ANNUAL AND DIURNAL WIND PATTERNS IN THE CITY OF SÃO PAULO

AMAURI P. OLIVEIRA[1,*], ROBERT D. BORNSTEIN[2] and JACYRA SOARES[1]
[1] *University of São Paulo, IAG, Department of Atmospheric Sciences, Micrometeorology Group, São Paulo, SP, Brazil;* [2] *Department of Meteorology, San Jose State University, San Jose, CA, U.S.A.*
(author for correspondence, e-mail: e-mail:apdolive@usp.br, Fax: +11 3091 4714)*

(Received June 2002; accepted 1 November 2002)

Abstract. The major topographic, mesoscale, and urban influences on the wind patterns of the City of São Paulo are characterized using one year of surface wind velocity data observed at 11 surface stations within its urban limits. The data was used to study the diurnal and annual variations of wind velocity and horizontal wind divergence within the city. Results showed that the circulation over the investigated area is dominated by three major factors: sea breeze; mountain-valley circulations; and urban effects, such as roughness, building-barrier, and urban heat island. The sea breeze was found to be the dominant feature of the monthly-averaged diurnal variation of São Paulo surface winds during the eight warmest months of the year. The sea breeze front induces a velocity minimum at the time of its passage and a post-frontal afternoon velocity maximum. Mountain-valley thermal effects on the flow can be seen in the temporal divergence/convergence patterns. These thermal effects tend to be more important during colder months, at night, and when the wind velocities are low. Nighttime downslope convergent flows are present over the city during winter and spring and daytime upslope divergent flows are present over the city during summer months.

Keywords: local winds, São Paulo City, sea breeze, urban effects, urban heat island

1. Introduction

Wind patterns in complex-topography urban areas are intricate because of urban canopy effects – such as, roughness changes, street canyon channeling, urban building barrier effects, and urban heat island (UHI) circulations – are embedded inside the circulations induced by (thermal and mechanical) topographic, sea/land, and large-scale effects (Plate, 1995). For instance, urban areas in a valley are likely to show thermally induced circulations that produce surface convergence, during nighttime hours, due to the cold downslope drainage flows and divergence, during daytime hours due, to the warm up-slope flows (Flohn, 1969; Garret and Smith, 1985).

The urban surface roughness is responsible for reductions in surface wind velocities during high wind velocity conditions and by the formation of deceleration-produced convergence areas upstream of the center of urban regions during both low and high wind conditions (Munn, 1970). Urban building-barrier effects cause

Water, Air, and Soil Pollution: Focus **3:** 3–15, 2003.

upwind flows to go around a city (producing divergence over the city) and then to re-converge downwind of the city (Bornstein, 1987; Bornstein and Lin, 2000).

In tropical and subtropical cities, shelter-level UHI magnitude is also controlled by soil moisture contrasts between urban and rural areas, with its intensity more pronounced during daytime for cities surrounded by wet rural areas and at nighttime for those with dry rural areas (Imamura, 1991; Imamura *et al.*, 1991). Jauregui *et al.* (1992) found a maximum shelter-level UHI intensity at night in tropical Guadalajara, Mexico, during its dry season. During low velocity conditions, UHIs are strong and they produce convergent mesoscale circulation towards the urban core in the form of centripetal circulation (Vucovich, 1971; Shreffler, 1978, 1979).

São Paulo City, the largest city in South America, with more than 10 million habitants, has a high degree of air pollutant contamination (Kretzschmar 1994). Lombardo (1984) and Monteiro (1986), using satellite images, have found surface-radiative temperature UHIs in São Paulo with intensities similar to middle latitude regions during daytime hours (up to 12 °C).

According to Imamura (1991) and Imamura *et al.* (1991) the shelter-level UHI of the São Paulo City should be larger during winter nighttime and summer daytime due to the fact that, in São Paulo, the amount of precipitation generated by winter wave cyclone is smaller than that generated by summer convection. However, observational evidence of UHI induced convergent centripetal circulation in the City of São Paulo is not available in the literature, and the complexity of the local topography render identification of this pattern an observational challenge.

This paper attempts to characterize the major topographic, mesoscale, and urban influences on the surface wind patterns in São Paulo City using one year (1988) of surface wind velocity and direction data observed at 11 surface stations within its urban limits. The data is used to study the diurnal and annual variations of surface wind and surface horizontal divergence within the city.

2. Site

The São Paulo City is located in the State of São Paulo, Brazil, at approximately 770 m above mean sea level, 60 km westward from the Atlantic Ocean, at a subtropical latitude of 23°30′S, and longitude of 46°40′W (Figure 1a) and it has a high degree of air pollutant contamination (Kretzschmar, 1994). Oliveira *et al.* (1996) detected a reduction of up to 18% in the direct beam radiation associated to a progressive increase in the concentration of particulate matter during a period of five cloudless days over the City of São Paulo. Its urban core of densely spaced tall buildings is situated in a basin formed by the Tiete and Pinheiros Rivers (Figures 1b and c), which cross the region at an elevation of approximately 740 m. Higher elevation terrain (above 780 m) is confined to areas NW, SW, and SE of the urban area.

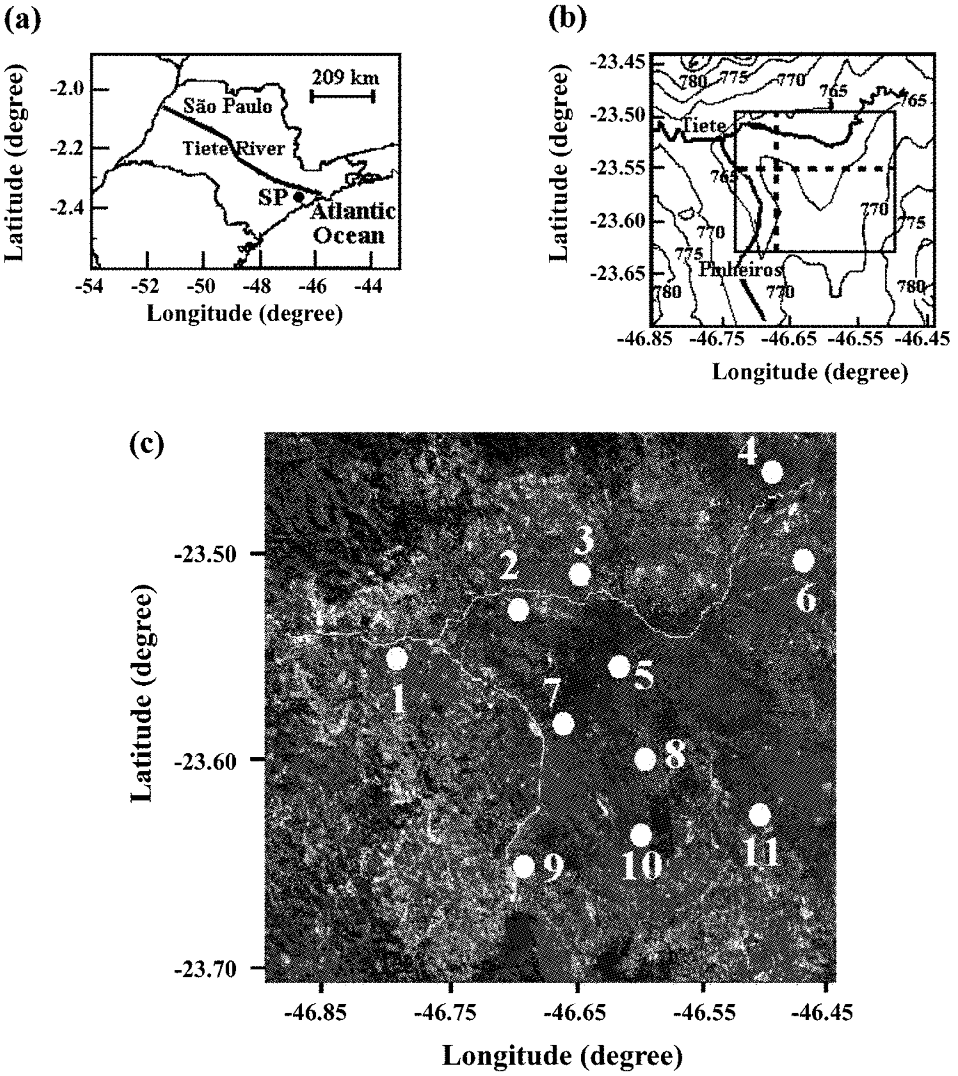

Figure 1. (a) Map of the State of São Paulo at Brazil. A full circle, labeled SP, indicates São Paulo City. The City of São Paulo is about 60 km far from the Atlantic Ocean coastal line; (b) topographic representation of the São Paulo City. Blue lines indicate the rivers. The red dashed lines indicate sub-domains used to evaluate wind divergence and (c) land use of the São Paulo City. The green, brown and purple colors indicate vegetation, suburban and urban areas, respectively. Numbered full circles indicate surface stations.

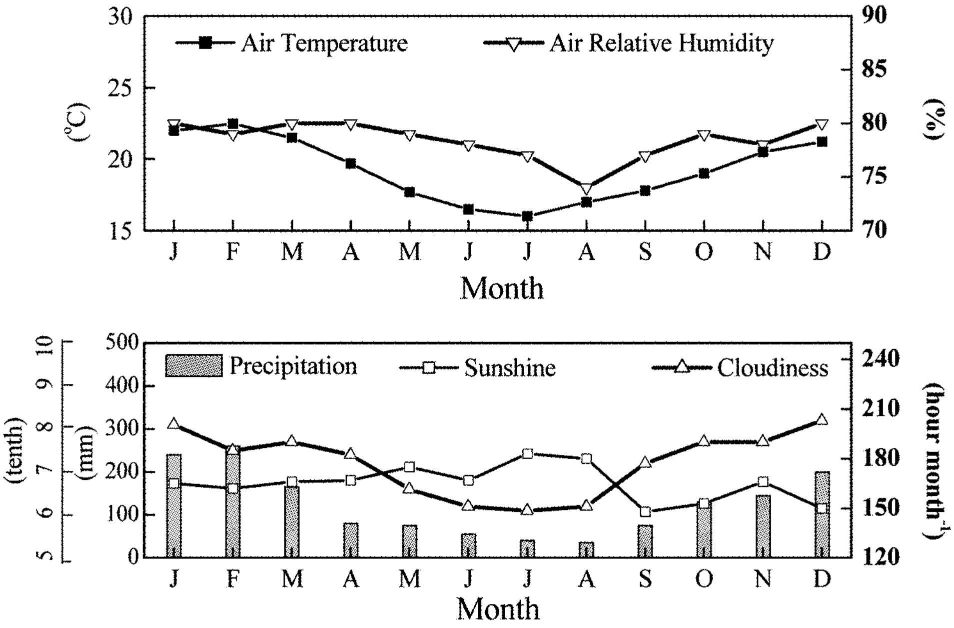

Figure 2. Seasonal variation of air temperature and relative humidity (top) and precipitation, sunshine hours and cloudiness (bottom). Air temperature, relative humidity and cloudiness correspond to monthly-averaged values. Precipitation and sunshine hours correspond to monthly-accumulated values. These observations were carried out in São Paulo City, during 1960–1990 (From Oliveira *et al.*, 2002).

According to Oliveira *et al.* (2002), the climate of São Paulo City – typical of subtropical regions of Brazil – is characterized by a dry winter during June–August and a wet summer during December–March (Figure 2). 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 duration is 10.6 hr (June) and 13.4 hr (December) when the sun reaches the maximum elevation of 54 and 89°, respectively. The maximum value of monthly accumulated period of sunshine occurs in July (183 hr) and the minimum in September (149 hr). The maximum daily monthly-averaged cloudiness occurs in December (8.2 tenths) and the minimum in July (6.1 tenths).

Combined effects of the 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. They induce surface winds from N-NE during summer and from NE-E during winter. This pattern is frequently affected by winter synoptic scale systems, such as cold fronts, and by summer sea breeze fronts. Cold fronts penetrate into the area in association with NW pre-frontal winds and SE post-frontal winds (Garreaud and Wallace, 1998; Schwerdtfeger, 1976). Despite the high elevation and distance from the ocean, the sea breeze penetrates into São Paulo City about 50% of the days of the year, as seen in the wind flow charts of Oliveira and Dias (1982) and Dias and Machado (1997). Other mesoscale effects in São Paulo could include: thermal circulation induced by the mountain-valley system and urban effects due to roughness, building barrier, and shelter-level UHI effects.

3. Methodology

The data used here consist of surface wind measurements from 11 stations within the urban limit of São Paulo area during 1988. These stations (Figure 1c) are part of the surface network operated by the São Paulo State Air Quality Control Agency (CETESB, 1988). Surface wind velocity measurements were made with cup anemometers and vanes whoses accuracies are respectively, 0.5 m s^{-1} and 5 degrees. The data were sampled every minute and, subsequently, hourly-averaged wind velocity values (centered on the half-hour) were calculated. Corresponding wind direction values were estimated from the most frequent direction within each one-hour period. Quality-assurance consistency tests were carried out for each station.

The data was first used to calculate the zonal and meridional wind components (u and v, respectively) for each site. The wind components were then interpolated using the objective interpolation scheme of Goodin *et al.* (1979), which uses wind observation sites as triangle vertices (Figures 3a and b). The grid point values of u and v were evaluated within of each triangle, totalizing 55 evenly spaced grid points (0.025° or approximately 3 km) in the January–June domain (Figure 3a) and 53 in July–December domain (Figure 3b). Finally, horizontal divergence was evaluated at the non-boundary grid points, indicated by crossed-squares in Figure 3, using centered finite difference technique.

During January to June, the wind observations at Station 4 (Figure 1b) were not always available and therefore, only 27 divergence values could be calculated in the sub-domain shown in Figure 3a (crossed-squares), i.e., area of Figure 1b southward of its horizontal red dashed line. Likewise, during July to December, the observations from Station 1 (Figure 1b) were not always available and therefore only 28 divergence values could be calculated in the sub-domain of Figure 3b, i.e., area of Figure 1b eastward of its vertical dashed line.

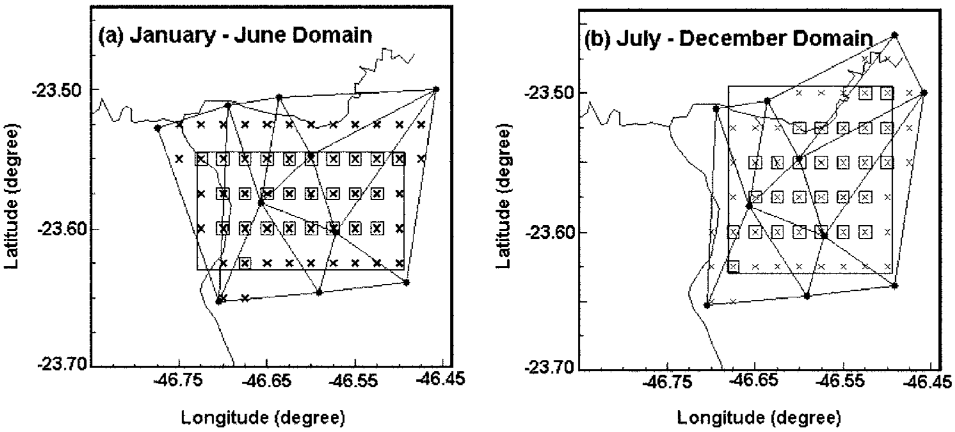

Figure 3. (a) Wind divergence computation domain for January–June and (b) July–December of 1988. Solid circles show the stations where the surface wind data was measured. Cross symbols represent the grid points where the horizontal wind velocity components were interpolated. The crossed-squares represent the grid points where the divergence was calculated. Big triangles are used in the interpolation scheme to evaluate the wind at the grid points.

4. Results

The annual evolution of area-averaged monthly mean wind velocity (Figure 4a) shows São Paulo City with consistently low wind velocities (<1.5 m s^{-1}) during both daytime and nighttime periods. The minimum velocity (about 0.5 m s^{-1}) occurs during May, the transitional period between the summer north-northeasterly flow period and the winter northeast-easterly flow period. On the other hand, the maximum velocity occurs between September and November, the spring transitional period, in association with their higher nocturnal velocities, as explained below.

Looking at the diurnal evolution of the area-averaged hourly-mean wind velocity is possible to classify the months of the year in ‘typical’ (Figure 4a) and ‘non-typical’ São Paulo months (Figure 4b).

The wind velocity values during the eight ‘typical’ months (August to December and February to April) show a reverse behavior of that expected over flat and homogeneous terrain: daytime velocity maximum and nighttime velocity minimum (Figure 4b). The São Paulo pattern does show a slight increase of daytime velocities until about 10:00 LT (Local Time), followed by a sharp decrease of velocities until about 13:00 LT, then a sharp increase of velocities, about 17:00 LT, and finally by a sharp decrease of velocities to about 06:00 LT.

The observed early-afternoon minimum wind velocity of Figure 4b, could be explained by the passage of a sea breeze front – formed from a SE sea breeze flow in combination with a weak prevailing north-northeasterly flow – which penetrates São Paulo (Figure 4d) often between 13:00 and 14:00 LT (Oliveira and Dias, 1982).

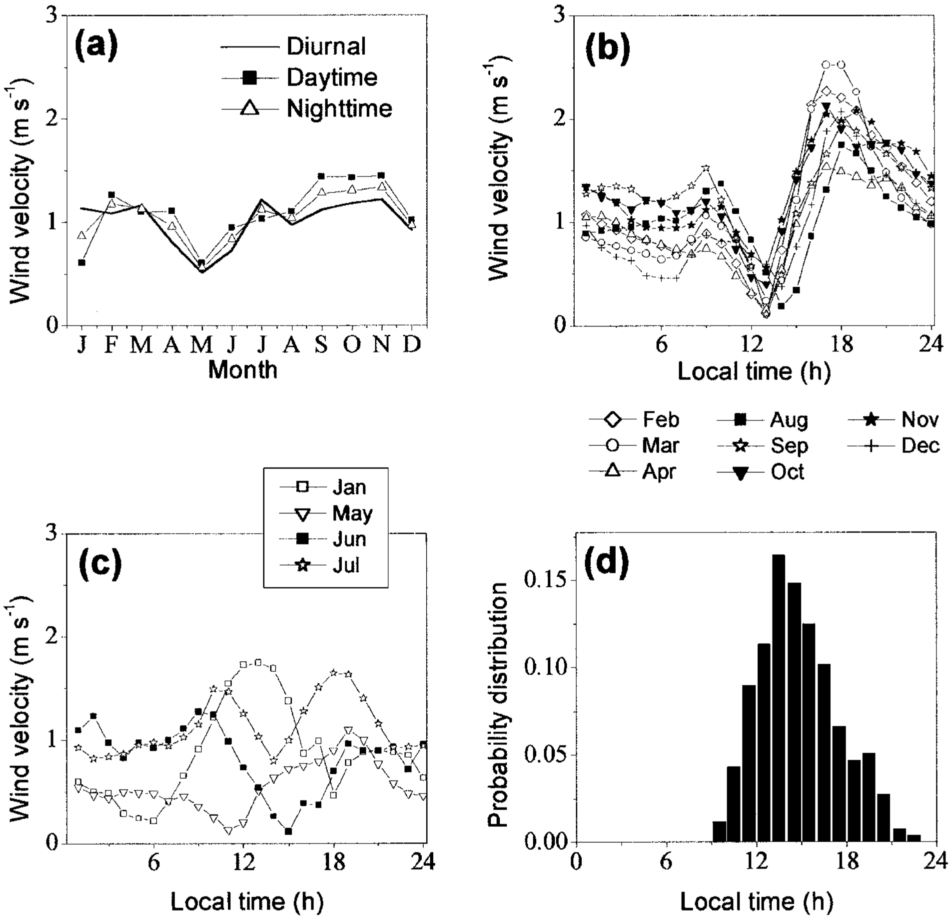

Figure 4. (a) Annual evolution of the area-averaged monthly mean surface horizontal wind velocity during the daytime period (daytime), night time (nighttime) and total (diurnal); (b) Diurnal evolution of the area-averaged hourly-mean surface horizontal wind velocity during the 'typical' months; (c) Diurnal evolution of the area-averaged hourly-mean surface horizontal wind velocity during the 'non-typical' months and (d) Probability distribution of sea breeze in São Paulo as a function of local time (Adapted from Oliveira and Dias, 1982).

The post-frontal SE flow being stronger than the pre-frontal northwesterly flow, explains the late afternoon maximum wind velocities in the figure. The pre-frontal flow can undertake two additional significant contributions, a vertical turbulent transport of upper level westerly momentum – due to diurnal planetary boundary layer (PBL) evolution – and the summer intensification of the continental stationary low pressure system ('Baixa do Chaco') located SW of São Paulo City (Garreaud and Wallace, 1998).

Looking at the four 'non-typical' months (January, May, June, and July), only the summer month (January) shows a significant daytime maximum, while the other three months show a midday minimum and late afternoon maximum of velocity (Figure 4c). June shows a wind velocity maximum in the early morning; May displays a lower velocity version of the typical São Paulo pattern and July presents an almost equal early morning and late afternoon peaks of velocity.

During January 1988, an El Niño year, the continental stationary low-pressure system was particularly strong at SW of São Paulo City (Salio *et al.*, 2000), altering the expected north-northeasterly flow into a northwesterly flow. The northwesterly flow is opposed to the SE sea breeze flow. The summer sea breeze therefore systematically penetrated later (about 16:00–18:00 LT) despite the normally large summer land-ocean thermal contrast. Even assuming a high PBL vertical extent during the summer months, the associated vertical mixing mechanism could not explain the large intensity of daytime NW flow observed in January 1988, because the upper level westerly flow velocities in this month was consistently below 2–3 m s^{-1}.

During winter, the land-ocean thermal contrast is less intense than during summer months and therefore the presence of the sea breeze is fewer and weaker in São Paulo City. However, due to the position of the Atlantic-Ocean High Pressure system – partially over the continental area – the prevailing flow is systematically from east, and under this condition the sea breeze fronts are less defined and tend to occur early in São Paulo. Although the upper level westerly flow, in this area, being stronger in the winter, it only offsets partially the SE sea breeze flow because the daytime PBL vertical extent, in this season, is shallow. These factors could explain the latter daytime minima in July (14:00 LT, Figure 4c) and June (15:00 LT, Figure 4c).

During the fall transition month (May), when both the prevailing north-northeasterly flow and the sea breeze are weakening, velocities are generally low throughout most of the day (Figure 4c).

During the spring transition (August–November) the land-ocean thermal contrast is intensified by the thermal inertia of the ocean and by the progressive intensification of the Continental Low-Pressure System (Garreaud and Wallace, 1998). The sea breeze also is stronger, more frequent and occurs early during these months. All these mechanism reinforce the SE flow observed during this period.

Most of the monthly domain-average hourly-mean wind hodographs have an elliptical shape, centered on a flow from the SE (Figure 5), consistent with an inertial-rotational sea-land breeze flow regime in the Southern Hemisphere. Transition month hodographs (May and June) still show sea breeze rotations but with reduced amplitudes. The winter month (July) presents a non-elliptical hodograph and its counter inertial direction of rotation is indicative of a non-sea breeze regime, i.e., vertical mixing due to PBL evolution, as discussed above, and probable local terrain-induced effects (discussed next in this section).

Topographic effects are not obvious in the previous velocity results because large scale and sea breeze frontal effects can mask them. These effects, however, are evident in the horizontal surface wind divergence analyses. The diurnal variation of domain-averaged hourly wind divergence, in São Paulo City, shows

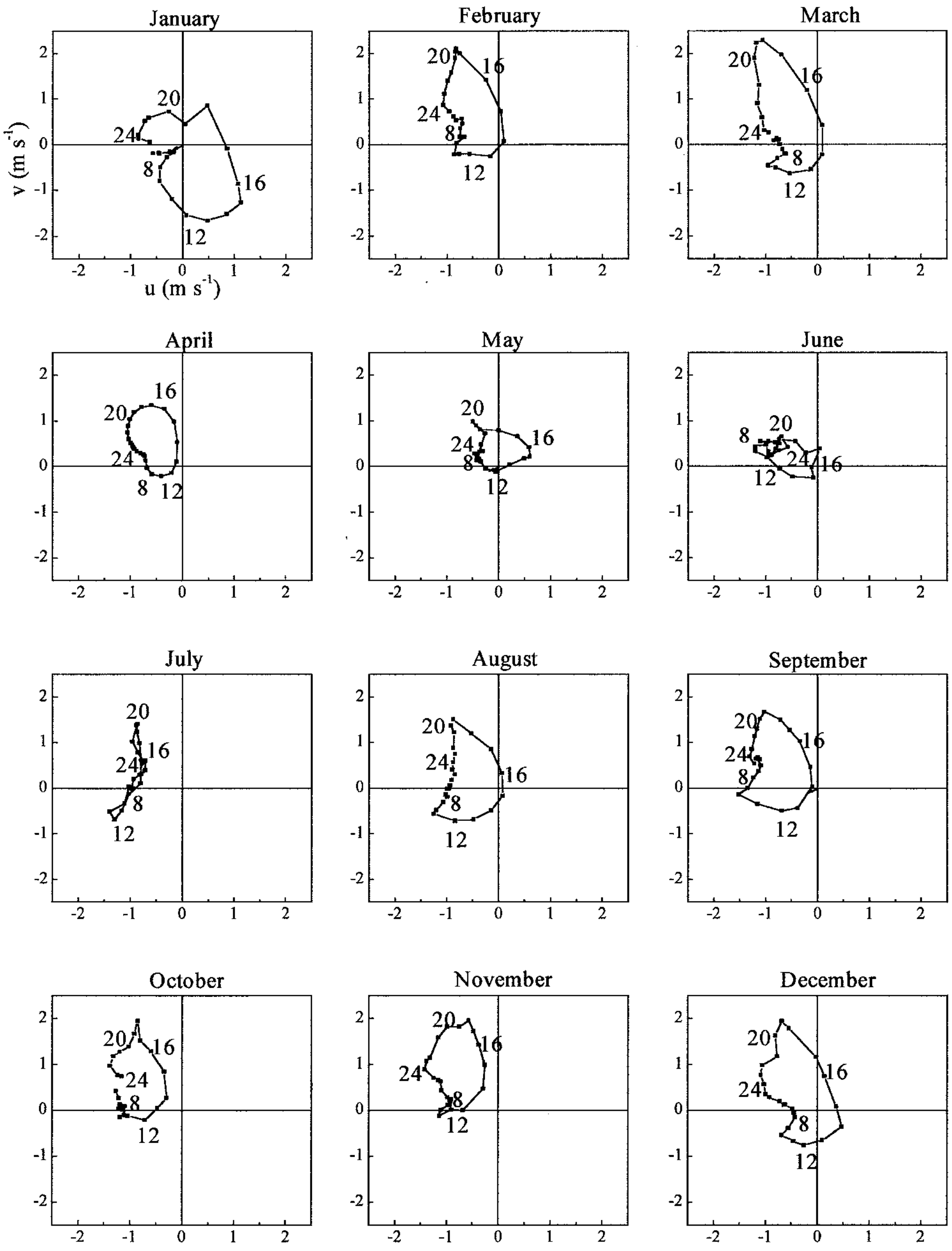

Figure 5. Surface wind hodograph for January to December 1988. Numbers indicate the local time.

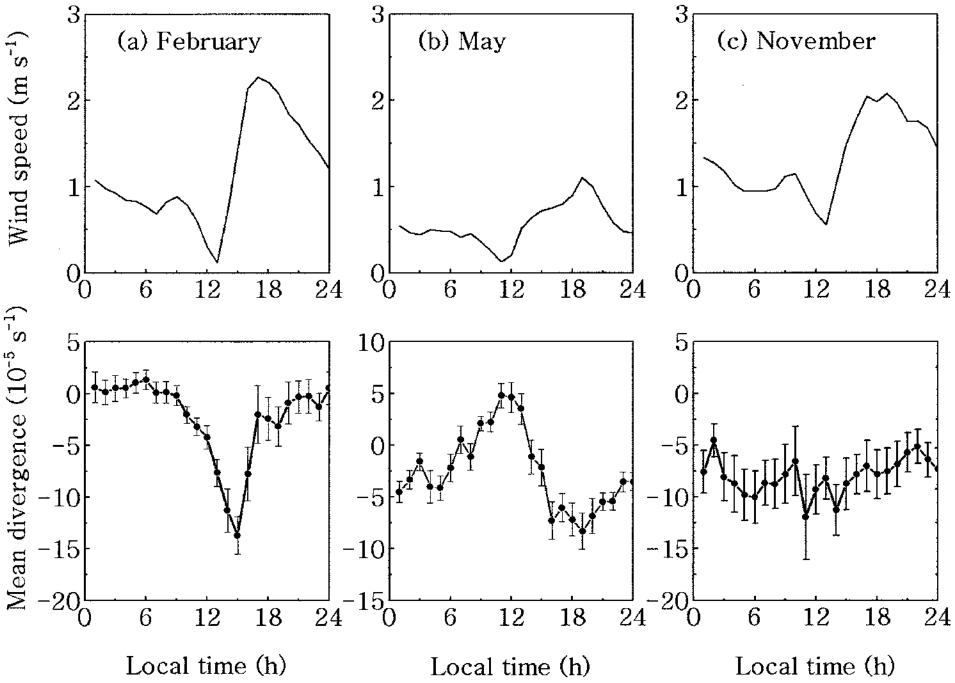

Figure 6. Diurnal evolution of the space and hourly averaged wind velocity (top) and wind divergence (bottom) over whole region of São Paulo in (a) February, 1988; (b) May, 1988; and (c) November 1988. The error bars indicate the standard deviation of the divergence average values.

basically three distinct patterns. The first one occurring during the summer months (December to March), the second one during fall and winter months (April to July) and the last one during spring period (August to November).

To illustrate the observed divergence patterns over the whole region of São Paulo City, the diurnal evolution of the space averaged wind speed and wind divergence are analyzed during the months of February, May and November, as representative of summer, fall-winter and spring months, respectively (Figure 6).

The summer months show a strong daytime convergence (maximum between 13:00 and 17:00 LT; Figure 6a, bottom), weak early evening convergence and near-zero nighttime divergence/convergence. The strong daytime convergence can be caused by the strong sea breeze flow (Figure 5), penetrating São Paulo City around this time (Figure 4d). This convergence is thus stronger than any daytime upslope divergent flow that might have been formed and moreover, a wet-season daytime UHI-induced centripetal circulation may have reinforced the convergence. The weak early evening convergence and its subsequent dissipation after midnight (Figure 6a, bottom) associated with low wind velocities (Figure 6a, top) could be indicative of a weak downslope convergence of cold air into the valley and the countering effects of a non-UHI urban barrier divergence effect.

Fall and winter months show strong divergence during the morning (maximum between 11:00 and 12:00 LT; Figure 6b, bottom), followed by an even stronger convergence during the afternoon (but not as strong as in summer) and at night with a maximum convergence at about 19:00 LT (stronger than in summer). The weaker afternoon convergence (relative to summer) is explained by the weaker sea breeze flow (Figure 5). During these colder and drier months (Figure 2), there is a combination of a stronger nighttime downslope (convergent) flow and an expected dry-season nighttime UHI convergent flow. A weak daytime upslope breeze may produce the observed late-morning divergence, but it may also be developed from the urban barrier effect.

Spring months show a continuous moderate convergence over the entire day, with afternoon values somewhat more pronounced because of the now stronger sea breeze compared to fall and winter months. This period shows relatively high nighttime wind velocities (Figure 6), as downslope mountain flow still extends daytime sea breeze convergence into the evening.

5. Conclusion

Results show that the circulation over the São Paulo City area is dominated by three major factors: (i) sea breeze, (ii) mountain-valley circulation and (iii) urban effects, such as roughness, building-barrier, and UHI effects. The sea breeze seems to be the dominant feature of the monthly-averaged diurnal variation of São Paulo City surface winds during the eight warmest months of the year. The sea breeze fronts induce a minimum velocity at the time of its passage – about 13:00 LT – and a post-frontal afternoon maximum velocity – at about 17:00 LT. The sea breeze also produces a strong convergence zone during its lifetime – between 12:00 and 18:00 LT – which moves from east to west across the city. Mountain-valley thermal effects on the flow are more easily seen in the temporal divergence/convergence patterns. These thermal effects tend to be more important during the colder months, at night, and when the wind velocities are low (<1.2 m s^{-1}). Over the city, nighttime downslope convergent flows are present during winter and spring months and daytime upslope divergent flows (are present) during summer months.

Urban effects on the flow are also more easily seen in the temporal divergence/convergence patterns. During higher velocity (>1.5 m s^{-1}), non-UHI periods (warm season days and cold season mornings and nights), the urban building-barrier effect induces a systematic urban flow divergence effect, as the air flows around the City, followed by a re-convergent downwind flow. Upwind urban roughness, inducing deceleration and convergence, seems to exist during fall daytime flow periods (non-UHI), while UHI induced convergent centripetal circulation over the City is observed during spring-summer daytime and fall-winter nighttime periods.

Given the complex interactions between the sea breeze, mountain-valley, and urban induced flows over the City of São Paulo, and given the inherent uncertainties of the divergence calculations, the current analyses should be extended for periods longer than one year. To separate out the complex interactions between topographic, land-sea, and urban influences on the São Paulo City, a series of numerical model simulations should be carried out, each of them excluding one or more of these potential causal factors (Stein and Alpert, 1993).

Acknowledgements

The first and third authors acknowledge the financial support provided by the 'Conselho Nacional de Desenvolvimento Científico e Tecnológico' and 'Fundação de Amparo à Pesquisa do Estado de São Paulo'.

References

Bornstein, R.: 1987: 'Mean Diurnal Circulation and Thermodynamic Evolution of Urban Boundary Layers', *Modeling the Urban Boundary Layer*, American Meteor. Soc., Boston, MA, pp. 53–93.

Bornstein, R. and Lin, Q.: 2000: 'Urban heat islands and summertime convective thunderstorms in Atlanta', *Atmos. Environ.* **34**, 507–516.

CETESB: 1988 'Relatório de qualidade do ar na região metropolitana de São Paulo e Cubatão', *Report*, CETESB-Secretaria do Meio Ambiente do Estado de São Paulo, São Paulo, pp. 137 (in Portuguese).

Dias, M. A. F. S. and Machado, A. J.: 1997: 'The role of local circulation in summertime convective development and nocturnal fog in São Paulo, Brazil', *Boundary-Layer Meteor.* **82**, 135–157.

Flohn, H.: 1969: 'Local Wind Systems', *World Survey of Climatology*, Vol 2, pp. 139–171.

Garreaud, R. D. and Wallace, J. M.: 1998, 'Summertime incursions of midlatitude air into subtropical and tropical South America', *Mon. Wea. Rev.* **126**, 2713–2733.

Garret, A. J. and Smith, F. G.: 1985, 'Average diurnal behavior of surface winds during summer at sites in complex terrain', *J. Climate Appl. Meteor.* **24**, 174–183.

Goodin, W. R., MacRae, G. J. and Seinfeld, J. H.: 1979, 'A comparison of interpolation methods for sparse data: Applications to wind and concentration fields', *J. Appl. Meteor.* **18**, 761–771.

Imamura, I. R.: 1991, 'Observational Studies of Urban Heat Island Characteristics in Different Climate Zones', *Ph.D. Thesis*, Inst. of Geoscience, University of Tsukuba, Japan, 156 pp.

Imamura, I. R., Nishizawa, T., Kobayashi, M. and Bornstein, R.: 1991, 'Preliminary Results from the Sacramento Urban Heat Island Study (SUSHIS)', *Proceedings of the 7th AMS Conf. On Air Pollut. Meteorology*, New Orleans, U.S.A., 14–18 January, pp. 318–319.

Jauregui, E., Godinez, L. and Cruz, F.: 1992, 'Aspects of heat island development in Guadalajara, Mexico', *Atmos. Environ.* **26B**, 391–396.

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.

Lombardo, M. A.: 1984, 'A ilha de calor da Metropole Paulistana', *Ph.D. Thesis*, Dept. Geografia, Universidade de São Paulo, Brazil, 270 pp. (in Portuguese).

Monteiro, C. A. F.: 1986, 'Some Aspects of the Urban Climates of Tropical South America: The Brazilian Contribution', in T. R. Oke (ed.), *Urban Climatology and its Applications with Special Regard to Tropical Areas*, WMO No. 652, World Meteorol. Organiz., Geneva, pp. 166–198.

Munn, R. E.: 1970, 'Airflow in Urban Areas. In Urban Climates', *WMO Tech. Note 108*, Geneva, pp. 15–39.

Oliveira, A. P. and Dias, P. L. S.: 1982, 'Aspectos Observacionais da Brisa Marítima em São Paulo', *Proceedings of the II Congr. Brasil. de Meteor.*, Pelotas, RS, Brazil, 18–22 October 1982, II, pp. 129–161, (in Portuguese).

Oliveira, A. P., Escobedo, J. F, Plana-Fattori, A., Soares, J. and Santos, P. M.: 1996, 'Medidas de radiação solar na Cidade de São Paulo: Calibração de piranômetros e aplicações meteorológicas', *Revista Brasileira de Geofísica* **14**, 203–216 (in Portuguese)

Oliveira, A. P., Machado, A. J., Escobedo, J. F. and Soares, J.: 2002, 'Diurnal evolution of solar radiation at the surface in the city of São Paulo: seasonal variation and modeling', *Theor. Appl. Climatol.* **71**(3–4), 231–249.

Plate, E. J.: 1995, 'Urban Climates and Urban Modelling: An Introduction', in J. E. Cermak, A. G. Davenport, E. J. Plate and D. X. Viegas (eds), *Wind Climate in Cities*, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 383–403.

Salio, P., Nicolini, M. and Saulo, C.: 2000, 'Low Level Circulation Characteristics during two Extreme Precipitation Regimes over South America', *Proceedings of the Sixth International Conference on Southern Hemisphere Meteorology and Oceanography*, Santiago, Chile, 3–7 April 2000, pp. 334–335.

Schwerdtfeger, W.: 1976, 'Climates of Central and South America', in *World Survey of Climatology*, New York, Vol. 12., pp. 1–12.

Shreffler, J. H.: 1978, 'Detection of centripetal heat island circulation from tower data in St. Louis', *Bound.-Layer Meteor.* **15**, 229–242.

Shreffler, J. H.: 1979, 'Heat Island convergence in St. Louis during calm periods', *J. Appl. Meteor.* **18**, 1512–1520.

Stein, U. and Alpert, P.: 1993, 'Factor separation in numerical simulations', *J. Atmos. Sci.* **14**, 2107–2115.

Vucovich, F. M.: 1971, 'Theoretical analysis of the effect of mean wind and stability on heat island circulation characteristics of an urban complex', *Mon. Wea. Review* **99**, 919–926.