{o}C in the summer. The minimum precipitation (108.6 mm) occurs in August and maximum (309.6 mm) in February (Souza, 2002).

Table 1: Geographic characteristics of São Paulo and Botucatu

City	Distance from the Atlantic Ocean (km)	Latitude and longitude	Altitude (m)	Population
São Paulo	60 km	(23^{0}33'S, 46^{0}44'W)	742	*10,405,867
Botucatu	240 km	(22^{o}51'S, 48^{o}26'W)	786	108,112

(*18 million habitants in the metropolitan area)

3. Seasonal Variation of the Solar Radiation Components

All solar radiation quantities used in this section are expressed in units of megajoules per unit of area (MJ m^{-2}) and they correspond to the flux of energy in three intervals of one hour. The flux of energy associated to the global solar radiation, at the surface, is indicated by E_G^h, where subscript G refers to the global solar radiation and the superscript h refers to time interval of one hour. Equivalent symbols are used for the diffuse $\left(E_{DF}^h\right)$ and the direct $\left(E_{DR}^h\right)$ components of the global solar radiation at the surface. In this section the direct solar radiation, at the surface, was always estimated as the difference between the global and its diffuse components observed at the surface. The flux of energy received from the sun at the top of the atmosphere, per unit of area and per interval of time of 1 hour, $\left(E_T^h\right)$ is estimated analytically (Iqbal, 1983) considering the solar constant equal to 1356 W m^{-2}. In this section all the energy fluxes of solar radiation per unit of area, per interval of time of 1 hour will be referred as *hourly values*. The monthly-averaged hourly values are indicated by "$\langle\ \rangle$".

Due to the geographical proximity between IAG and UNESP sites, the diurnal hourly values of solar radiation at the top of the atmosphere are approximately the same in both places, with a maximum at noontime of 5.0 MJ m^{-2}, in January, and 3.3 MJ m^{-2}, in July (equivalent to ~1394 W m^{-2} and ~924 W m^{-2}). In Botucatu, the amplitude of the global solar radiation in January and July (respectively, 2.57±0.15 MJ m^{-2} and 2.25±0.07 MJ m^{-2}) is larger than in São Paulo (respectively, 2.47±0.07 MJ m^{-2} and 1.82±0.05 MJ m^{-2}). It is interesting to observe that during the winter month the global radiation in Botucatu is about 24 % larger than in São Paulo, while in the summer the difference is not as large as in the winter (Table 2).

Figure 2: Geographic position of São Paulo (star) and Botucatu (solid circle) cities.

Table 2: Amplitude of the diurnal evolution of monthly average hourly values of solar radiation components measured in São Paulo City from April 26, 1994 to March 31, 2001. The symbols E_T^h, E_G^h, E_{DF}^h and E_{DR}^h correspond to the flux of energy received from the sun per - unit of area and per interval of time of 1 hour – respectively, at the top of the atmosphere, at the surface as global, diffuse and direct solar radiations.

	São Paulo		**Botucatu**	
Parameter	January (MJ m^{-2})	July (MJ m^{-2})	January (MJ m^{-2})	July (MJ m^{-2})
$\langle E_T^h \rangle \pm e_T^h$	5.02	3.33	5.03	3.38
$\langle E_G^h \rangle \pm e_G^h$	2.47±0.07	1.82±0.05	2.57±0.15	2.25±0.07
$\langle E_{DF}^h \rangle \pm e_{DF}^h$	1.34±0.05	0.63±0.03	1.19±0.08	0.52±0.05
$\langle E_{DR}^h \rangle \pm e_{DR}^h$	1.13±0.08	1.19±0.07	1.39±0.17	1.73±0.11

This difference can be identified, visually, by following $\langle E_G^h \rangle$ in Figure 3. The most pronounced differences between the two cities are found for the diffuse $\langle E_{DF}^h \rangle$ and direct $\langle E_{DR}^h \rangle$ components of the solar radiation measured at the surface (Table 2 and Figure 3). In Botucatu the amplitude of the diurnal cycle of diffuse component of the solar radiation in January and July (respectively, 1.19±0.08 MJ m^{-2} and 0.52±0.05 MJ m^{-2}) is smaller than in São Paulo (respectively, 1.34±0.05 MJ m^{-2} and 0.63±0.03 MJ/m^2). On the other hand, the amplitude of the diurnal cycle of direct component in Botucatu in January and July (respectively, 1.39±0.17 MJ m^{-2} and 1.73±0.11 MJ/m^2) is considerable larger than in São Paulo (respectively, 1.13±0.08 MJ m^{-2} and 1.19±0.07 MJ/m^2). In the winter month arrives in Botucatu about 45 % more solar radiation, at the surface, as direct beam than in São Paulo. The amplitude of the diurnal cycle of the fractions $\langle E_G^h \rangle / \langle E_T^h \rangle$ (clearness index), $\langle E_{DF}^h \rangle / \langle E_T^h \rangle$, $\langle E_{DR}^h \rangle / \langle E_T^h \rangle$ and $\langle E_{DF}^h \rangle / \langle E_G^h \rangle$ (diffuse fraction) also indicates significant variations between Botucatu and São Paulo (Table 3) with large contrasts observed in the winter. During July, the clearness index reaches in Botucatu 66.6 % and in São Paulo only 54.7%. On the other hand, in July the diffuse fraction reaches in Botucatu only 23.1% while in São Paulo is 34.8%.

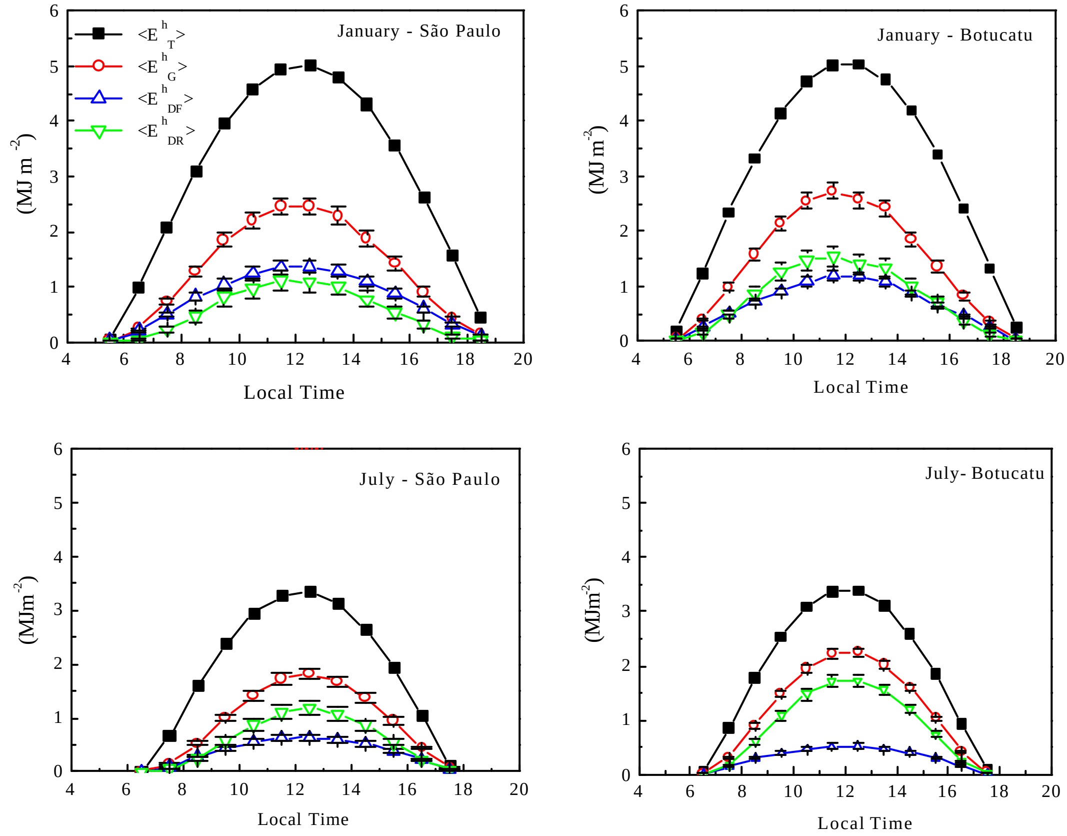

Figure 3: Diurnal evolution of monthly averaged hourly values of solar radiation reaching the top of the atmosphere, and the surface as global, diffuse and direct components, in Botucatu and São Paulo during January (*top*) and July (*bottom*). Observations carried out in São Paulo from April 26, 1994 to May 31, 2001, and in Botucatu, from January of 1996 to December of 2001.

Table 3: Amplitude of the diurnal cycle of the fractions $\langle E_G^h \rangle / \langle E_T^h \rangle$ (clearness index), $\langle E_{DF}^h \rangle / \langle E_T^h \rangle$, $\langle E_{DR}^h \rangle / \langle E_T^h \rangle$ and $\langle E_{DF}^h \rangle / \langle E_G^h \rangle$ (diffuse fraction) for São Paulo and Botucatu.

	São Paulo		**Botucatu**	
Parameter	January (%)	July (%)	January (%)	July (%)
$\langle E_G^h \rangle / \langle E_T^h \rangle$	49.2	54.7	51.1	66.6
$\langle E_{DF}^h \rangle / \langle E_T^h \rangle$	26.7	19.0	23.7	15.5
$\langle E_{DR}^h \rangle / \langle E_T^h \rangle$	22.5	35.7	27.4	51.1
$\langle E_{DF}^h \rangle / \langle E_G^h \rangle$	54.3	34.8	46.3	23.1

4. Seasonal Variation of the Long Wave Downward Atmospheric Emission in São Paulo

To describe the seasonal evolution of long wave radiation emitted downward by the atmosphere, the pyrgeometer used in São Paulo was calibrated against a reference radiometer. The calibration procedure took place in Botucatu, during the period August 17 to September 15, 2000. Figure 4 shows the dispersion diagram indicating the similar response between the pyrgeometer used in São Paulo and the reference one. The linear correlation coefficient (R) was of the order of 0.98315 indicating a good matching.

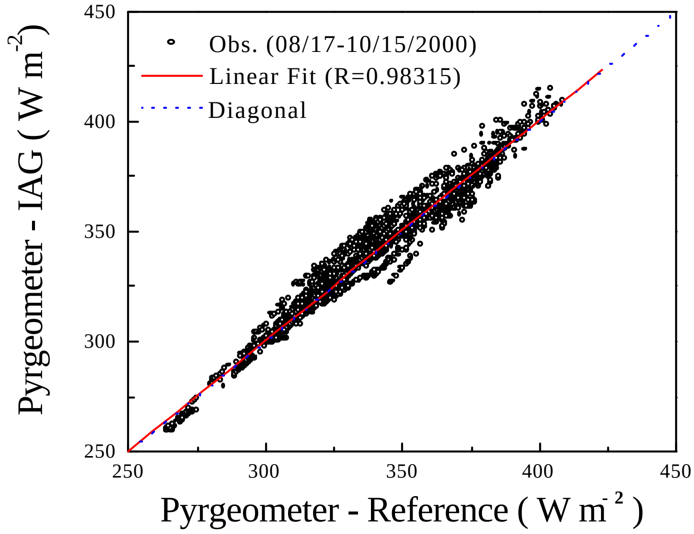

Figure 4: Dispersion diagram of atmospheric long wave downward radiation measurements carried out from August 17 to September 15 of 2000 in the IAG site. The observations correspond to 5 minutes averaged values. The linear fit was obtained by linear regression method. The parameter R is the linear regression coefficient.

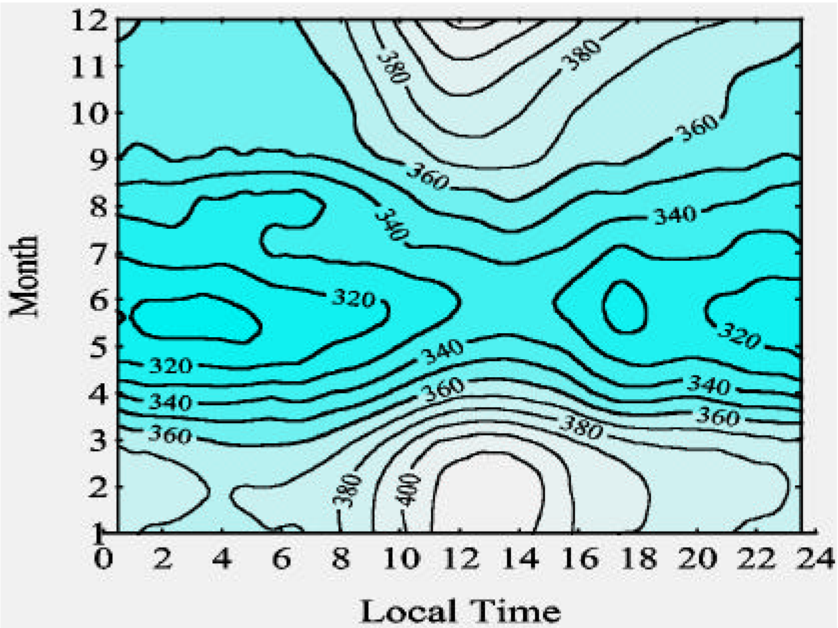

Figure 5: Seasonal evolution of hourly values of atmospheric long wave downward radiation measured in the IAG site. The hourly values are expressed in W m^{-2}, and they correspond to the monthly averaged values measured from September of 1997 to March of 2001.

Figure 6 shows the diurnal evolution of the monthly average values of long wave radiation emitted downward by the atmosphere, air temperature; relative humidity, vapor pressure, mixing ratio and atmospheric pressure. They correspond to observations carried out in IAG Site, from September 1997 to May 2000. Comparing the diurnal evolution of atmospheric long wave emission downward, in January, with all meteorological parameters measured at the surface (1.5 m above the surface in the top of the IAG-Building) becomes clear that the atmospheric downward emission is, primarily, controlled by air temperature (Fig. 6a-left). However, during the month of winter the long wave emission is not strongly correlated with air temperature at the surface (Fig. 6a-right). It is also interesting to note that the other parameters that indicated the content of moisture in the atmosphere (vapor pressure and mixing ratio) do not show a diurnal evolution as defined as air temperature

The monthly averaged hourly values of long wave radiation emitted downward by the atmosphere, measured from September of 1997 to March of 2001, are indicated in Figure 5. The hourly values, differently from what was done in section 3, were estimated in terms of W m^{-2}. The seasonal evolution of long wave radiation based on 4 years of data clearly reflects the seasonal evolution of the thermal structure of the atmosphere in the City of São Paulo. The maximum amplitude - about 420 W m^{-2} - occurs in the summer at noon time and, the minimum - of order of 300 W m^{-2} – occurs between May and June, around 2:00 and 3:00 LT (Figure 5).

5. Clear Sky Characteristics in São Paulo and Botucatu

During the period of observation in the IAG site was possible to identify days when the sky was not significantly covered by clouds (Oliveira, *et al.* 2002a). This corresponds to approximately 10 % of time in São Paulo. Table 4 shows the distribution of days with clear sky, per year, during the period considered in this work, at IAG and at IAG and UNESP sites simultaneously. About 74 out the total of 87 days prevail clear day conditions in both cities.

The diurnal evolution for a clear day (January 23, 2000) at IAG and UNESP sites is displayed in Figure 7. The smooth evolution during daytime is the criteria to consider a clear sky day. In this particular day the global solar irradiance was larger in Botucatu (Figure 7a). On the other hand the long wave downward emission from the atmosphere was larger in Sao Paulo (Figure 7b). The diffuse and beam components (Figure 7c and d) indicate that in Botucatu occur a increase of diffuse solar radiation in the second half of the day followed by an increase in the beam radiation. The temperature and vapor pressure diurnal evolutions are quite distinct and more difficult to compare (Figure 7d and e). It is interesting to observe that during the morning period the solar radiation components measured in the two places are comparable. After noontime, the increase in the beam irradiance UNESP site is followed by a sharp decrease in the water content measured by vapor pressure at the surface (Figure 7e).

Table 4: Number of days with clear sky conditions in the Cities São Paulo and Botucatu during 1996 and 2001.

Year	IAG site	IAG and UNESP sites
2001	8	6
2000	12	10
1999	26	22
1998	10	10
1997	16	14
1996	15	12
Total	87	74

6. Conclusion

The main goal of this work is to describe the temporal and spatial evolution of the components of radiation budget and comparing the observed solar and long wave downward atmospheric emission in the Cities of São Paulo and Botucatu. The comparison was carried out using global and diffuse solar radiations measured in São Paulo since 1994 (April 26, 1994 to May 31, 2001) and in Botucatu since 1996 (January 1, 1996 to December 31, 2001). It was also include measurements of long wave downward atmospheric emission, air temperature, humidity and pressure carried out in São Paulo since 1997 (September 10, 1997-May 31, 2001). This work included a study case of one day characterized by clear sky conditions in São Paulo and Botucatu in order to compare the diurnal evolution of solar radiation components (global, direct, beam and normal beam), long wave downward atmospheric emission, air temperature and vapor pressure.

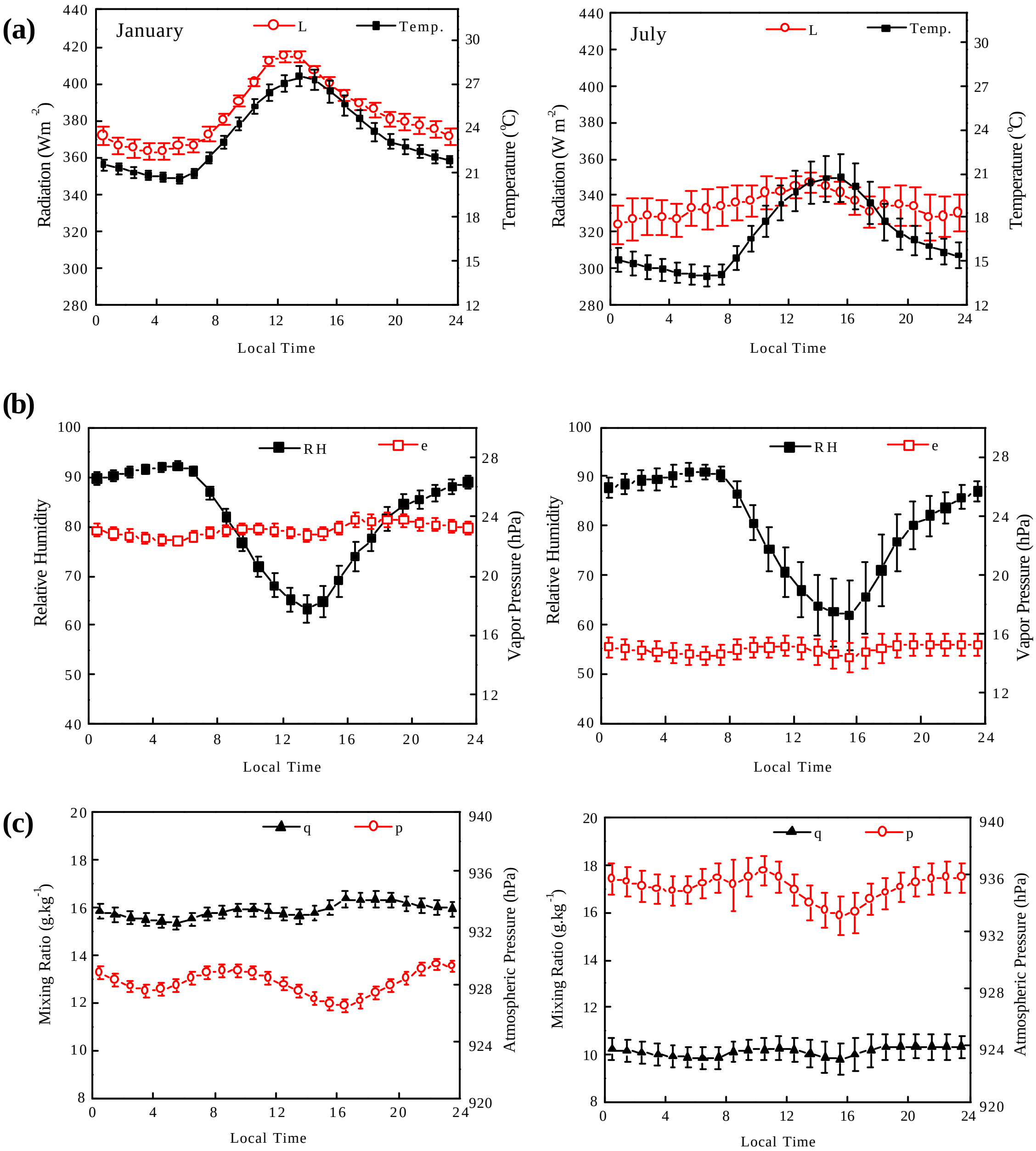

Figure 6. Diurnal evolution of monthly-averaged hourly values of (a) long wave radiation (L, in W m^{-2}) and air temperature (Temp, in °C); (b) relative humidity (RH, in %) and vapor pressure (e, in hPa) and (c) mixing ratio (q, in g Kg^{-1}) and atmospheric pressure (p, in hPa). On the left side January and on the right side July. Observations carried out in IAG site from September 1997 to May 2000. Vertical bars correspond to the interval of confidence of 95%.

The diurnal evolution of monthly averaged hourly values of solar radiation reaching the top of the atmosphere, and the surface as global, diffuse and direct components, in Botucatu and São Paulo, during January and July indicated significant differences. During the winter month of June the global radiation in Botucatu is about 24 % larger than in São Paulo while in the summer the difference is not as large as in the winter. In the winter month arrived in Botucatu about 45 % more solar radiation at the surface as direct beam.

The monthly averaged hourly values of long wave radiation emitted downward by the atmosphere indicated, based on 4 years of data, that the seasonal evolution of long wave radiation clearly reflects the seasonal evolution of the thermal structure of the atmosphere in the City of São Paulo. The maximum amplitude is, in the summer and at noon time, about 420 W m^{-2} and, the minimum is of order of 300 W m^{-2} around 2:00 and 3:00 LT in between May and June. Estimates of long wave atmospheric emission, in Botucatu, is undertaking at moment and will be used to compare with the São Paulo.

The distribution of days with clear sky, per year, during the period considered in this work (January 1, 1996 to December 31, 2001) indicated that in 74 days (out the total of 87 days with clear sky conditions in São Paulo) prevails clear sky condition in both cities.

The comparison between the diurnal evolution of radiation budget components available in the cities of São Paulo and Botucatu in one clear day (January 23, 2000) indicated good matching for the solar components and large discrepancy for long wave downward atmospheric emission at the surface. The diurnal evolution of temperature and moisture content (vapor pressure) indicated that for this particular clear day the moisture in Botucatu was systematically smaller than in São Paulo. The diurnal evolution of air temperature has shown inverse pattern.

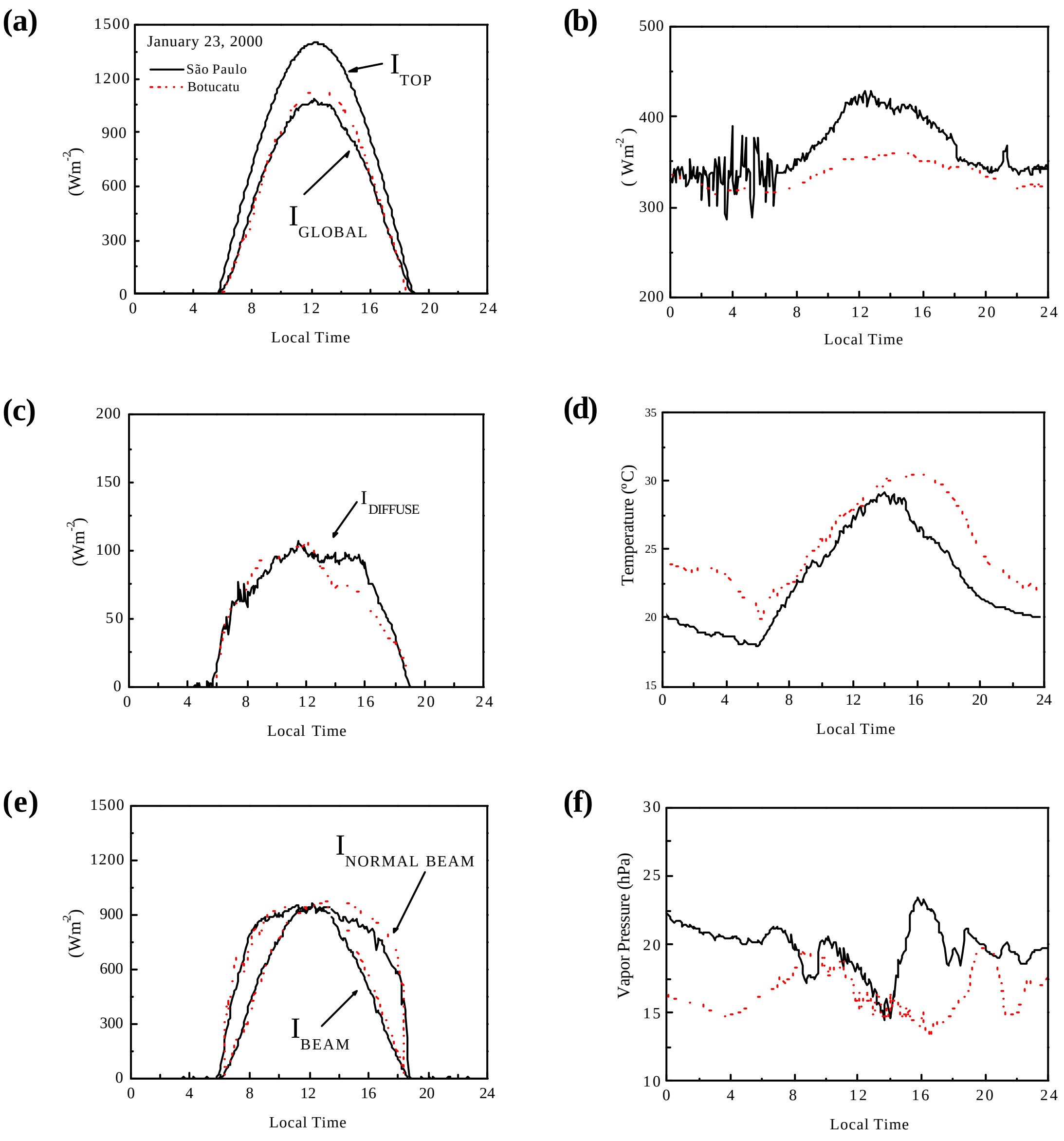

Figure 7: Diurnal evolution of (a) global solar irradiance at the surface (I_{GLOBAL}) and at the top of the atmosphere (I_{TOP}), (b) long wave downward emission from the atmosphere, (c) diffuse solar irradiance at the surface ($I_{DIFFUSE}$), (d) air temperature, (e) normal beam irradiance ($I_{NORMAL\ \ BEAM}$) and (f) beam irradiance at the surface (I_{BEAM}). IAG site in black solid line and UNESP site in red dashed line.

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