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Theoretical and Applied Climatology

[1] Group of Micrometeorology, Department of Atmospheric Sciences, Institute of Astronomy, Geophysics and Atmospheric Sciences, University of São Paulo, SP, Brazil
[2] Department of Natural Resources, School of Agronomic Sciences, State University of São Paulo, SP, Brazil

Global and diffuse solar irradiances in urban and rural areas in southeast Brazil

G. Codato[1], A. P. Oliveira[1], J. Soares[1], J. F. Escobedo[2], E. N. Gomes[2], A. D. Pai[2]

With 10 Figures

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Summary

The seasonal evolution of daily and hourly values of global and diffuse solar radiation at the surface are compared for the cities of São Paulo and Botucatu, both located in Southeast Brazil and representative of urban and rural areas, respectively. The comparisons are based on measurements of global and diffuse solar irradiance carried out at the surface during a six year simultaneous period in these two cities. Despite the similar latitude and altitude, the seasonal evolution of daily values indicate that São Paulo receives, during clear sky days, 7.8% less global irradiance in August and 5.1% less in June than Botucatu. On the other hand, São Paulo receives, during clear sky days, 3.6% more diffuse irradiance in August and 15.6% more in June than Botucatu. The seasonal variation of the diurnal cycle confirms these differences and indicates that they are more pronounced during the afternoon. The regional differences are related to the distance from the Atlantic Ocean, systematic penetration of the sea breeze and daytime evolution of the particulate matter in São Paulo. An important mechanism controlling the spatial distribution of solar radiation, on a regional scale, is the sea breeze penetration in São Paulo, bringing moisture and maritime aerosol that in turn further increases the solar radiation scattering due to pollution and further reduces the intensity of the direct component of solar radiation at the surface. Surprisingly, under clear sky conditions the atmospheric attenuation of solar radiation in Botucatu during winter – the biomass burning period due to the sugar cane harvest – is equivalent to that at São Paulo City, indicating that the contamination during sugar cane harvest in Southeast Brazil has a large impact in the solar radiation field at the surface.

1. Introduction

Anthropogenic aerosol sources are fossil fuel and biomass burning. Most aerosols are located at the troposphere and have a short lifetime (days to weeks) compared to greenhouse gases (decades to centuries). Tropospheric aerosols can produce a direct negative radiative effect by reflecting solar irradiance, a direct positive effect by absorbing solar irradiance, and an indirect negative effect by increasing the amount of cloud and varying their properties. The global radiative impact aerosols is of the order of $-1\,\mathrm{W\,m^{-2}}$ (IPCC 2001).

The objective of this study is to compare global and diffuse solar irradiance measured at the surface in an urban area, represented by the city of São Paulo, with a rural area, represented by the city of Botucatu. Both cities are located in the State of São Paulo, southeastern Brazil (Fig. 1a).

Correspondence: Amauri Pereira de Oliveira, Departamento de Ciencias Atmosfericas – IAG/USP, Rua do Matao 1226, 05508-900 Sao Paulo, SP, Brazil, e-mail: apdolive@usp.br

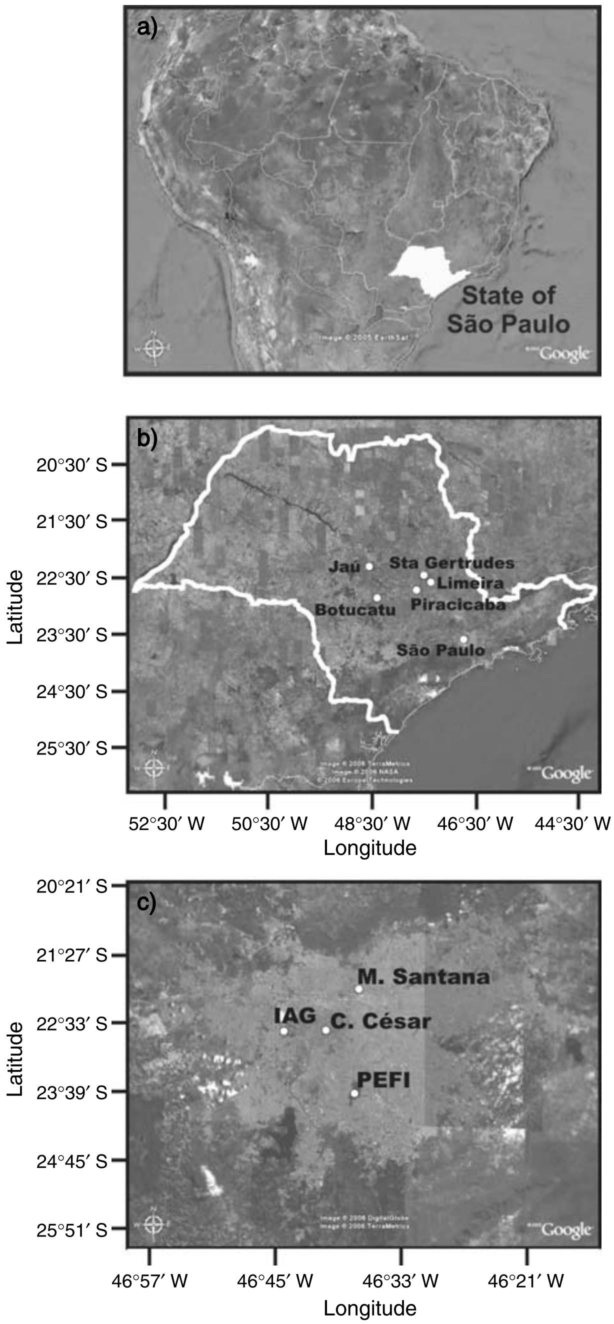

Fig. 1. Geographic position of the (**a**) State of São Paulo; (**b**) cities where solar irradiance and particulate matter are measured in the State of São Paulo and (**c**) stations where solar irradiance, meteorological parameters and particulate matter are measured in the Metropolitan Region of São Paulo

Special attention will be given to the impact caused by particulate matter on the solar radiation fields of these two cities.

The city of São Paulo, with about 11 millions inhabitants, together with 39 other smaller cities, forms the Metropolitan Region of São Paulo (MRSP). This region is occupied by 20.5 million inhabitants and has more than six million vehicles (IBGE 2006a). In contrast, Botucatu is a small countryside city, with less than 120,000 inhabitants, characterised by agricultural activity and is therefore expected to have a smaller anthropogenic impact on the local atmosphere than the MRSP. Another difference is that São Paulo is located about 60 km far from the Atlantic Ocean, while Botucatu is located 221 km from the ocean (Fig. 1b). The MRSP has an area of 8051 km^2, is the largest urban area in South America and one of the 10 largest in the world (Fig. 1c). Previous studies have indicated that the diurnal evolution of diffuse, direct and global solar irradiance components is correlated with air pollution events in the city of São Paulo, mainly particulate matter (Oliveira et al. 1996, 2002a, b). However, a direct comparison with a rural area has not yet been performed. In order to unravel the role played by air pollution on the solar radiation field it is crucial to develop more precise models for diffuse solar radiation estimates (Soares et al. 2004), to understand the atmospheric downward emission of longwave radiation (Oliveira et al. 2006) in the São Paulo city area, and to improve satellite estimates of solar radiation (Ceballos et al. 2004).

In this work, the seasonal evolution of monthly averaged 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 a six year period, from 1996 to 2001. Both cities have similar latitude and altitude implying that the solar irradiance at the top of the atmosphere and the trajectory in the atmosphere will be similar. However, global and diffuse solar radiation in Botucatu are not expected to have the same characteristics as at São Paulo because of the differences in the distance from the Atlantic Ocean, local circulation, land use, and air pollution levels. The similarities and differences between the two cities will be explored in this paper with a focus on the impact caused by particulate matter on the solar radiation fields. The measurements used in this work are presented in Sect. 2. The climates of São Paulo and Botucatu are described in Sects. 3 and 4. The results concerning the clear sky days, seasonal distribution of daily and hourly values of global and diffuse solar radiation and the effect of aerosol and sea breeze penetration are discussed in Sect. 5. The major conclusions are summarised in Sect. 6.

2. Measurements

2.1 Solar irradiance

In São Paulo, solar irradiance measurements were taken on a platform located at the top of the IAG building (*Institute of Astronomy, Geophysics and Atmospheric Sciences*) at the University of São Paulo Campus, west side of the city of São Paulo (Fig. 2a and Table 1). At the IAG site, global solar irradiance and its diffuse component were measured, by model 8–48 and PSP pyranometers, respectively. Both were manufactured by Eppley Lab Inc. These sensors are periodically calibrated, using as secondary standard PSP pyranometer (Oliveira et al. 2002a). In Botucatu, equivalent measurements were taken by the Solar Radiation Laboratory at the Department of Natural Resources, State University of São Paulo Campus (Fig. 2b).

The Botucatu measurement site corresponds to a rural area characterised by homogeneous horizontally distributed short green grass surrounded by stands of deciduous forest in the south (Fig. 2b). The pyranometers used in Botucatu (Fig. 2b and Table 1) are similar to the ones used in São Paulo (Assunção et al. 2003). They were also periodically calibrated using another radiometer as reference. Recently, the calibration procedure in both sites has been carried with an absolute radiometer. Diffuse solar irradiance was also measured using a shadow-band device similar to the device used in São Paulo (Oliveira et al. 2002c). At both sites, solar irradiance was measured between 1996 and 2001 with a sample frequency of 0.2 Hz and storage (average) every 5 minutes.

The total number of days with solar irradiance observations is 1826 and 2065 in São Paulo and Botucatu, respectively. Considering the period of six years (2192 days), measurements of solar radiation were taken for more than 83% of days in São Paulo and more than 94% in Botucatu. This indicates that the results shown here should be representative of the solar radiation mean conditions at São Paulo and Botucatu.

2.2 Other meteorological parameters

Air temperature and relative humidity were measured at the IAG site between 1996 and 2001 (Table 1 and Fig. 1c). The climatological station of M. Santana (23°30′S, 46°37′W), located at 792 m above mean sea level (amsl) in the northern portion of São Paulo City is shown in Fig. 1c. This station is approximately 10 km from the IAG site (Fig. 1c). These data were used to evaluate monthly averaged air temperature, relative humidity and precipitation used to characterise the climate in São Paulo described in the section below.

Diurnal evolutions of air temperature and relative humidity observed on August 24, 1999, were measured at the meteorological station located in the southeast side of São Paulo City at 780 m amsl, identified in Fig. 1c as PEFI (23°39′S, 46°37′W). Diurnal evolutions of wind speed and direction, observed on August 24, 1999, were also measured at PEFI and in Botucatu (Table 1). Air temperature, relative humidity and precipitation were also measured at the radiometric station of Botucatu from 1971 to 2004 (Table 1). These data were used to evaluate monthly averaged air temperature, relative humid-

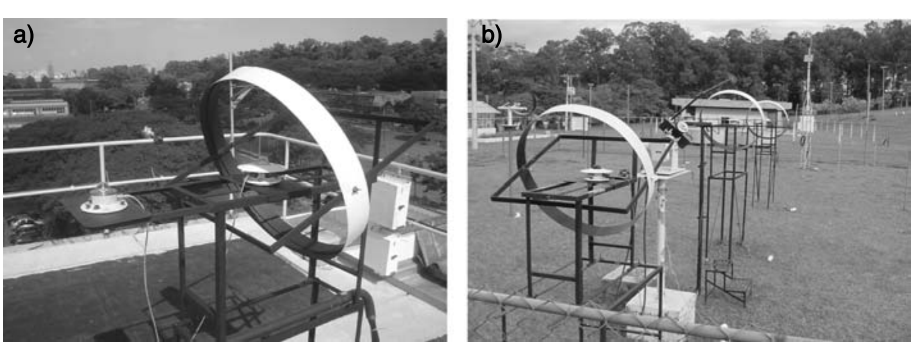

Fig. 2. The shadow-band devices, with 40 cm of diameter, used to measure diffuse solar irradiance at (**a**) IAG site in São Paulo and (**b**) Botucatu

Table 1. Sensors and observation period of the data used in this work

Variable	Sensor	Period
IAG		
Global solar irradiance	Pyranometer – Eppley model 8–48	1996–2001
Diffuse solar irradiance	Pyranometer – Eppley model PSP and shadow-band	1996–2001
Air temperature	Vaisala	1996–2001
Relative humidity	Vaisala	1996–2001
PEFI		
Wind velocity	Anomegrapher – Fuess	August 24, 1999
Wind direction	Anomegrapher – Fuess	August 24, 1999
Air temperature	Termographer – Fuess	August 24, 1999
Relative humidity	Hygrographer – Fuess	August 24, 1999
M. Santana		
Air temperature	Not available	1961–1990
Relative humidity	Not available	1961–1990
Precipitation	Not available	1961–1990
Botucatu		
Global solar irradiance	Pyranometer – Eppley model PSP	1996–2001
Diffuse solar irradiance	Pyranometer – Eppley model PSP and shadow-band	1996–2001
Air temperature	Vaisala	1997–2001
Relative humidity	Vaisala	1997–2001
Air temperature	Thermographer – Filotecnica Milano	1971–2004
Relative humidity	Hygrographer – Filotecnica Milano	1971–2004
Precipitation	Recording Rain Gauge – Ota Keiki Seisakusho Co Ltda	1971–2004
Wind velocity	Cup anemometer model DINES Instrumental Hidráulico SA	August 24, 1999
Wind direction	Instrumental Hidráulico SA, Model DINES	August 24, 1999

Station	Sensor	Period
Metropolitan region of São Paulo – Particulate matter (PM_{10})		
C.H César	Automated network station – Beta Attenuator Method	1996–2000
Cities around Botucatu – Particulate matter (PM_{10})		
Piracicaba	Not-automated network station Gravimetric Methods with exchangeable filters	Annual averaged 2001 – 2004
Limeira	Not-automated network station Gravimetric Methods with exchangeable filters	Annual averaged 2003 – 2004
Jaú	Automated network station – Beta Attenuator Method	Monthly averaged 2004
Sta Gertrudes	Not-automated network station Gravimetric Methods with exchangeable filters	Annual averaged 2001 – 2004

ity and precipitation used to characterise the climate in Botucatu described in the section below.

2.3 Particulate matter

Particulate matter (PM_{10}) at the surface was measured by the São Paulo State Environmental Agency (CETESB), using the Beta Attenuator Method at surface stations located in the MRSP every hour (CETESB 2004). The surface station used here is C. César, the nearest station to the IAG site (Fig. 1c). The data used to evaluate the monthly averaged PM_{10}, corresponds to five years of continuous observation from 1996 to 2000 (Table 1).

Unfortunately, no information about particulate matter is available for Botucatu. Therefore, all cities near Botucatu with particulate matter measurements were investigated. These date tend to be representative of small city areas (Fig. 1b). Annual averaged values of particulate matter were available in Limeira, Piracicaba and Sta Gertrudes. In Jaú, data were available as monthly averaged values. These surface stations are also

Table 2. Information about São Paulo, Botucatu and the cities around Botucatu

City	Distance from Atlantic Ocean	Latitude and longitude	Altitude amsl (m)	Population	Sugar cane yield** (tons)	Sugar cane area** (%)	Industrial activity on GNP** (%)	Particulate matter average ($\mu g\, m^{-3}$)
São Paulo	67 km	(23°33′ S, 46°44′ W)	742	10,405,867*	Near 0	Near 0	35	65.1
Botucatu	221 km	(22°51′ S, 48°26′ W)	786	108,112	420,000	4	36	Not available
City	**Distance from Botucatu**	**Latitude and longitude**	**Altitude amsl (m)**	**Population**	**Sugar cane yield** (tons)**	**Sugar cane area ** (%)**	**Industrial activity on GNP ** (%)**	**Particulate matter average ($\mu g\, m^{-3}$)**
Piracicaba	81 km	(22°41′ S, 47°39′ W)	554	355,039	3,120,000	29	46	54
Limeira	111 km	(22°33′ S, 47°23′ W)	567	270,223	1,050,000	26	47	66
Jaú	63 km	(22°17′ S, 48°33′ W)	522	121,333	3,070,000	54	26	33
Sta Gertrudes	102 km	(22°27′ S, 47°31′ W)	595	18,687	400,000	53	35	65

* 18 millions in the Metropolitan Region of São Paulo. ** Averaged over 2001 and 2002

operated by CETESB and the annual averaged concentration of particulate matter is indicated in Table 2 (CETESB 2004). The observation periods are indicated in Table 1.

In this area of about 2.5 million inhabitants, the gross national product (GNP) is around US$ 10 billion and about 36% is due to industrial activities (IBGE 2006a). As displayed in Table 2, there is a clear correlation between the level of particulate matter (averaged over 2001 and 2002) and the fraction of industrial participation on the local GNP. For example, the industrial activity in Jaú (26%) is below the regional average of 36% (70 cities within 100 km radius), and the particulate matter concentration in Jaú is also the smallest (33 $\mu g\, m^{-3}$). In cities where the industrial activity was equal to or greater than 36% of the local GNP (Piracicaba, Limeira, and Sta Gertrudes), the concentration of particulate matter was much higher (54 $\mu g\, m^{-3}$, 66 $\mu g\, m^{-3}$, 65 $\mu g\, m^{-3}$, respectively).

A major difficulty in the investigation of the impact of air pollution on climate, particularly in third world countries, is the lack of observations with the required spatial and temporal resolution. To represent Botucatu, the particulate matter observed in Jaú will be considered (Fig. 1b) because it is the only city, among the four investigated, with available monthly averaged particulate matter data and it is the nearest city to Botucatu (Table 2). It is important to emphasise that the particulate matter data used here as surrogate for the Botucatu data were not collected during the same period as the solar radiation data. Therefore, a definitive link between the behavior of solar radiation at the surface and the particulate matter in Botucatu is not possible. Hereafter, the particulate matter observed at Jaú will be used as proxy for the particulate matter at Botucatu.

3. Climate of São Paulo

The city of São Paulo is located in the State of São Paulo, Brazil, at approximately 770 m amsl and 60 km west of the Atlantic Ocean. Its climate – typical of sub-tropical regions of Brazil – is characterised by a dry winter during June–August and a wet summer during December–March. According to Fig. 3, the minimum values of monthly averaged daily temperature and relative humidity occur in July and August (16 °C and 74%, respectively), and the minimum total monthly precipitation occurs in August (35 mm). The maximum value of monthly averaged daily temperature occurs in February (22.5 °C) and the maximum value of monthly averaged daily relative humidity occurs from December through January and from March through April (80%). The maximum value of total monthly precipita-

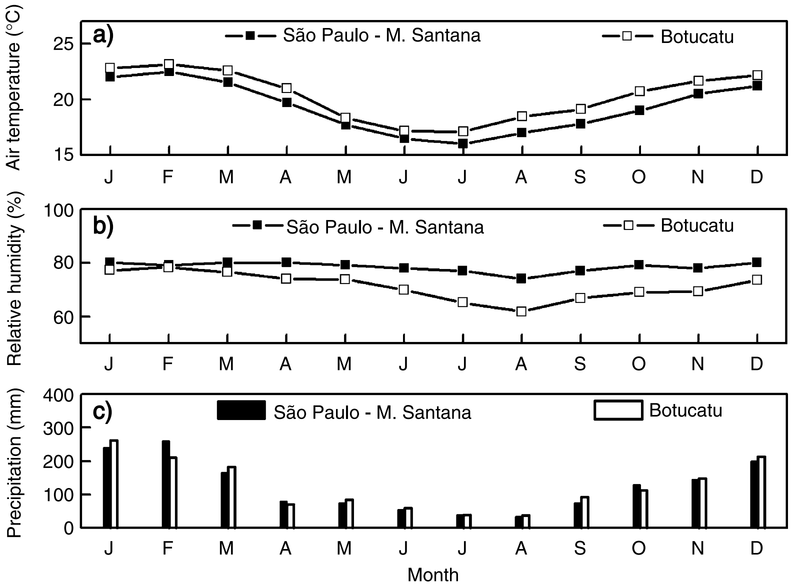

Fig. 3. Seasonal evolution of monthly-averaged daily values of (**a**) air temperature; (**b**) relative humidity and (**c**) precipitation for São Paulo and Botucatu. Observation period: 1961–1990 (São Paulo) and 1971–2004 (Botucatu). São Paulo observations were carried out in M. Santana climatological station

tion occurs in February (255 mm). The shortest and the longest daylight 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 total monthly sunshine occurs in July (183 hours) and the minimum in September (149 hours). According to Oliveira et al. (2002a) maximum daily monthly averaged cloudiness occurs in December (8.2 tenths) and the minimum in July (6.1 tenths).

The seasonal distribution of surface wind speed in the MRSP area is characterised by light winds throughout the year, with intensity varying between 0.5 m s^{-1} and 1.5 m s^{-1} (Oliveira et al. 2003). The combined effects of geographic position and the relative intensity of the semi-stationary South Atlantic anticyclone and continental low pressure systems control the seasonal variation of surface winds in São Paulo City, inducing surface winds from north-north-east during the summer and from east-north-east during winter. This pattern is affected frequently by synoptic scale winter systems such as cold fronts which penetrate into the area in association with north-westerly pre-frontal winds and south-easterly post-frontal winds (Schwerdtfeger 1976; Garreaud and Wallace 1998).

The diurnal evolution of surface winds in the MRSP is systematically affected by sea breeze penetration and by the topography (Dias et al. 1995; Dias and Machado 1997; Karam et al. 2003; Oliveira et al. 2003). Despite the high altitude and distance from the ocean, sea breeze penetrates São Paulo City on about 50% of the days of the year, as seen from the wind flow charts of Oliveira et al. (2003). Other mesoscale effects in São Paulo may include thermal circulation induced by the mountain-valley system and urban effects due to roughness, building barrier and shelter-level urban heat island effects.

The MRSP, with more than six million motor vehicles (CETESB 2004) is characterised as having a moderate degree of contamination by particulate matter and other pollutants (Andrade et al. 1994; Kretzschmar 1994; Massambani and Andrade 1994; Allen and Miguel 1995; Souza et al. 1999; Colón et al. 2001; Nguyen et al. 2001; Ulke and Andrade 2001; Miranda et al. 2002; Sanchez-Ccoyllo and Andrade 2002; Rocha et al. 2003; Vautz et al. 2003). Chemical analysis of the rainwater in São Paulo indicates a pH of 6.2, well below the expected acidity due to the H_2SO_4 (Fornaro and Gutz 2003). Castanho and Artaxo (2001) found considerable differences between the diurnal evolution of particulate matter during the winter and summer, weekdays and weekend days, and cloudy and clear sky-days. Their analysis on PM_{10} measurements, carried out during two winter months (from July 10 to September 10, 1997) and two summer months (January 16 to March 6, 1998), indicated that soil dust and automobile traffic are responsible for most of the particulate matter present in the São Paulo atmosphere. Their principal factor analysis indicated that sea salt, brought by the sea breeze circulation, contributes 11% of the aerosol coarse mode in the winter and 6% in the summer. They also concluded that the averaged daily value concentration of particulate matter was 77 $\mu g\, m^{-3}$ during winter and 32 $\mu g\, m^{-3}$ during summer. Based on a worldwide inventory for relative humidity of 50% and for a cutoff radius of 7.5 μm, Hess et al. (1998) found typical values of aerosol mass concentration of 99.4 $\mu g\, m^{-3}$ for urban areas such as MRSP, 47.7 $\mu g\, m^{-3}$ for continental polluted areas, and 8.8 $\mu g\, m^{-3}$ for continental clean areas. These values are representative of the mixed layer and are similar to those observed at the surface in the MRSP.

The analysis of five days of continuous observations of solar irradiance in São Paulo has shown a systematic reduction in the direct solar beam associated with a progressive increase in the concentration of particulate matter (Oliveira et al. 1996). Extending this analysis to approximately six years (April 26, 1994–June 30, 1999) of continuous observations of global, diffuse and direct solar irradiance at the surface in São Paulo City, Oliveira et al. (2002a), have confirmed that large concentrations of particulate matter at the surface are positively correlated with a reduction in the direct solar beam at the surface in São Paulo.

4. Climate of Botucatu

Botucatu, a city with 119,300 inhabitants, is located in the Brazilian countryside, at 786 m amsl, and approximately 221 km from the Atlantic Ocean. It is characterised by cool, dry winters (June to August) and warm, wet summers (December to February). The average air temperature varies from a minimum of 16.5 °C in the winter to a maximum of 23.9 °C in the summer (Fig. 3a). Compared to São Paulo, the relative humidity of Botucatu is lower, particularly during the winter months (Fig. 3b). Minimum precipitation occurs in August and a maximum in January (Fig. 3c). There is no information available about patterns of atmospheric circulation or air pollution in Botucatu. However, taking into consideration observations carried out in the rural areas of São Paulo State (Oliveira 2003) there is a high chance that the prevailing winds in Botucatu are east-north-easterly, associated mainly with the seasonal variation of the South Atlantic anticyclone. Due to the altitude, a high frequency of low-level jets, mainly during nighttime is also expected (Karam 2002).

As highlighted by Lara et al. (2001), very little is known about the atmospheric chemistry in tropical and sub-tropical areas in comparison to other regions. In the case of southeast Brazil, most of the studies are concentrated in the Piracicaba area (Fig. 1b). Lazutin et al. (1996), have shown that C_4 organic material that was introduced in the Piracicaba basin by the replacement of primary forests by sugar cane and pasture, was already present in soils and in rivers. Lara et al. (2001) performed a chemistry analysis of the rain in the Piracicaba river basin (an area of 4000 km^2 located in the State of São Paulo, east of Botucatu, Fig. 1b) and found that, between May and October, about 1,000,000 tonnes of organic matter from the sugar cane crop was burned, releasing into the atmosphere about 50,000 tonnes of carbon and an undetermined amount of organic acids, sulphates and nitrates. The chemical rain analysis in the Piracicaba river basin area, from August of 1997 to July of 1998, indicated a high acidity, with pH varying from 4.4 to 4.5. Soil dust and sugar cane burning emissions are responsible for 85% of the acidity in these areas. The NO_X emissions associated with sugar cane burning are responsible for the high acidity of the rain the region. The SO_2 emissions associated with industrial activity in the Piracicaba region is responsible for the other 15%. Martinelli et al. (2002) examined ozone levels and Sikar and Scala (2004) looked at methane and carbon dioxide, few other observational analyses of the environmental impact of urban pollution in the State of São Paulo have been conducted.

Botucatu is located in a region of intense sugar cane production and moderate industrial activity (Table 2). However, Botucatu has only about 4% of its terrestrial area (1483 km^2) occupied by sugar cane, yielding about 420,000 tonnes of sugar cane per year, a modest amount compared to nearby cities. For example, the cities in the vicinity of Botucatu (70 cities within 100 km radius), including those cities that have measurements of particulate matter (Limeira and Sta Gertrudes), totals about 36 million tonnes of sugar cane yield per year, spread over about 14% of the entire area (32,095 km^2) (based on

2001 and 2002; IBGE 2006b). Therefore, around Botucatu, there is a significant contribution to air pollution from burned biomass.

5. Results

Here, solar irradiance will be indicated by "I" and the time-integrated solar irradiance by "E". The subscripts G, DF, A and T refer, respectively, to global, diffuse, attenuated and extraterrestrial solar irradiance. The superscripts h or d refer to the time interval used to perform the average ($< >$) of one hour or one day, respectively. In this work, direct solar irradiance was estimated as the difference between the global and its diffuse component observed at the surface. Attenuated solar irradiance was evaluated as the difference between extraterrestrial and global solar irradiances at the surface. The solar irradiance at the top of the atmosphere (extraterrestrial) was estimated analytically (Iqbal 1983) considering the solar constant equal to $1366\,\mathrm{W\,m^{-2}}$ (Frölich and Lean 1998). Some emphasis is placed on August (particularly August 24, 1999), the driest month of the year at both sites (Fig. 3b, c) and, consequently, has a large number of clear sky days. As an example of the seasonal pattern of the solar irradiance components, June will be use to represent winter conditions and December to represent summer conditions.

5.1 Clear days

Following the diurnal evolution of global and diffuse solar irradiance at the surface (I_G and I_{DF}) it is possible to identify days when the sky was not significantly covered by clouds (Oliveira et al. 2002a). The days with clear sky conditions were estimated by visual inspection of the time evolution of global and diffuse solar irradiance at the surface in São Paulo and Botucatu for each day of the period considered (from January 1, 1996 to December 31, 2001). Here, a clear sky day was considered when the curves of the diurnal evolution of global and diffuse solar irradiance are simultaneously smooth and have a distinct separation early in the morning and come together only at the end of the day.

As an example of typical clear day, the diurnal evolutions of global and diffuse solar irradiance for Julian day 236 of 1999 (August 24, 1999) are displayed in Fig. 4, for São Paulo and Botucatu. For comparison, the extraterrestrial solar irradiance (I_T) for both sites is also displayed in Fig. 4a. On this particular day, global solar irradiance was slightly larger in Botucatu than in São Paulo (Fig. 4a). The incoming solar irradiance at the top of the atmosphere in São Paulo and Botucatu was almost indistinguishable, suggesting that the solar irradiance at the top of the atmosphere is similar at both sites. However, there is a time lag in the intensity of the solar irradiance in Botucatu with respect to São Paulo due to the Botucatu location, about 2° further west than São Paulo (Table 2). Figure 4b shows the hourly values of the difference in extraterrestrial solar irradiance intensity between São Paulo and Botucatu. The difference amplitude varies from $+37.8\,\mathrm{W\,m^{-2}}$ early in the morning to $-45.1\,\mathrm{W\,m^{-2}}$ later in the afternoon.

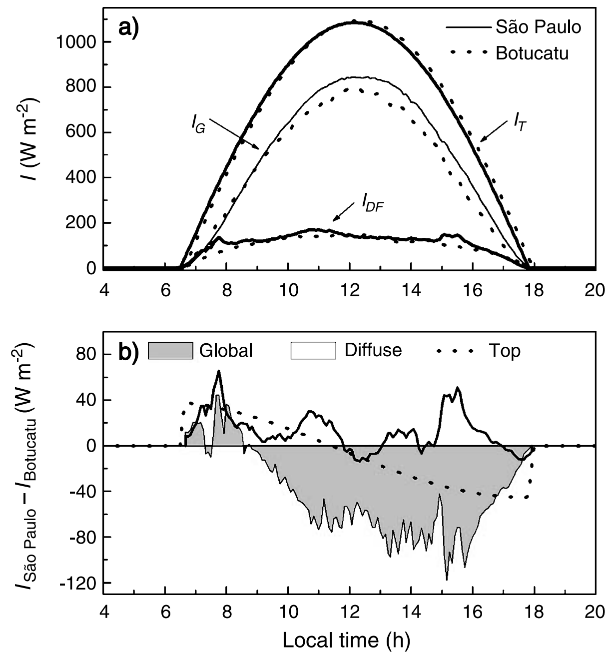

Fig. 4. Diurnal evolution of (**a**) global (I_G), diffuse (I_{DF}) and extraterrestrial solar irradiance (I_T) for São Paulo (continuous line) and Botucatu (dotted line) and (**b**) difference between solar irradiances in São Paulo and Botucatu. August 24, 1999

The daily values of extraterrestrial solar irradiance during this day are $28.29\,\mathrm{MJ\,m^{-2}}$ and $28.58\,\mathrm{MJ\,m^{-2}}$, respectively, in São Paulo and Botucatu. The small localisation difference between these two places induces a time lag in the solar irradiance intensity; however, for daily values, this difference is only $-0.29\,\mathrm{MJ\,m^{-2}}$; about

1% of the Botucatu value. Given the fact that São Paulo and Botucatu are located approximately at the same altitude (Table 2), it could be assumed that solar irradiance travels to both places along very similar path lengths. Therefore, differences in the solar irradiance field at the surface, which are larger than the one produced by the time lag, may be associated with the spatial variation in the optical path depth of aerosol, clouds and water vapour content in the atmosphere.

The monthly frequency distributions of clear sky days, between 1996 and 2001, are indicated in Fig. 5 for São Paulo and Botucatu. Both places display a similar seasonal distribution with maximum frequency during winter and minimum during summer. As expected, the largest number of clear sky days occurs in August, the driest month of the year at both sites (Fig. 3b, c). The number of simultaneous clear sky days (63 days) is equivalent to 72% of all clear sky days in São Paulo and 29% in Botucatu, indicating that most of the days with clear sky in São Paulo are associated with meteorological conditions of larger spatial scale, affecting the atmosphere of both places equally. Considering the investigated period (1996–2001), clear sky days were observed, on average, about 4.7% of the time in São Paulo and about 10.4% in Botucatu. Approximately 2.9% of the total of 2192 days had clear day conditions in both cities. This agreement indicates that both places are under the influence of similar seasonal cloud patterns; but a higher frequency of clear sky days is found in Botucatu because this city is more distant from the Atlantic Ocean than São Paulo (Table 2). The number of days with clear skies is larger in Botucatu than São Paulo during all months of the year. In August, Botucatu had 51 clear sky days and São Paulo had 29 days (Fig. 5). Considering all months of the investigated period, Botucatu had 214 clear sky days and São Paulo had 88 days (Fig. 5).

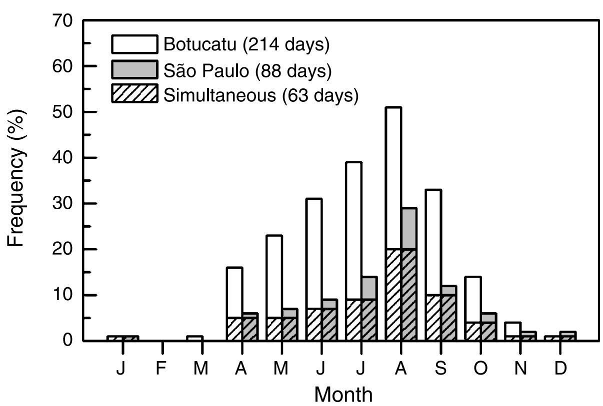

Fig. 5. Seasonal evolution of the monthly-averaged frequency of clear sky days in São Paulo and Botucatu. "Simultaneous" stands for clear sky days observed simultaneously in both cities. Period: 1996–2001

5.2 *Seasonal variation of daily values*

The seasonal evolution of monthly averaged daily values of global and diffuse solar irradiance

Table 3. Monthly-averaged daily values of solar radiation measured at the surface at São Paulo and Botucatu in June and December days between 1996 and 2001

($MJ\,m^{-2}$)	Monthly averaged for clear sky days			Monthly averaged		
	June	December	August	June	December	August
	São Paulo					
Top	22.2 ± 0.1	42.39 ± 0.02	26.9 ± 0.3	22.14 ± 0.02	42.48 ± 0.01	27.0 ± 0.1
Global	15.0 ± 0.3	30.1 ± 0.4	17.4 ± 0.3	11.0 ± 0.3	19.2 ± 0.5	14.1 ± 0.4
Diffuse	2.0 ± 0.2	4.6 ± 0.1	3.80 ± 0.2	3.9 ± 0.1	9.5 ± 0.2	5.2 ± 0.2
Direct	13.0 ± 0.3	25.5 ± 0.4	13.6 ± 0.3	8.8 ± 0.3	9.7 ± 0.5	9.0 ± 0.4
Number of days	9	2	29	143	173	150
	Botucatu					
Top	22.06 ± 0.05	42.23	27.3 ± 0.1	22.55 ± 0.02	42.35 ± 0.01	27.3 ± 0.1
Global	15.8 ± 0.1	32.61	18.9 ± 0.2	12.7 ± 0.3	20.1 ± 0.5	16.1 ± 0.3
Diffuse	1.73 ± 0.06	2.43	2.8 ± 0.2	3.6 ± 0.1	9.1 ± 0.2	4.3 ± 0.2
Direct	14.1 ± 0.1	30.23	16.1 ± 0.3	9.1 ± 0.3	11.0 ± 0.6	5.9 ± 0.4
Number of days	31	1	51	162	175	180

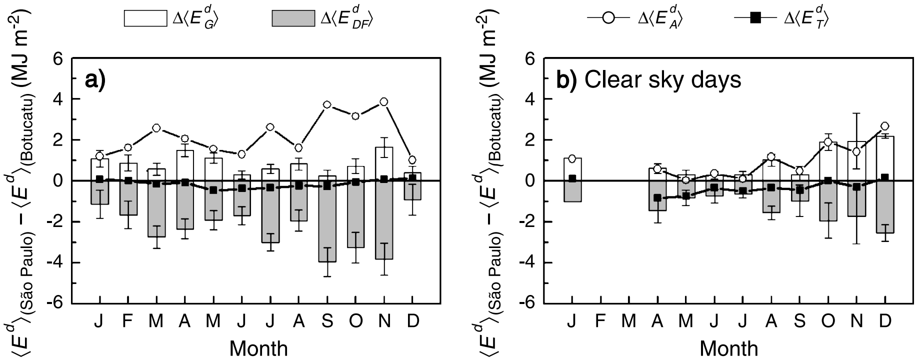

Fig. 6. Seasonal evolution of monthly-averaged daily values of global solar radiation differences between São Paulo and Botucatu. Period: 1996–2001. Vertical bars correspond to the error values

indicated that, in general, Botucatu receives more global solar irradiance at the surface than São Paulo (see Fig. 4 of Oliveira et al. 2002a). The difference is less pronounced during clear sky days. On the other hand, Botucatu receives less diffuse solar irradiance at the surface than São Paulo when considering either all or just clear sky days. Table 3 summarises the daily values of solar irradiance at the surface for June (winter), December (summer) and August (month with more clear days) at São Paulo and Botucatu, during 1996–2001.

Using Botucatu as a reference, São Paulo receives 13.4% less global solar irradiance in June and 5.0% less in December. Besides, São Paulo receives 8.3% more diffuse solar irradiance at the surface in June and 4.4% more in December than Botucatu. With respect to the direct solar irradiance, São Paulo receives 3.3% less in June and 13.4% less in December than Botucatu. Considering only clear sky days, São Paulo receives 5.7% less global, 15.6% more diffuse and 7.8% less direct solar irradiance at the surface in June than Botucatu. December is not considered here because there was only one clear sky day in Botucatu and two clear sky days in São Paulo (Table 3). The differences between São Paulo and Botucatu are better visualised in Fig. 6. The seasonal evolution of differences between monthly averaged daily values of global and diffuse solar irradiance at the surface shows that during all months of the year São Paulo receives less global solar irradiance and more diffuse solar irradiance than Botucatu.

Three main factors contribute to the observed solar irradiance difference between São Paulo and Botucatu: less clear sky days, more particulate material and more moisture content in São Paulo.

The seasonal evolution of the horizontal contrast of atmospheric attenuation for solar irradiance between São Paulo and Botucatu is indicated in Fig. 6 (by lines with open circles) and is estimated as $\Delta\langle E_A^d\rangle = [\langle E_T^d\rangle - \langle E_G^d\rangle]_{\text{São Paulo}} - [\langle E_T^d\rangle - \langle E_G^d\rangle]_{\text{Botucatu}}$. This result indicates that the atmosphere of São Paulo attenuates much more solar irradiance than at Botucatu ($\Delta\langle E_A^d\rangle > 0$).

Surprisingly, during clear sky days the attenuation in São Paulo remains only slightly larger than in Botucatu (Fig. 6). During wintertime and clear days, the attenuation difference is around the same order of magnitude of the solar irradiance horizontal contrast at the top of the atmosphere between these two sites (line with square in Fig. 6b), indicating that the largest contrast occurs during summertime. The observed attenuation pattern will be better explored in the next sections considering the hourly values of global and diffuse solar irradiance.

Considering only clear sky days (i.e., removing the cloud effects), besides pollution, a significant factor decreasing global and increasing the diffuse solar radiation is the larger moisture content of the São Paulo atmosphere (Fig. 3a). Atmospheric water vapour absorbs both direct and scattered solar radiation components, attenuating them. On the other hand, large water vapour content affects the size distribution of aerosols particles, altering their optical properties and increasing the fraction of diffuse solar radiation.

The effect of pollution can be better assessed considering the differences of solar irradiance between São Paulo and Botucatu during clear sky days. It is expected that the higher levels of pollution content in São Paulo with respect to Botucatu is the factor causing smaller values of global solar irradiance and larger values of diffuse solar irradiance in São Paulo. Atmospheric aerosol particles scatter and absorb direct solar beam. Both attenuation effects seem to be particularly strong in the case of São Paulo, reducing global solar radiation and increasing its diffuse fraction at the surface, when compared with Botucatu.

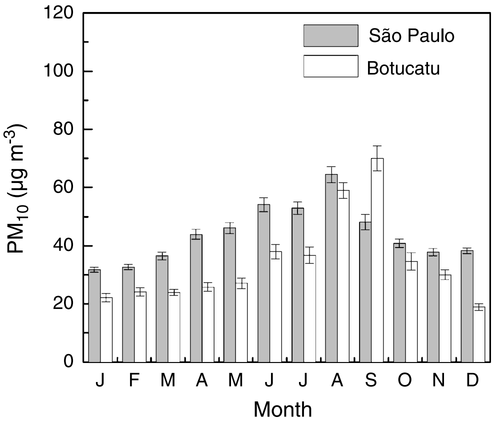

Fig. 7. Seasonal evolution of monthly-averaged daily values of particulate matter in São Paulo (1996–2001) and Botucatu (2004). Vertical bars correspond to the error values

Figure 7 shows that the PM_{10} concentration in São Paulo is larger than in Botucatu during most of the year. The seasonal evolution of monthly averaged PM_{10} concentrations in São Paulo is consistent with previous measurements carried out by Castanho and Artaxo (2001). However, the PM_{10} concentrations in Botucatu are larger than the expected values for clean continental areas, according to Hess et al. (1998) which should be around $8.8\,\mu g\,m^{-3}$.

There is no information about albedo in São Paulo and Botucatu and the lack of information precludes any evaluation of the albedo effect upon the solar irradiance field. However, typical middle latitude albedo values over urban areas are 0.15 ± 0.02 (Sailor and Fan 2002), which are slightly smaller than typical albedo values

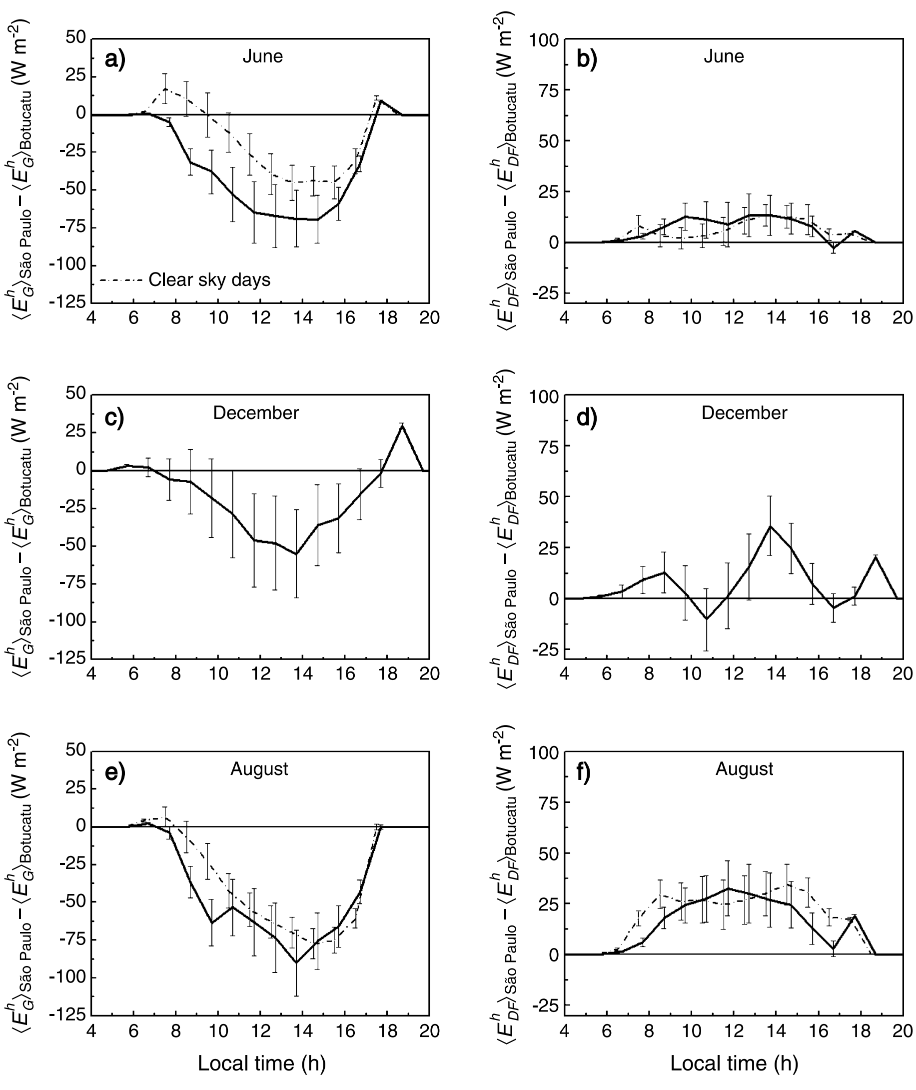

Fig. 8. Diurnal evolution of monthly-averaged hourly values of global and diffuse solar irradiance differences between São Paulo and Botucatu (continuous line) and clear sky days (dashed line). June, December and August (1996–2001). Vertical bars correspond to the error values

over rural areas of 0.18 (Oke 1988; Atkinson 2003). Therefore, the impact of the albedo on diffuse solar irradiance at the surface should be smaller over urban areas than in rural ones indicating that the observed atmospheric contribution to the diffuse solar irradiance in São Paulo, under clear sky conditions, may be even larger than that detected by direct comparison with Botucatu.

5.3 Seasonal variation of diurnal evolution

Figure 8 shows the difference between São Paulo and Botucatu for the diurnal evolution of monthly averaged hourly global solar irradiance $\langle E_G^h \rangle$ and diffuse solar irradiance $\langle E_{DF}^h \rangle$ for June, December and August. The small number of clear sky days in December (Table 3) precludes any analysis of this situation.

As expected, São Paulo receives less global and more diffuse solar irradiance than Botucatu during all hours of the day, throughout the year (Fig. 8). The differences between the global irradiance in São Paulo and Botucatu are less pronounced during summer months and intensify around 1400 local time (LT). In general, before 1200 LT the horizontal contrast in global solar irradiance is smaller when only clear sky days are considered (Fig. 8). Considering the error bars in Fig. 8b and f, the difference in the diffuse solar radiation intensity is independent of the cloud cover condition.

The horizontal contrast intensity for global solar irradiance follows a pattern with larger values between 1000 LT and 1600 LT (Fig. 8a, c, e). The amplitude of the diffuse solar irradiance horizontal contrast, during clear sky days of August, shows larger values between 1000 LT and 1600 LT (Fig. 8f).

Figure 9a, b displays the diurnal evolution of the monthly averaged hourly particulate matter

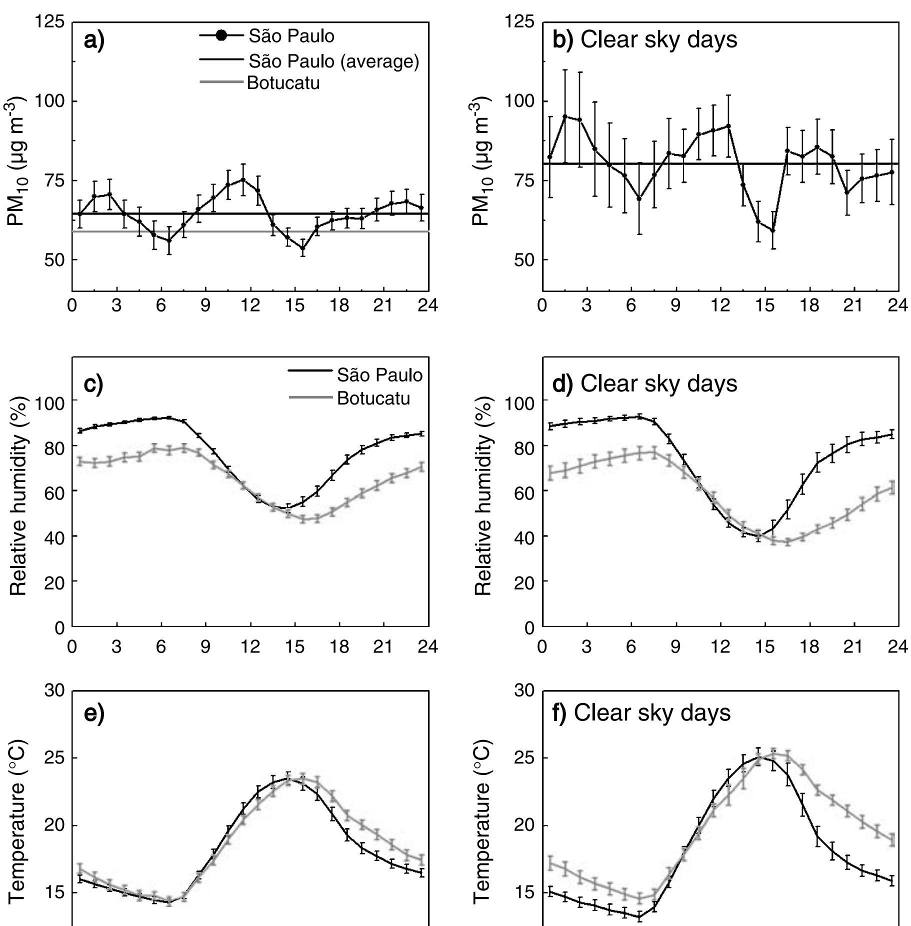

Fig. 9. Diurnal evolution of monthly-averaged hourly values of (**a**, **b**) particulate matter (PM_{10}) measured in São Paulo; (**c**, **d**) relative humidity; (**e**, **f**) temperature. In (**a**) and (**b**) the black thick continuous lines correspond to the 24 h averaged PM_{10} for São Paulo. The observational period are indicated in Table 1. Vertical bars correspond to the error values

concentration measured at São Paulo during August (Fig. 9a) and during clear sky days (Fig. 9b). The diurnal evolution shows two minima: one early in the morning and the other in the middle of the afternoon (Fig. 9a, b). The particulate matter concentrations in São Paulo are larger than the PM_{10} average value for Botucatu ($59\,\mu g\,m^{-3}$, based on the monthly averaged value for August, Fig. 7).

In general, for August, clear day (Fig. 9b) PM_{10} concentrations are larger than for monthly averaged hourly values (Fig. 9a). The daily average concentration of particulate matter in August ($64.7\,\mu g\,m^{-3}$, black line in Fig. 9a) is smaller than the average value considering only clear sky days ($80.4\,\mu g\,m^{-3}$, black line in Fig. 9b). However, these values are higher than the value assumed as representative of Botucatu ($59\,\mu g\,m^{-3}$, grey line in Fig. 9a).

Considering only clear days, the particulate matter concentration reduction in the afternoon in São Paulo can be associated with the diurnal cycle of vehicular emissions which are closely related to the bi-modal diurnal evolution of traffic (Andrade et al. 1994; Massambani and Andrade 1994; Castanho and Artaxo 2001; Martinis et al. 2002; Miranda et al. 2002; Sanchez-Ccoyllo and Andrade 2002). The PM_{10} diurnal pattern explains the increase in the scattering difference at the beginning and end of clear sky days (Fig. 8b, f).

Another important mechanism that reduces the particulate matter concentration at the surface during the day is the entrainment of cleaner and drier air due to the vertical evolution of the planetary boundary layer. This reduction can be seen in August after noon (Fig. 9a, b). The reduction in PM_{10} concentration after 1200 LT is in phase with the diurnal evolution of the horizontal contrast of global and diffuse solar radiations in August (Fig. 8e, f).

The increase in the diffuse solar irradiance contrast amplitude between São Paulo and Botucatu, in the beginning of the afternoon, in June, December and August (Fig. 8b, d, f) can also be related to the systematic penetration of the sea breeze in São Paulo (Oliveira et al. 2003).

The sea breeze intensity depends on the horizontal thermal contrast between ocean and continent. Therefore, the smaller the cloud frequency (which occurs in August, Fig. 5) the greater the possibility of observing the sea breeze circulation in São Paulo. Besides, the horizontal thermal contrast between Atlantic Ocean and continent is stronger in August, due to the thermal inertia of the ocean in the transition between winter and summer (van Loon 1972). Between 1000 LT and 1400 LT, there is no significant difference between the monthly averaged hourly relative humidity in São Paulo and Botucatu even if only clear days are considered (Fig. 9c, d). Before 1000 LT and after 1400 LT, the relative humidity in São Paulo is larger than in Botucatu due to the systematic penetration of the sea breeze in São Paulo bringing moisture from the Atlantic Ocean.

During August, the monthly averaged hourly air temperature shows similar diurnal evolution in São Paulo and Botucatu with Botucatu showing slightly smaller values during morning and larger values during afternoon and early evening periods (Fig. 9e, f). The differences between air temperature in São Paulo and Botucatu are larger when only clear days are considered (Fig. 9e, f).

An important conclusion of this section is that the sea breeze penetrates São Paulo at around 1400 LT in August, increasing relative humidity and decreasing air temperature systematically. Even though both effects are related, the relative humidity increase is also followed by an increase in the global solar radiation attenuation (Fig 8e) and an augmentation of the intensity of diffuse solar radiation in São Paulo with respect to Botucatu (Fig. 8f) caused by the alteration of the optical properties of the aerosols. These effects are also observed during the summer and winter months (Fig. 8a–d, respectively) suggesting that the sea breeze affects solar radiation during the entire year at the regional scale.

5.4 Sea breeze event in São Paulo

To characterise the impact of the sea breeze on the São Paulo atmosphere, one event will be discussed in details in this section. Figure 10a shows the diurnal evolution of the solar irradiance differences between São Paulo and Botucatu on August 24, 1999, a clear sky day (Fig. 4). The diurnal evolution of the difference between São Paulo and Botucatu indicates that around 1400 LT the maximum difference in the diffuse con-

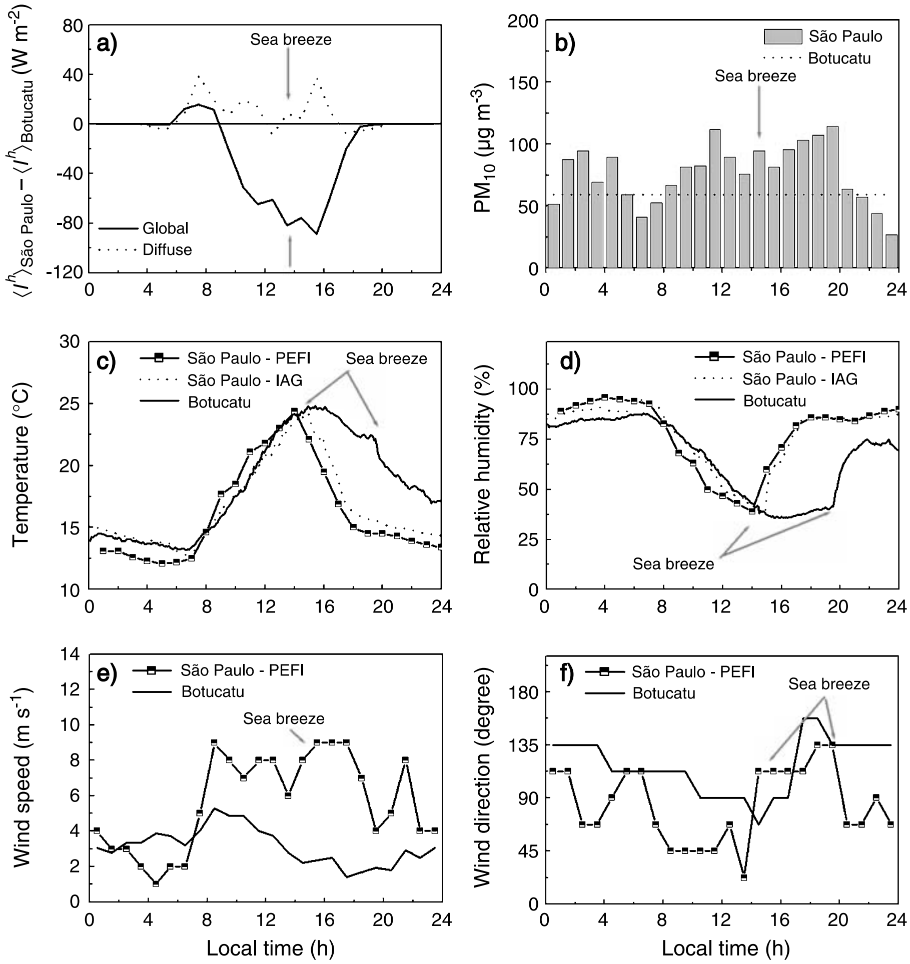

Fig. 10. Diurnal evolution of hourly values of (**a**) difference between solar irradiances in São Paulo and Botucatu; (**b**) particulate matter in São Paulo and the August average value of Botucatu (dotted line); (**c**) air temperature in São Paulo (PEFI and IAG) and Botucatu; (**d**) relative humidity in São Paulo (PEFI and IAG) and Botucatu; (**e**) wind speed in São Paulo (PEFI) and Botucatu and (**f**) wind direction in São Paulo (PEFI) and Botucatu. August 24, 1999

trast (Fig. 10a) is associated with a local maximum in the particulate concentration at São Paulo (Fig. 10b).

Air temperature and relative humidity show the moment when the sea breeze penetrates São Paulo (Fig. 10c, d). A drop in air temperature and a rise in relative humidity follow the sea breeze penetration, first at the PEFI station and about one hour later at the IAG site (Fig. 1c, for locations). Wind speed and direction indicate that the sea breeze passage at the PEFI station is followed by an increase in wind speed (Fig. 10e) and a shift in the wind direction from north-easterly to south-easterly (Fig. 10f). Theoretically, the effects caused by the penetration of the sea breeze into São Paulo are not felt in Botucatu. Curiously, on this particular day, the sharp drop in the temperature followed by the sharp increase in the relative humidity observed in Botucatu after 2000 LT (Fig. 10c, d) may be related to the propagation of the sea breeze front inland in the countryside of São Paulo. Possibly the local topographic effects modify the wind speed and direction at Botucatu resulting in the diurnal evolution of the wind field being in related to the wind speed and direction in São Paulo, as would be expected in the case of sea breeze penetration (Fig. 10e, f).

To summarise, the diurnal evolution of global and diffuse solar radiation at the surface is strongly correlated to sea breeze events in São Paulo. The moisture carried by the breeze reduces the intensity of both the direct and scattered solar radiation components. Large water vapour content affects the size distribution of aerosols particles, altering their optical properties and increasing the fraction of diffuse solar radiation. Besides moisture, the sea breeze also brings maritime aerosols to São Paulo (Castanho and Artaxo 2001), which, due to their hygroscopic character, may further increase the scattering of direct solar radiation.

6. Conclusion

This work compares the seasonal evolution of monthly averaged values of daily and hourly global and diffuse solar radiation at the surface, in São Paulo and Botucatu. Monthly averaged daily and hourly values of solar radiation are based on observations carried out simultaneously in São Paulo and Botucatu during a six year period, from 1996 to 2001, using similar sensors and sampling frequency.

The frequency distributions of clear days indicated that the total number of clear sky days in Botucatu is larger than in São Paulo. Consequently, São Paulo receives less global and more diffuse radiation at the surface than Botucatu during the entire year. The seasonal variation of the diurnal cycle confirmed the differences. This behaviour is closely related to (i) the distance from the Atlantic Ocean, (ii) the systematic penetration of the sea breeze in São Paulo and (iii) the higher atmospheric pollution in São Paulo.

The proximity of São Paulo to the Atlantic Ocean favours higher air moisture content that, when combined with topographic uplift of air masses, generates a larger cloud frequency compared with Botucatu.

The sea breeze penetration in São Paulo brings moisture and maritime aerosols which increase solar radiation scattering and reduces the intensity of the direct component of solar radiation at the surface. The atmospheric water vapour absorbs both direct and scattered solar radiation components, attenuating them. Large water vapour content affects the size distribution of aerosols particles, altering their optical properties and increasing the fraction of diffuse solar radiation. The hygroscopic character of the maritime aerosol may further increase the scattering of the direct solar radiation.

Based on the size and population of São Paulo and Botucatu, it was thought that the particulate matter concentration in São Paulo would always be higher than at Botucatu. The analysis carried out here indicates that this is not true in September. It was found that the atmosphere at São Paulo reduces more solar radiation than at Botucatu. However, under clear sky conditions the atmospheric attenuation of solar radiation in Botucatu during winter and the beginning of spring, the time of the biomass burning due to the sugar cane harvest, is equivalent to that of São Paulo City, indicating that contamination during the sugar cane harvest in southeast Brazil has a large impact on the solar radiation field at the surface.

The pattern of solar radiation attenuation observed at the surface in São Paulo indicates that particulate matter associated with traffic, the entrainment of cleaner and drier air due to vertical evolution of the planetary boundary layer, and the sea breeze penetration effects associated with the advection of moisture and maritime aerosol, should be taken into consideration explicitly in the development of models to simulate diffuse solar radiation at the surface based on neural network techniques (Soares et al. 2004). In Botucatu, the source of aerosols must be associated with the biomass burning of sugar cane, and the transportation of moisture and aerosols by the sea breeze should be discarded.

Finally, it is important to emphasise that the solar radiation measurements used here were made by high precision pyranometers (1–2% error). The shadow-band device used to measure diffuse solar radiation was extensively tested and all measurements were corrected for the blocking effects, reducing the error to a minimum (Oliveira et al. 2002c). However, the meteorological data used here are not long enough to prove definitively the similarity of the particulate matter characteristics in São Paulo and Botucatu. The analysis of the available data provided evidence to support the hypothesis that the sugar cane plantation has an important impact on the local climate, attenuating considerably the solar radiation in Botucatu during winter.

List of symbols

Symbols	*Description*
$< >$	Monthly and hourly average
I	Solar irradiance (W m^{-2})
I^h	Hourly values of solar irradiance (W m^{-2})
I_G	Global solar irradiance (W m^{-2})
I_{DF}	Diffuse solar irradiance (W m^{-2})
I_T	Extraterrestrial solar irradiance (W m^{-2})
E^d	Daily values of solar radiation (MJ m^{-2})
E^d_G	Daily values of global solar radiation (MJ m^{-2})
E^d_{DF}	Daily values of diffuse solar radiation (MJ m^{-2})
E^d_A	Daily values of atmospheric attenuation of solar radiation (MJ m^{-2})

E_T^d	Daily values of extraterrestrial solar radiation ($\mathrm{MJ\,m^{-2}}$)
E_G^h	Hourly values of global solar radiation ($\mathrm{W\,m^{-2}}$)
E_{DF}^h	Hourly values of diffuse solar radiation ($\mathrm{W\,m^{-2}}$)
PM_{10}	Particulate matter ($\mu\mathrm{g\,m^{-3}}$)
σ	Standard deviation
N	Size of the sample
MRSP	Metropolitan region of São Paulo
IAG	Institute of Astronomy, Geophysics and Atmospheric Sciences
PEFI	State Park of the Ipiranga Fountain
CETESB	São Paulo State Environmental Agency
GNP	Gross National Product
IBGE	Brazilian Institute of Research and Statistics
LT	Local Time (GMT – 3 hours)
IPCC	Intergovernmental Panel on Climate Change

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