VARIABILITY OF BOUNDARY LAYER PROCESSES FOR THE METROPOLITAN AREA OF SÃO PAULO DURING WINTER

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RESUMO

As variações espaciais e temporais da Camada Limite planetária (CLP) da Área Metropolitana da cidade de São Paulo (RMSP) durante o período de 23 de julho a 15 de Agosto de 1999 são estudas utilizando dados de um Sodar Doppler. RMSP (λ = 23º34' S e ϕ = 46º44' W) está numa altitude de 800 m acima do nível médio do mar, localizada 60 km à noroeste do oceano Atlântico, limitada por cadeias de montanhas ao norte, tendo uma orografia complexa e configura-se numa ilha de calor urbana.

Este trabalho tem o objetivo de entender o impacto da urbanização sobre os processos de CLP particularmente durante a estação

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de inverno. Um número de diferentes tipos de experimentos estiveram em operação durante uma campanha de inverno organizada pelo IAG-USP. O Sodar Doppler fornece dados sobre (i) função estrutura de temperatura, C_T^2, (ii) velocidade do vento horizontal, ***u,*** (iii) velocidade do vento vertical, w, (iv) desvios padrão do vento horizontal e vertical, σu, σv e σw, e (v) altura da inversão de temperatura, Z_i.

A análise dos dados fornecidos pelo Sodar mostra claramente as variações desses parâmetros em alturas indo de 50 m até 1500 m com intervalos de 50 m num intervalo de tempo de 15 minutos. Existe grande variação desses parâmetros com a altura.

O aumento noturno no campo do vento horizontal com a altura é bem marcado indicando a quase ausência de transporte vertical de momento horizontal durante a noite em condições estáveis. Durante as horas da manhã a aceleração na velocidade do vento é evidente. O aumento anormal em Z_i durante a noite sob condições estáveis prevalece durante o inverno com valores mais altos em agosto do que em julho.

1. INTRODUCTION

The city of São Paulo (MASP) is 800 m above mean sea level, 60 km northwest of south Atlantic Sea coast bounded by mountain ranges with complex orography. One of the climatic effects of urbanization is the increase in surface and air temperatures (Gallo and Owen, 1999). The term Urban Heat Island, is coined from the apparent similarity of isotherms to contours of elevation for an isolated island in the ocean. The intensity of an urban heat island depends on the size of the city and its energy consumption, geographical location, month or season, time of day, and synoptic weather conditions (Oke, 1973). The behavior of Urban Boundary Layer is well documented, which are briefed below. There are likely to be marked differences in the diurnal variations between winter and summer, related to the anthropogenic heat release, which need to the better documented for the MASP. Urban areas may have different roughness (mechanical, thermal, moisture and radiation) and thermal characteristics from their rural surroundings. The increased surface roughness affects both the vertical wind and temperature profiles. The urban plume rise and the circumferencial rural subsidence induce the urban heat island circulation. An increase in friction velocity induces veering (clockwise motion) where as higher temperature gradient promotes backing (anti clockwise motion) for the wind field. Enhanced surface friction turns the wind towards low-pressure side leading to cross-isobaric flow. The rural areas surrounding the city experience relatively high pressure with poor ventilation resulting from low temperature inversion and high stagnation. This results in higher level of pollution dumping from the urban atmosphere.

The communication aims at in understanding the general characteristics of PBL with particular emphasis to the time evolution of the depth of planetary boundary layer (PBL), Zi which is influenced by the scaling velocity, the surface temperature and sensible heat flux and other meteorological forcing during fully convective PBL conditions.

2. EXPERIMENTAL DATA

The SODAR (SOund Detection And Ranging) is a powerful tool for probing the PBL. In SODAR short pulses of acoustic energy at a particular carrier frequency (~ 2 kHz in our set up) are transmitted upward from an antenna (1.4 m x 1.4 m) emitting 10 W of acoustic power. Scattering of acoustic energy takes place from inhomogeneities in the acoustic refractive index within the scattering volume. These inhomogenities are caused by fluctuations in temperature, wind and humidity. The backscattered energy is received by the same antenna array. For vertical operation the backscattered signal strength depends almost totally on temperature turbulence and the radar gives information on the movement of the medium along the vertical direction. The Doppler shift of the carrier frequency of the return signal gives the wind speed along the axis of propagation (Little, 1969, Nair et al., 1989). The REMTECH Doppler SODAR at IAG, University of São Paulo (USP), situated in MASP, is a phased array (PA-2) version, capable of suppressing ambient noise to a certain extend and has capability to invalidate fixed echo returns. The transmit/receive antenna array consists of 196 Piezoelectric ceramic transducers (Motorola type 1025, tweeters) arranged in 14x14 square array. The received echo power is proportional to the temperature structure function, C_T^2 which is a measure of the strength of temperature turbulence in arbitrary units of $°C^2\ m^{-2/3}$. The radial speeds are obtained for height ranges from 50 m to 1500 m at steps of 50 m sampled for every transmission/reception cycle along the beam axis. There is a provision for other options as well, based on the requirements. The SODAR electronically generates five beams namely along the vertical and tilted 30° from the vertical along, north, east, south and west. Using mathematical coordinate transformation the sodar system provides, the horizontal wind speed, U wind direction, ϕ standard deviation of wind direction, $\sigma\phi$ vertical wind, W the standard deviations of the vector winds σu, σv, σw and compiled values of inversion height/ mixing height, Zi (Freitas et. al., 1999). For 15 minutes averaging periods, the maximum range attainable is 1500 m, which is decided by the pulse repetition period. Also available are the stability of PBL (stability in five gradations namely (1 and 2) stable, 3 neutral, (4 and 5) unstable).

3. TEMPORAL AND SPATIAL VARIABILITY OF PBL PROCESSES FOR MASP

Figure 1 shows the time variation of the depth of PBL, Zi for the period from July 23, 1999 to August 14, 1999 spaced at 15 minutes interval, derived from the Doppler Sodar. During the period from August, 1 to August, 15 various experiments were conducted to understand the level of pollution at MASP in a well-coordinated manner. It can be seen that during daytime convective condition there are events when the Z_i values are more than even 1.5 km. It is seen that on an average the depth of stable boundary layer during nighttime is as high as 200 m for July 1999 and 300 m for August 1999. The abnormal enhancement in Z_i during night stabile condition is associated with enhanced surface heating, relatively cloud free sky during nighttime and advective motion associated with discontinuity of nighttime cooling. It is reported that during calm clear nights, cities can be hotter than the surrounding rural areas. Hilder Brand and Ackerman (1984), from aircraft based measurements have reported that the urban heat flux can be as high as 2 to 4 times compared to nearby rural areas, which is probably a major factor for the enhanced depth of stable layer seen. Light absorption by aerosol particles like black carbon has a heating effect in the atmosphere, which contrasts with the cooling effects by non-absorptive particles. The balance between the cooling and heating effects depends on the absorption and scattering properties of the particles. Smoke particles produced by biomass burning have significant fraction of light absorption material composed of black carbon particles (Martin et al, 1998). Compared to July months, August months are seen to have higher level of pollution with particles size less than 10 μ for MASP.

Figure 2 shows the time variation of the surface temperature for the period from July 23, 1999 to August 14, 1999 spaced at every 30 minutes interval (for São Paulo). Temperature maximum (θmax), temperature minimum (θmin) and the daily temperature range, ($\Delta\theta$) defined by (θmax - θmin) are known to the indicative of the buoyant thermal status of PBL and figure 2 gives indications of their relative contributions to the height of temperature inversion, Zi seen in figure 1.

Figure 3 gives the time variation of temperature structure parameter, C_T^2 in arbitrary units of $^oC^2\ m^{-2/3}$ for the period from July 23, 1999 to August 15, 1999 for the heights 100 m (well in the surface layer), 300 m and 500 m (in the mixed layer). In general, even amidst large variability, well-defined daily variation in C_T^2 is often seen during July compared to August. This feature is seen better at 500 m compared to 300 m and 100 m altitudes. A well-defined weekly periodicity is marked in C_T^2 with the recurrence of mesoscale cold front events and associated cloudiness.

Temporal variations in zonal wind are important to PBL dynamics. Figure 4 gives the temporal and spatial variations of the zonal wind, u computed from horizontal wind speed and direction. There is predominance of easterly flow mostly associated with sea breeze. Large variability due to strong wind shear during August, 1999 severely mask the periodicities seen during July, associated with the repeated recurrence of the cold fronts on July 27, August 7 and August 15, 1999. The predominance of westerly shift in the zonal wind from August, 13 onwards is well marked. Progressive logarithmic enhancement in zonal wind from 100 m to 500 m through 300 m is any way expected.

Figure 5 gives the spatial and temporal variations of the meridional wind, ***v*** computed from Doppler Sodar derived horizontal wind speed and direction for MASP for three heights at 100 m, 300 m and 500 m. The cold front signatures on July 27, August 7 and 14, 1999 are clearly seen with strong southerly winds at all the three levels. Certain periodicities are seen during July 1999 same as that for the zonal wind seen in figure 4.

The standard deviations (square root of the variance) of the zonal wind component, σu (Figure 6) has an average value of $\sim$ 1.5 m s^{-1} at 100 m, 2.0 m s^{-1} at 300 m and $\sim$ 3.0 m s^{-1} at 500 m. A well marked periodicity in σu over riding throughout July and August for all the three levels, is significant. The near logarithmic enhancement in wind variance from 100 m to 300 m is expected.

The standard deviations of the meridional wind σv at 100 m, 300 m and 500 m (Figure 7) show similar features as that of σu but for their mean value. Here the average value of σv is nearly 1 ms^{-1} at 100 m, 1.5 ms^{-1} at 300 m and 2 ms^{-1} at 500 m.

The standard deviations of vertical wind, σw (Figure 8) show interesting features. There is similarity between σw and C_T^2 seen in figure 3. At 100 m level σw has an average value of 0.3 ms^{-1}, which accelerated to 0.6 at 300 m and 0.8 ms^{-1} at 500 m. Detailed studies are in progress to establish the parabolic relationship seen between C_T^2 and σw through proper dimensional analysis.

4. DISCUSSION

In this communication we examine the basic Sodar derived data for the boundary layer over Sao Paulo City recorded for the first time. The semi-processed data together with the preliminary results arrived at have special significance. This is because, Doppler Sodar probing of PBL and the atmosphere above, is part of a well conceived, planned and conducted winter schedule experiments on pollution monitoring, radiation measurements, dynamical meteorology matched with sophisticated modeling. The turbulent state of PBL depends on the microscale thermal agitation, mechanical forcing over the rough surface, eddy diffusivity variations including that due to humidity fluctuations and radiative effects.

The effect of urbanization, well defined as heat island and available details in literature matches, with the enhanced depth of PBL for MASP. The non-linear processes through which C_T^2 is related with σw is very clearly seen. This has far reaching implication in PBL dynamics because C_T^2 is derived from the intensity of backscattered acoustic signals which in turn depend on the number of turbulent eddies available at appropriate height where as σw depends on the vertical movements of these eddies and consequent Doppler shifts. The remarkable matching of the scalar parameter

C_T^2 and the vector counterpart σw are of great interest both on theoretical studies and modeling point of view.

Eventhough meteorological processes are by and large aperiodic for time scales under consideration, it is seen, that atmospheric circulations in the PBL are modulated by sources having definite periodicities.

The mechanical turbulence seen through the variances of σu and σv shows definite periodicity which has implications to eddy diffusivity and hence pollution meteorology.

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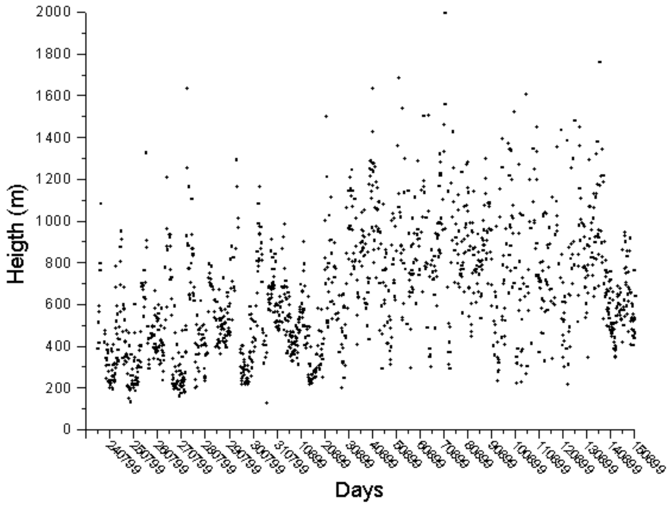


Figure 1: Sodar derived inversion height showing the evolution of PBL,over São Paulo for the period from 23/07/1999 to 15/08/1999.

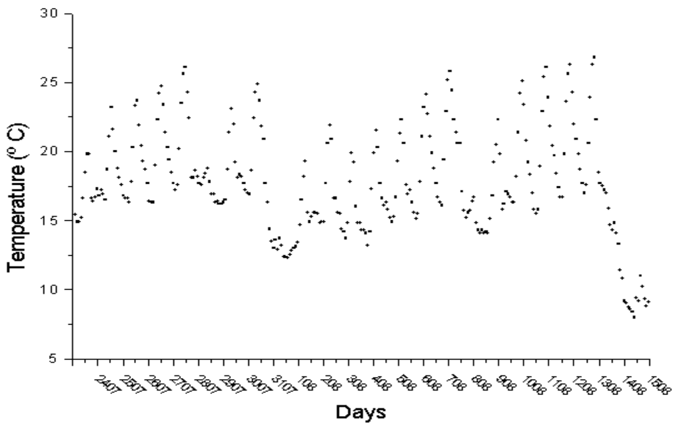


Figure 2: Time variation of the surface temperature for July 23 to August 15, 1999, for MASP.

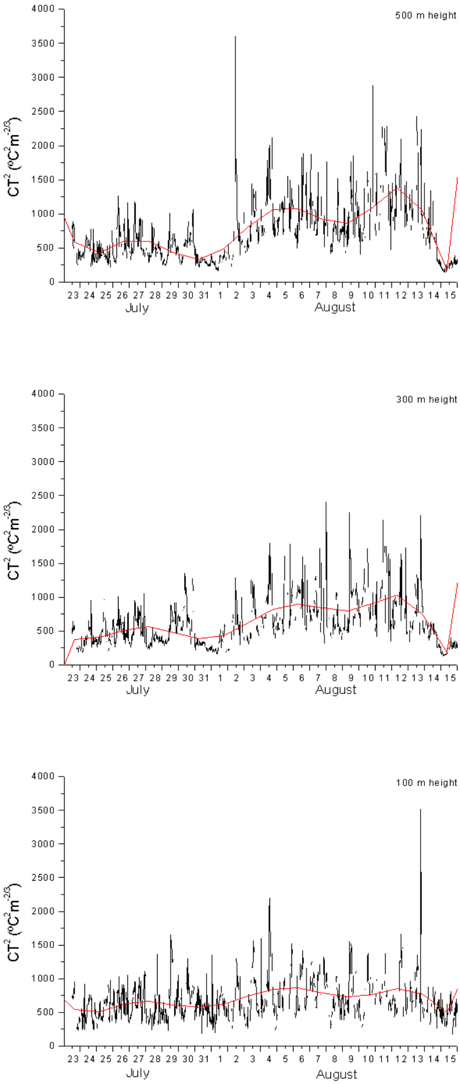


Figure 3: Time variation of temperature structure function, CT^2 at 100 (m), 300 (m) and 500 (m) for MASP during July to August 1999.

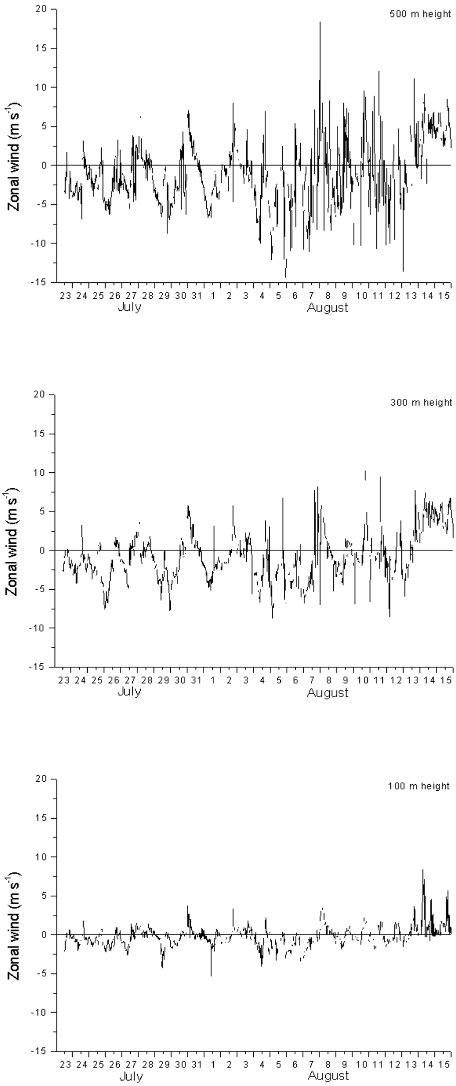


Figure 4: Time variation of zonal wind, ***u*** at 100 (m), 300 (m) and 500 (m) for MASP during July to August 1999.

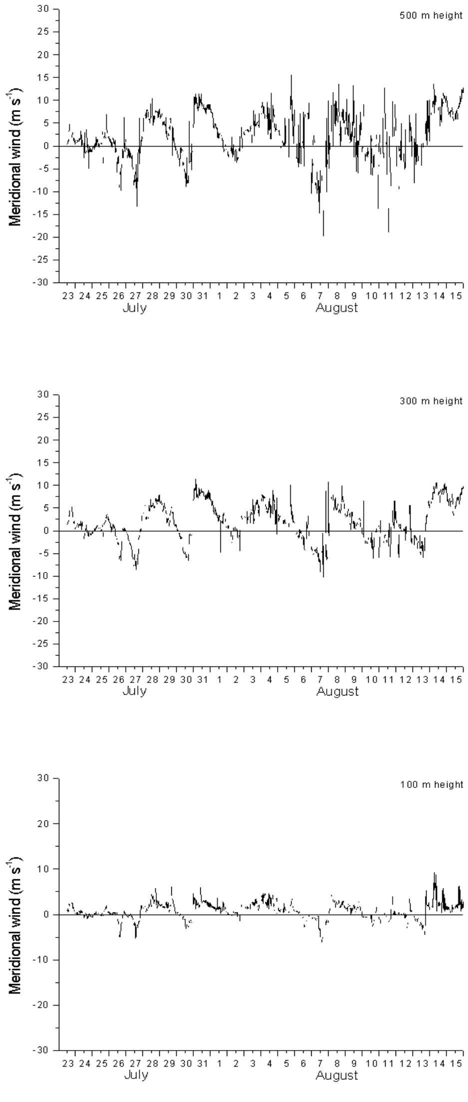


Figure 5: Time variation of meridional wind, ***v*** at 100 (m), 300 (m) and 500 (m) for MASP during July to August 1999.

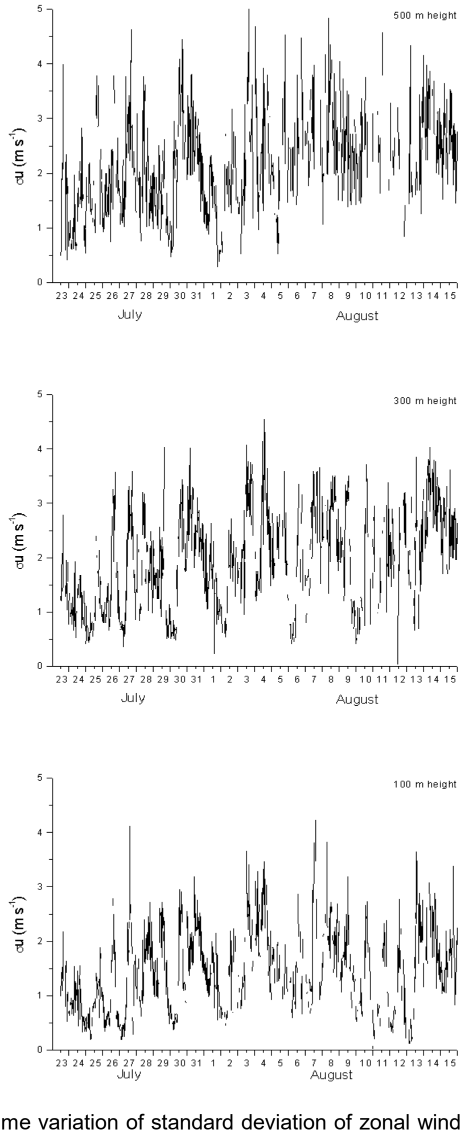


Figure 6: Time variation of standard deviation of zonal wind, σu at 100 (m), 300 (m) and 500 (m) for MASP during July to August 1999.

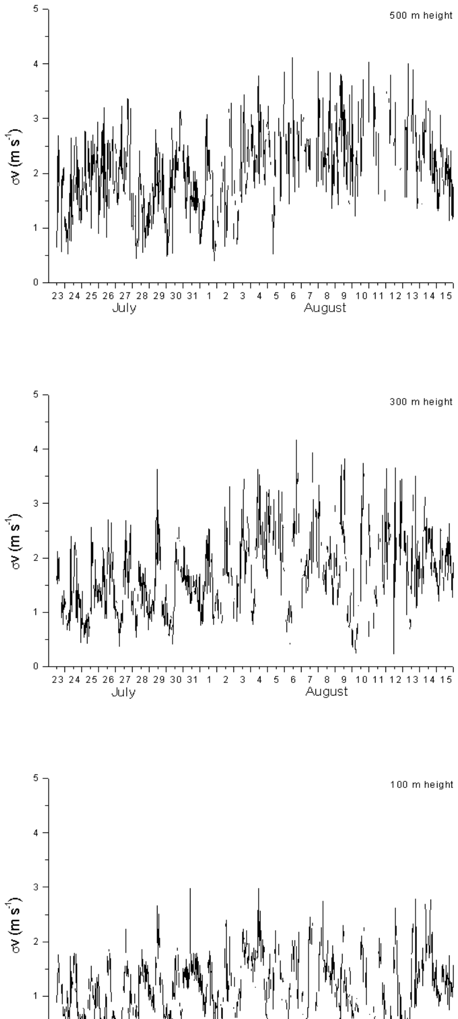
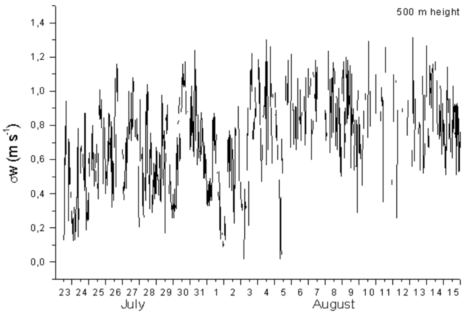
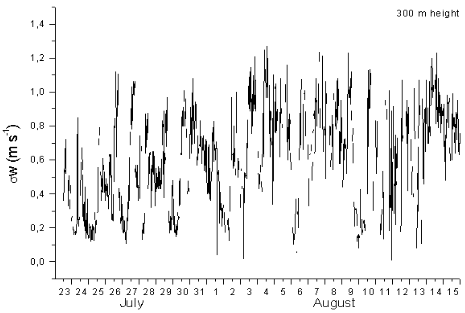


Figure 7: Time variation of standard deviation of meridional wind, σv at 100 (m), 300 (m) and 500 (m) for MASP during July to August 1999.





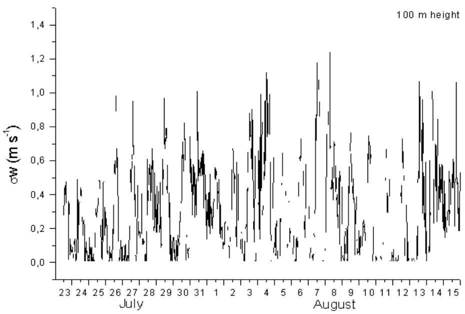


Figure 8: Time variation of standard deviation of vertical wind, σw at 100 (m), 300 (m) and 500 (m) for MASP during July to August 1999.