

COMPARATIVE STUDY OF SOLAR RADIATION IN URBAN AND RURAL AREAS

Georgia Codato¹, Amauri P. de Oliveira¹ and João F. Escobedo²

Abstract: Seasonal evolutions of daily and hourly values of global and diffuse solar radiations at surface are described in details for the cities of São Paulo and Botucatu. The description is based on measurements of global and diffuse solar radiation carried out during 6 years simultaneously in these two cities. Despite the similar latitude and altitude, the seasonal evolution of daily values indicated that São Paulo receives less global and more diffuse radiation at the surface than Botucatu. The seasonal variation of diurnal cycle confirmed these differences and indicated that they are related to the distance from the Atlantic Ocean, systematic penetration of the sea breeze and daytime intensification of the atmospheric pollution in São Paulo.

Key words: Global solar radiation; Diffuse solar radiation; São Paulo; Botucatu.

Resumo: A evolução sazonal dos valores diários e horários médios mensais da radiação solar global e difusa na superfície é descrita em detalhes para as cidades de São Paulo e Botucatu. Esta descrição está baseada nas medidas de radiação solar global e difusa realizadas durante o período de 6 anos de forma simultânea nestas duas cidades. Apesar das latitudes e altitudes destas duas cidades serem similares as variações sazonais dos valores diários de radiação indicam que São Paulo recebe menos radiação global e mais radiação difusa na superfície do que Botucatu. As variações sazonais do ciclo diurno destas grandezas confirmam estas diferenças, indicando que elas estão relacionadas à distancia ao oceano Atlântico, a penetração da brisa marítima e intensificação diurna da poluição em São Paulo.

Palavras-chave: Radiação solar global, Radiação solar difusa; São Paulo; Botucatu.

INTRODUCTION

The objective of this study is to compare the solar radiation components measured at the surface in an urban area, represented by the city of São Paulo, with a rural area, represented by city

¹ Department of Atmospheric Sciences, Institute of Astronomy, Geophysics and Atmospheric Sciences, University of São Paulo, Rua do Matão, 1226, São Paulo, 05508-900, SP, Brazil.

² Department of Environmental Sciences, State University of São Paulo, Lageado, Botucatu, 18603-970, SP, Brazil.

of Botucatu. These two cities are located at similar latitude and altitude (Table 1), however São Paulo has more than 10 million habitants and Botucatu less than 110 thousand. Another difference is that São Paulo is located about 60 km far from the Atlantic ocean, while Botucatu is 240 km.

City	Distance from Atlantic Ocean	Latitude and Longitude	Altitude (m)	Population
São Paulo	60 Km	(23°33'S,46°44'W)	742	*10,405,867
Botucatu	240 Km	(22°51'S,48°26'W)	786	108,112

Table 1: Geography position and population. (*)18 millions in the metropolitan area.

In these two sites measurements of global and diffuse solar radiation have been carried out continuously since 1994 using set of pyranometers that were regularly calibrated (Oliveira *et al.*, 2002a, Assunção *et al.*, 2004). The diffuse solar radiation was measured using a shadow-band device (Oliveira *et al.*, 2002b).

Previous studies have indicated that the diurnal evolution of diffuse, direct and global solar radiation components are correlated with air pollution events in the City of São Paulo (Oliveira *et al.*, 2002a). However, a direct comparison with a non-polluted area has not been done.

In this work the seasonal evolution of monthly average values of daily and hourly global and diffuse solar radiation at the surface are estimated based on observations carried out in São Paulo and Botucatu during 6 years, from 1996 to 2001.

Even tough, latitude and altitude similar makes the solar radiation at the top of the atmosphere and the length traveled in the atmosphere practically equal in these two cities, global and diffuse solar radiation in Botucatu are not expected to behavior like São Paulo, because of the distance from the Atlantic ocean, local circulations, land use and air pollution levels are quite different.

CLIMATE OF SÃO PAULO

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 km² and it is the largest urban area in South America and one of the 10 largest in the world. The MRSP, with more than 7 million of motor vehicles (CETESB, 2003), is

characterized as having moderate degree of contamination by 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.*, 2003). The diurnal evolution of the winds in the MRSP is systematically affected by sea breeze penetration and by the topography (Oliveira *et al.*, 2003; Karam *et al.*, 2003).

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 have 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.

The City of São Paulo (Fig. 1) 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°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°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 54° and 89° . 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).

CLIMATE OF BOTUCATU

Botucatu city (Fig. 1), with 110 thousand habitants 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 by warm and wet summer

(December to February). The averaged air temperature varies from a minimum of 16.5°C in the winter to a maximum of 23.9°C in the summer. The minimum precipitation (108.6 mm) occurs in August and maximum (309.6 mm) in February (Souza, 2002).



Figure 1: Geographic position of São Paulo (star) and Botucatu (solid circle) cities.

There is no information available about patterns of atmospheric circulation and pollution in Botucatu. However, taking into consideration observations carried out in the countryside of São Paulo State (Oliveira, 2003) there is high chance that the prevailing winds in Botucatu are from NE-E, associated mainly to seasonal variation of the South Atlantic Anticyclone. Due to the altitude it is also expected a high frequency of low level jets, mainly during nighttime, in Botucatu (Karam, 2002).

MESUREMENTS

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* (Fig. 2a). 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. These sensors are periodically calibrated, using as secondary standard another spectral precision pyranometer model 2 (Oliveira and Machado, 1999 and 2001).

In Botucatu, the equivalent measurements were taken in a rural area of Botucatu City (Fig. 2b). 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 (Tab. 1). The UNESP site corresponds to a rural area characterized by a homogeneous horizontally distributed green short grass surrounded by spots of deciduous forest at South (Fig. 2b). The radiometers used in Botucatu are similar to the ones used in Sao Paulo and they were also calibrated periodically using another radiometer as reference (Frisina, 1998, Galvani, 2001). Recently, the calibration procedure has been carried with an absolute radiometer.



Figure 2a: 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.

RESULTS

The flux of energy associated to the global solar radiation, at the surface, is indicated by E_G^h and E_G^d , where subscript G refers to the global solar radiation and the superscript h and d refers to time interval of one hour and one day respectively. Equivalent symbols are used for the diffuse E_{DF}^h (E_{DF}^d) and the direct E_{DR}^h (E_{DR}^d) components of the global solar radiation at the surface. These solar radiation quantities 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 or one day.



Figure 2b: The *UNESP site* in the State University of São Paulo, Botucatu, SP ($22^{\circ}51'S$). 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.

In this work 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, (E_T^h) is estimated analytically (Iqbal, 1983) considering the solar constant equal to 1366 W m^{-2} (Frölich and Lean, 1998). 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*.

Clear days

Following the diurnal evolution of global solar radiation in São Paulo and Botucatu is possible to identify days when the sky was not significantly covered by clouds (Oliveira *et al.*, 2002a). The diurnal evolutions of global and diffuse solar radiations for day 233 of year 1998 (August 21) are displayed in figure 3 for São Paulo and Botucatu as an example of typical clear day in both sites. The smooth evolution during daytime is the criteria used here to consider a clear sky day. In this particular day the global and diffuse solar irradiances were larger in Botucatu (Fig. 3). The incoming solar radiation at the top of the atmosphere is comparable in both sites.

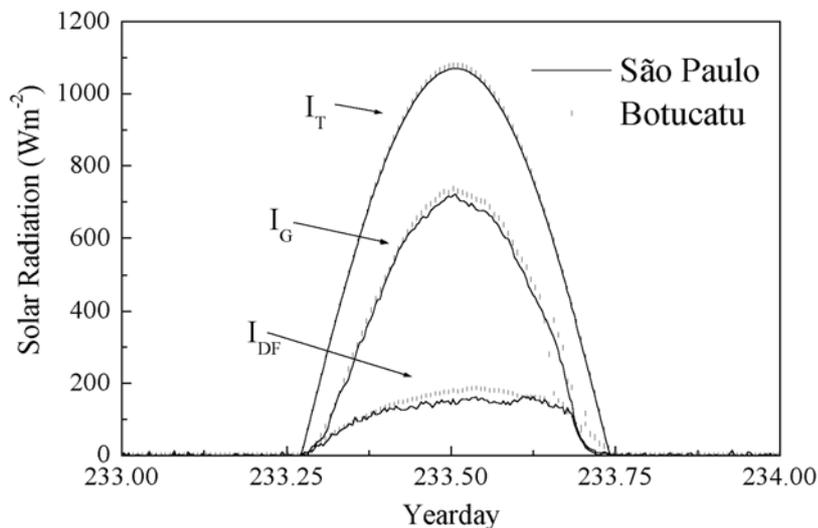


Figure 3: Diurnal evolution of global solar irradiance at the surface (I_G) and at the top of the atmosphere (I_T) and diffuse solar irradiance at the surface (I_{DF}). Continuous and dashed lines indicate observations from São Paulo and Botucatu, respectively.

The frequency distribution of clear sky days indicated in table 2 show that in Botucatu occurs larger number with clear sky days than in São Paulo. During 1996 and 2001 it was observed clear sky days in about 4.0 % of time in São Paulo and about 9.9% in Botucatu. About 2.9 % the total of 2192 days prevails clear day condition in both cities.

	1996	1997	1998	1999	2000	2001	Total
São Paulo	10	13	10	26	12	17	88
Botucatu	30	38	35	45	34	34	216
Simultaneous	6	11	9	18	8	11	63

Table 2: Number of days with clear sky conditions in the cities São Paulo and Botucatu during 1996 and 2001.

The monthly frequency distribution of clear days indicated in figure 4. It is interesting to observe that in both places a largest number of clear sky days occurred in August, the driest month of the year in both sites. This agreement indicates that both places are under influence of the similar climate. The number of days with clear skies is larger in Botucatu during all months of the year. In August it was found 51 days in Botucatu and 29 days in São Paulo and considering the entire period it was found 216 days in Botucatu and 88 days in São Paulo. The total number of days in São Paulo is 1690 while in Botucatu is 2050 days.

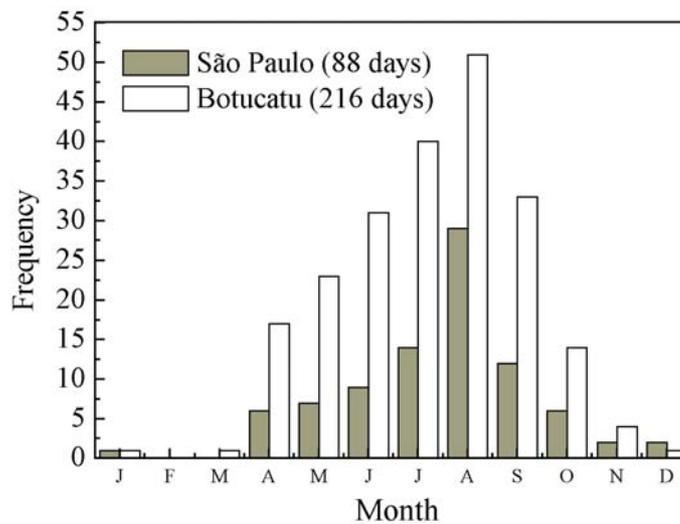


Figure 4: Seasonal evolution of clear sky day frequency in São Paulo and Botucatu during 1996-2001.

Seasonal variation of daily values

The seasonal evolution of monthly average daily values of global and diffuse solar radiation are indicated in the figures 5 and 6 considering all days and only clear days for São Paulo and Botucatu.

In general, considering all and clear sky days, Botucatu receives more global solar radiation at the surface than São Paulo (Figs. 5a and 5b). This pattern is less pronounced during clear sky days (Fig. 5b).

On the other hand, Botucatu receives less diffuse solar radiation at the surface than São Paulo either considering all or clear sky days (Figs. 6a and 6b).

Table 3 summarizes the differences between São Paulo and Botucatu for daily values of solar radiation at the surface for June and December.

Considering all days, São Paulo receives 16 % less global solar radiation in June and 4 % less in December than Botucatu. Besides, São Paulo receives 11 % more diffuse solar radiation at the surface in June and 5% more in December than Botucatu. With respect to the direct solar radiation, São Paulo receives 33 % less in June and 10 % less in December than Botucatu.

Considering only clear sky days, São Paulo receives 5 % less global, 16 % more diffuse and 7 % less direct solar radiation at the surface in June than Botucatu. December is not considered because there was only one day of clear sky in Botucatu and two days in São Paulo.

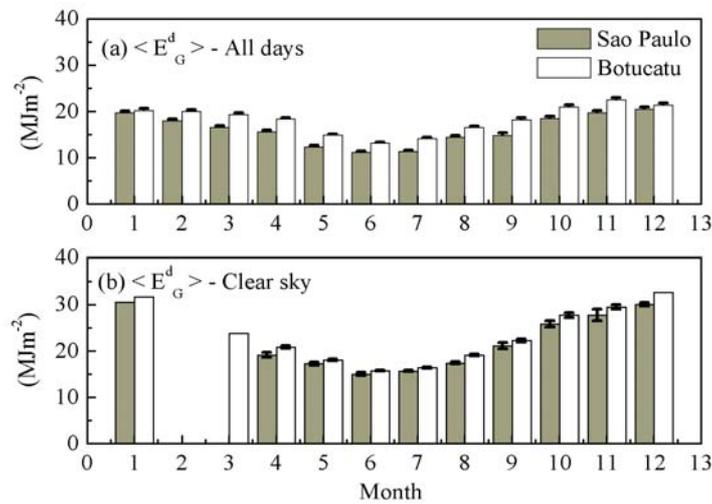


Figure 5: Seasonal evolution of daily values of global solar radiation at the surface in São Paulo and Botucatu considering all days (a) and only days with clear sky conditions (b).

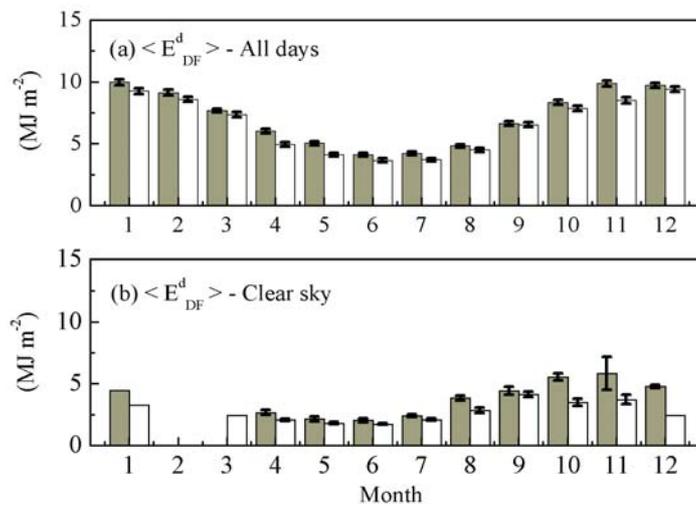


Figure 6: Same as Fig.5 for daily values of diffuse solar radiation at the surface.

The larger frequency of clouds in São Paulo is the main cause for the differences with respect to Botucatu when all days are considered. The higher levels of pollution and moisture content are the major factors causing smaller values of global solar radiation and larger values of diffuse solar radiation in São Paulo during clear sky days. The urban-rural surface albedo contrast may also contribute to the observed pattern of the components of the solar radiation in all conditions.

Solar radiation (MJ m ⁻²)	São Paulo			
	Clear sky		All days	
	June	December	June	December
Top	22.24 ± 0.11	42.39 ± 0.02	22.14 ± 0.02	42.48 ± 0.01
Global	15.05 ± 0.30	30.10 ± 0.40	11.13 ± 0.30	20.51 ± 0.47
Diffuse	2.06 ± 0.18	4.79 ± 0.11	4.11 ± 0.15	9.72 ± 0.20
Direct	13.00 ± 0.41	25.31 ± 0.28	7.03 ± 0.37	10.79 ± 0.60
Number of days	9	2	146	155
Solar radiation (MJ m ⁻²)	Botucatu			
	Clear sky		All days	
	June	December	June	December
Top	22.23 ± 0.05	42.36	22.18 ± 0.02	42.47 ± 0.01
Global	15.80 ± 0.11	32.67	13.16 ± 0.26	21.35 ± 0.49
Diffuse	1.75 ± 0.06	2.47	3.66 ± 0.15	9.42 ± 0.22
Direct	14.04 ± 0.15	30.20	9.50 ± 0.38	11.93 ± 0.62
Number of days	31	1	158	164

Table 3: Monthly average daily values of solar radiation measured at the surface.

Seasonal variation of diurnal evolution

Considering all days, the diurnal evolution of $\langle E_G^h \rangle$ indicates that Botucatu receives more global radiation than São Paulo during all hours of the daytime in June (Fig. 6) and December (Fig. 7). This effect is less pronounced in summer months and intensifies after noontime. On the other hand, the diurnal evolution of $\langle E_{DF}^h \rangle$ indicates that there is more scattering of solar radiation in São Paulo than in Botucatu in June (Fig. 8). In December this patterns reverts, and less diffuse solar radiation reaches the surface in São Paulo (Fig. 9).

Considering only clear sky days, the difference between Botucatu and São Paulo decreases in intensity both in June (Figs. 10 and 12). The small number of days in December precludes any conclusive analysis (Fig. 11 and 13).

These differences seem to be related to the systematic penetration of the sea breeze in São Paulo (Oliveira et al., 2003) and to the intensification of the atmospheric contamination due to the urban emissions.

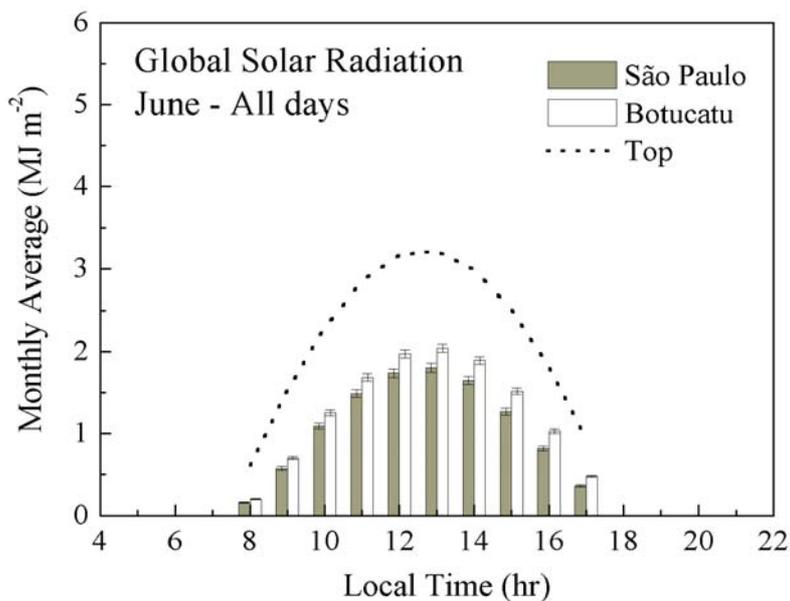


Figure 6: Diurnal evolution of monthly average values of solar radiation at the top of the atmosphere and global solar radiation at the surface in São Paulo and Botucatu, considering all days in June, between 1996 and 2001.

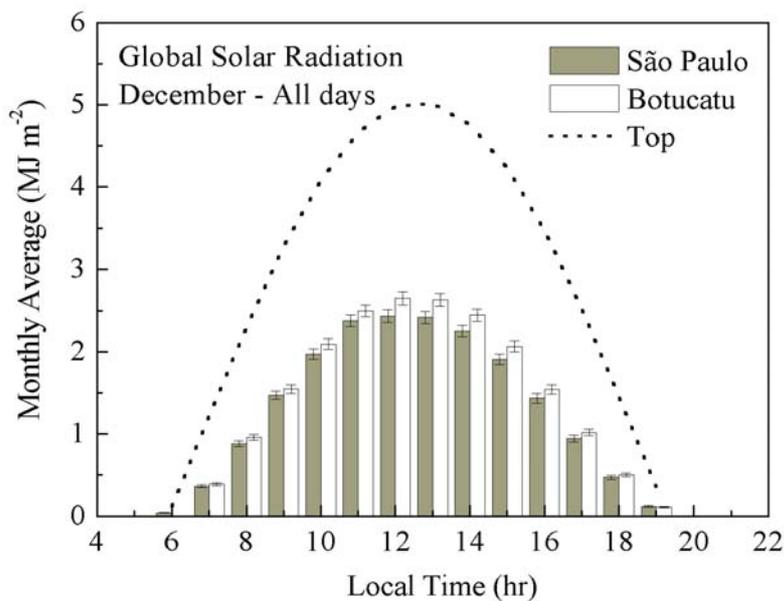


Figure 7: Same as Fig. 6 for December.

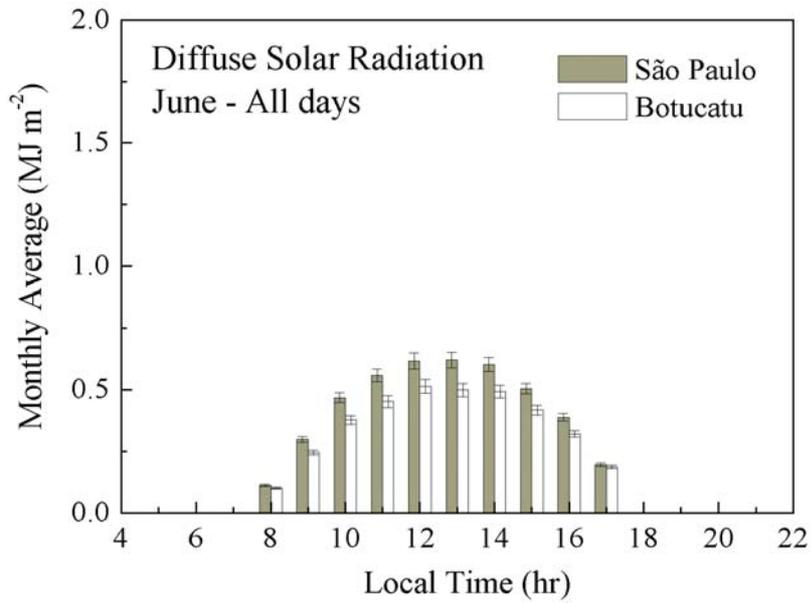


Figure 8: Diurnal evolution of monthly average values of diffuse solar radiation at the surface in São Paulo and Botucatu, considering all days in June between 1996 and 2001.

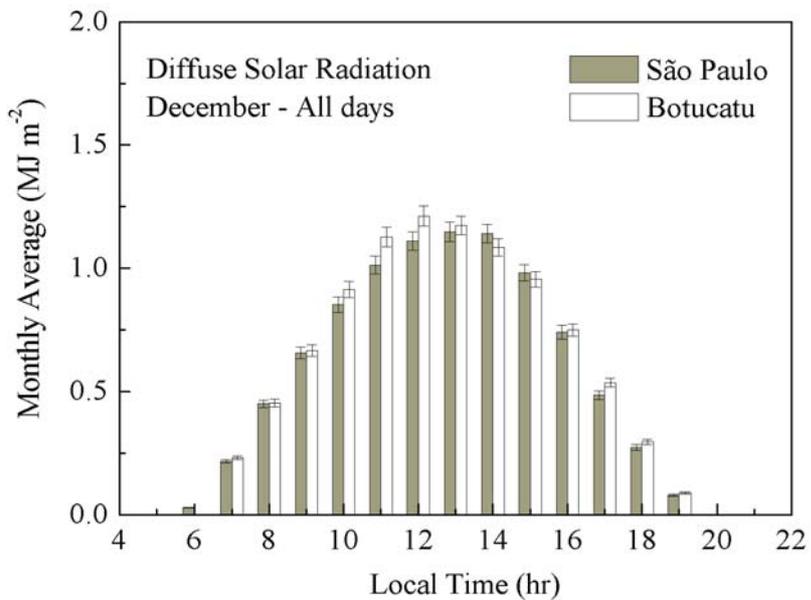


Figure 9: Same as Fig. 8 for December.

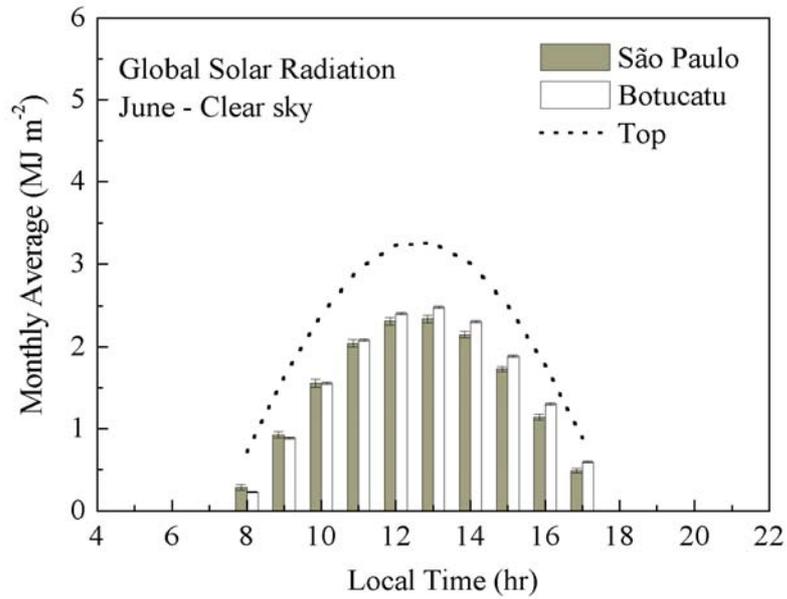


Figure 10: Diurnal evolution of monthly average values of solar radiation at the top of the atmosphere and global solar radiation at the surface in São Paulo and Botucatu, considering days with clear sky condition in June of 1996-2001.

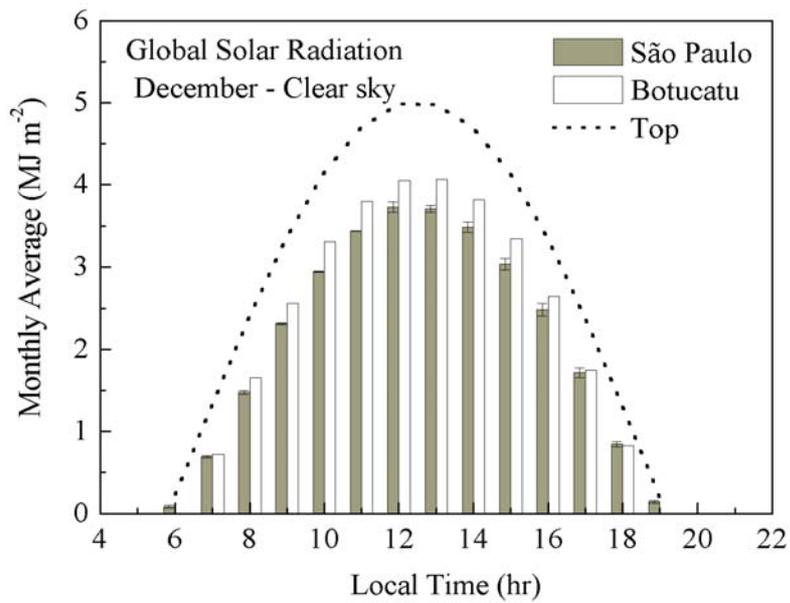


Figure 11: Same as Fig. 10 for December.

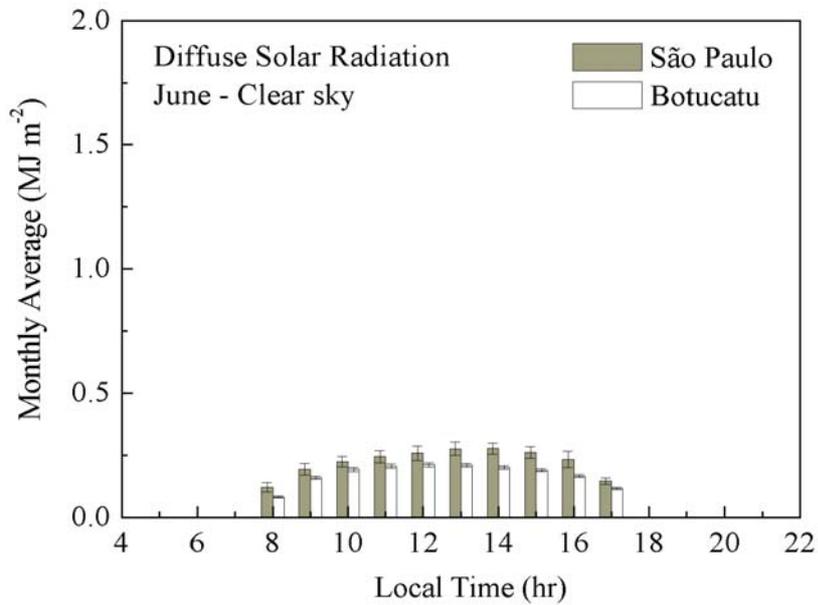


Figure 12: Diurnal evolution of monthly average values of diffuse solar radiation at the surface in São Paulo and Botucatu, considering days with clear sky condition in June 1996-2001.

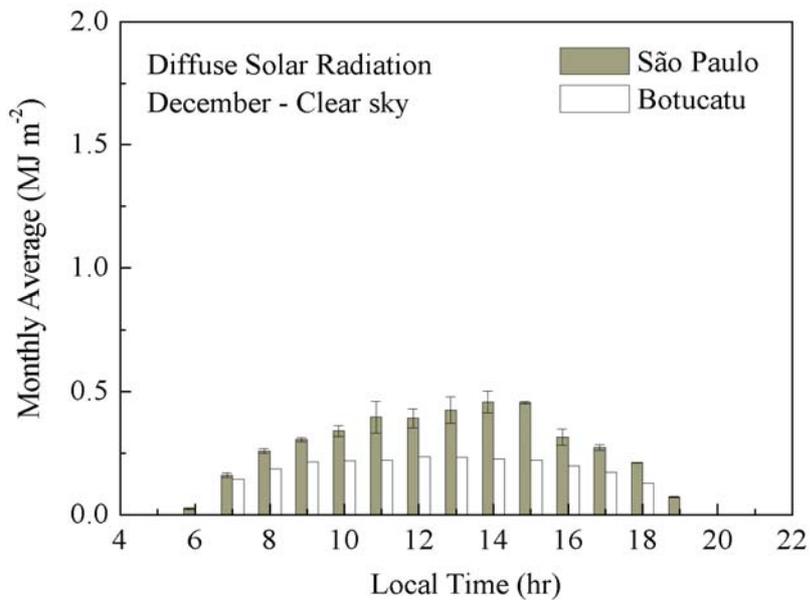


Figure 13: Same as Fig. 12 for December.

CONCLUSION

In this work the seasonal evolution of monthly average values of daily and hourly global and diffuse solar radiation at the surface are estimated based on observations carried out in São Paulo and Botucatu during 6 years, from 1996 to 2001.

The frequency distributions of clear days indicated that in Botucatu occurred a larger number with clear sky days than in São Paulo. During 1996 and 2001 it was observed clear sky days in about 4.0 % of time in São Paulo and about 9.9% in Botucatu. About 2.9 % the total of 2192 days prevails clear day condition in both cities.

The seasonal evolution of daily values indicated that São Paulo receives less global and more diffuse radiation at the surface than Botucatu during entire year and considering all and clear sky days. The seasonal variation of diurnal cycle confirmed these differences. This behavior seems to be related to the distance from the Atlantic ocean, the systematic penetration of the sea breeze in São Paulo (Oliveira *et al.*, 2003) and to the intensification of the atmospheric pollution.

Acknowledgments. The authors acknowledge the financial support provided by CNPq and Fapesp.

REFERÊNCIAS

- Assunção, F.H., Escobedo, J.F. and Oliveira, A.P., 2003: Modelling frequency distributions of 5 minute-averaged solar radiation indexes using Beta probability functions. *Theoretical and Applied Climatology*, **75**, 213-224.
- CETESB - *Relatório de Qualidade do Ar no Estado de São Paulo - 2003*, Secretaria do Meio Ambiente, Série Relatórios - ISSN 0103-4103, São Paulo, 2002 (<http://www.cetesb.sp.gov.br>).
- Escobedo, J.F., Frisina, V.A., Saglietti, J.R. e Oliveira, A.P., 1997: Radiômetros Solares Com Termopilhas de Filmes Finos I - Descrição e Custos. *Revista Brasileira de Aplicações de Vácuo*, 16 (1), 10-15.
- Escobedo, J.F., Frisina, V.A., Saglietti, J.R. e Oliveira, A.P., 1997: Radiômetros Solares Com Termopilhas de Filmes Finos: II - Performance. *Revista Brasileira de Aplicações de Vácuo*, 16 (1), 16-21.
- Frisina, V. A., 1998: Otimização de um albedometro e aplicação no balanço de radiação e energia da cultura de alface (*Lactuca sativa L.*) no exterior e interior de estufa de polietileno.. Dissertação de Mestrado, Faculdade de Ciências Agrônômicas, Universidade Estadual Paulista, Botucatu, 86p.
- Frölich, C. and Lean, J., 1998: The sun's total irradiance: Cycles and trends in the past two decades and associated climate change uncertainties. *Geophys. Res. Lett.* **25**, 4377-4380.

- Galvani, E. 2001: Avaliação agrometeorológico do cultivo de pepino (*Cucumis sativas L.*) em ambientes protegido e a campo, em ciclos de outono-inverno e primavera-verão. Tese de Doutorado, Faculdade de Ciências Agrônômicas, Universidade Estadual Paulista, Botucatu, 124pp.
- Iqbal, M., 1983: *An introduction to solar radiation*, New York, Academic Press, 390 p.
- Karam, H., Oliveira, A.P., and Soares, J., 2003: Application of Mass Conservation Method to Investigate the Wind Patterns over an Area of Complex Topography, *Revista Brasileira de Ciências Mecânicas*, **25**, 107-113.
- Karam, H. A., 2002: Estudo Numérico dos Jatos de Baixos Níveis e suas Implicações na Dispersão de Poluentes no Estado de São Paulo, Tese de Doutorado, Departamento de Ciências Atmosféricas, IAG-USP. 196 pp.
- Kretzschmar, J. G. (1994) Particulate matter levels and trends in Mexico City, São Paulo, Buenos Aires and Rio de Janeiro. *Atmos. Environ*, **28**, 3181-3191.
- Oliveira, A.P., 2003: Investigação da Camada Limite Planetária na Região de Iperó. *Tese de Livre docência*. Departamento de Ciências Atmosféricas, IAG-USP, 220 pp225.
- Oliveira, A.P., R.D. Bornstein and J. Soares, 2003: Annual and diurnal wind patterns in the city os São Paulo. *Water, Air & Soil Pollution: FOCUS (WAFO)*. **3**, 3-15.
- Oliveira, A.P., Escobedo, J.F., Machado, A.J. and Soares, J., 2002a: Diurnal evolution of solar radiation at the surface in the City of São Paulo: seasonal variation and modeling. *Theoretical and Applied Climatology*, **71(3-4)**, 231-249;
- Oliveira, A.P, Soares, J., Escobedo, J.F., Machado, A.J., Codato, G. and Galvani, E. 2002b, Diurnal evolution of surface radiation budget components in the cities of São Paulo and Botucatu. *Proceeding of the ENCIT 2002*, Caxambú, MG, Brazil (CD-ROM).
- Oliveira, A. P., Escobedo, J. F., Machado, A. J., 2002c: A New Shadow-Ring Device for Measuring Diffuse Solar Radiation at Surface. *Journal of Atmospheric and Oceanic Technology* (in press).
- Oliveira, A.P. and Machado, A.J, 2001: Projeto Estudo Observacional da Radiação Solar na Cidade de São Paulo, *Relatório Técnico*, Departamento de Ciências Atmosféricas, IAG/USP, 113 pp.
- Oliveira, A.P. and Machado, A.J, 1999: Projeto Estudo Observacional da Radiação Solar na Cidade de São Paulo, *Relatório Técnico*, Departamento de Ciências Atmosféricas, IAG/USP, 120 pp.
- Oliveira, A.P., Escobedo, J.F., Plana-Fattori, A., Soares, J. e Santos, P.M., 1996: Medidas de Radiação Solar na Cidade de São Paulo: Calibração de Piranômetros e Aplicações Meteorológicas, *Revista Brasileira de Geofísica*, **14(2)**, 203-216.
- Souza, J.W., 2002: Efeito da Cobertura de Polietileno Difusor de Luz Em Ambiente Protegido Cultivado com Pimentão (*Capsicum annum L.*), *Tese de Doutorado*, Faculdade de Ciências Agrônômicas, Unesp, Botucatu, 113 pp.