# NUMERICAL INVESTIGATION OF THE PBL MOISTURE CONTENT IN THE CITY OF SÃO PAULO USING LES

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**RESUMO:** Um modelo LES foi utilizado para simular a evolução temporal da camada limite urbana representativa da região metropolitana de São Paulo durante um ciclo diurno. Perfis de radiossondagens médios e medidas de temperatura e umidade na superfície durante o mês de junho foram utilizados como condições iniciais e de contorno. A simulação numérica mostra uma CLP com dimensões compatíveis com estimativas de LIDAR e fluxos apropriados. Os perfis verticais das variâncias e covariâncias entre umidade especifica, componentes do vento e temperatura potencial simulados numericamente obedecem à Teoria de Similaridade da Camada de Mistura.

**ABSTRACT:** A LES model was used to simulate the time evolution of the urban boundary layer representative of the metropolitan region of São Paulo for a complete diurnal cycle. Mean radiosonde profiles and measurements of air temperature and specific humidity observed at the surface during June were used as initial and boundary conditions. The experiment shows a PBL with dimensions compatible with LIDAR estimations and appropriate fluxes. The vertical profiles of variances and covariances of specific humidity, wind components and potential temperature determined numerically obey the Mixed Layer Similarity Theory.

## 1 – INTRODUCTION

Even though it just represents 3% of the territory of the state of São Paulo, the metropolitan region of São Paulo (MRSP) increased from 874 m² to 2.209 m² between 1962 and 2002 and currently houses 10% of the Brazilian population (about 19.7 millions of residents). An understanding of the microclimate of the MRSP is essential, though, both for the regional economical development and for assure the air quality in what is one of the four most populous cities in the world (www.emplasa.sp.gov.br).

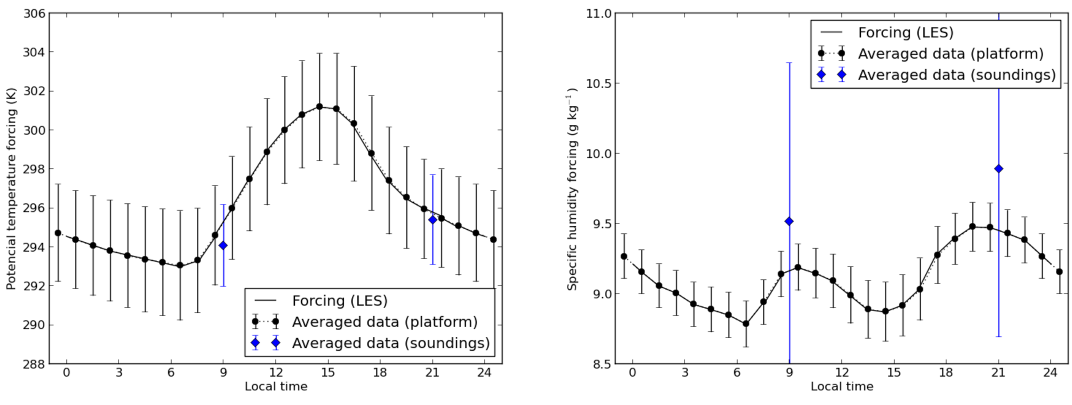
The urban effects on the wind patterns in São Paulo can be attributed to topography, surface roughness, barrier effects and to the urban heat island intensification (Oliveira *et al.*, 2003). Although São Paulo is at an altitude of 770 m above sea level and at a distance of 60 km from the ocean, the sea breeze penetrates the city in more than 50% of the days of the year (Oliveira *et al*., 2003). Sea breezes and cold fronts are responsible for a considerable inflow of moisture in the São Paulo's Planetary Boundary Layer (PBL), enhancing turbulent convection and altering the energy balance at surface.

The objective of this work is to use LES (large-eddy simulation) modeling to investigate the behavior of moisture in the MRSP's PBL considering as reference the winter conditions, when the local climate is dry and mild cold (Ferreira *et al.*, 2010). Numerical investigation of the PBL using LES model consist in direct simulations of the more energetic turbulent vortices and in the parametrization of the dissipative turbulent eddies. The advantage of LES models in relation to Reynolds-averaging models is that they are less dependent on the parametrization scheme adopted.

## 2 – DATA AND ANALYSIS METHOD

A numerical LES experiment of a diurnal cycle for the month of June was carried out. The simulation domain consists of a square box with $96^2 \times 192$ grid points and dimensions of $5.0^2 \times 2.0$ km³. The surface is characterized by a constant aerodynamic roughness length of 0.5 m.

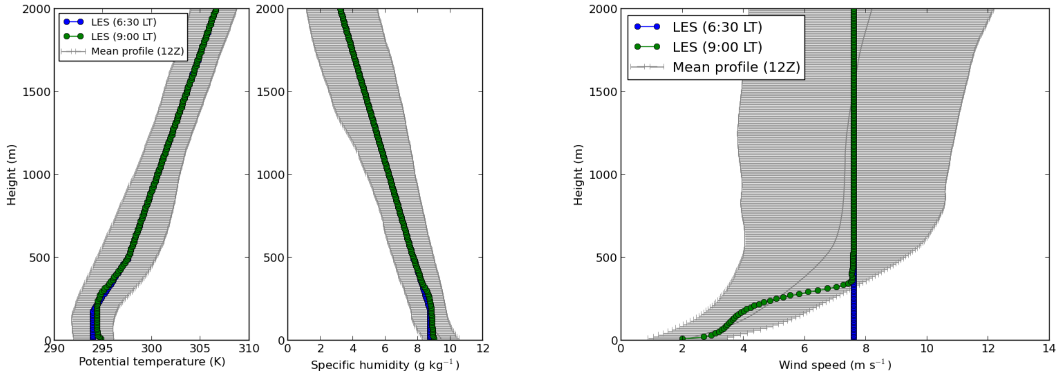
The study used data of specific humidity and potential temperature as lower boundary conditions, sampled on the micrometeorological platform at IAG-USP (solid lines in Figure 1), and mean interpolated vertical profiles as initial condition, taken at Campo de Marte airport station, among 2004 and 2010 (Figure 2).




(a) (b)

**Figure 1:** Hourly evolution for the month of June of **(a)** potential temperature and **(b)** specific humidity, both taken on the micrometeorological platform at IAG-USP (points). The average of radiosondes are indicated by blue diamonds. The solid lines represent forcings used in the numerical experiment.

The evolution of specific humidity shows two peaks: the first, with a maximum at 9:30 LT (9.2 g kg$^{-1}$), is related to the intense evaporation occurring in the early morning hours, followed by a decrease due to the entrainment of dry air when the PBL is growing fastly; the other peak, at 19:30 LT (9.5 g kg$^{-1}$), is related to the arrival of the sea breeze in the early afternoon (Oliveira *et al.*, 2003).



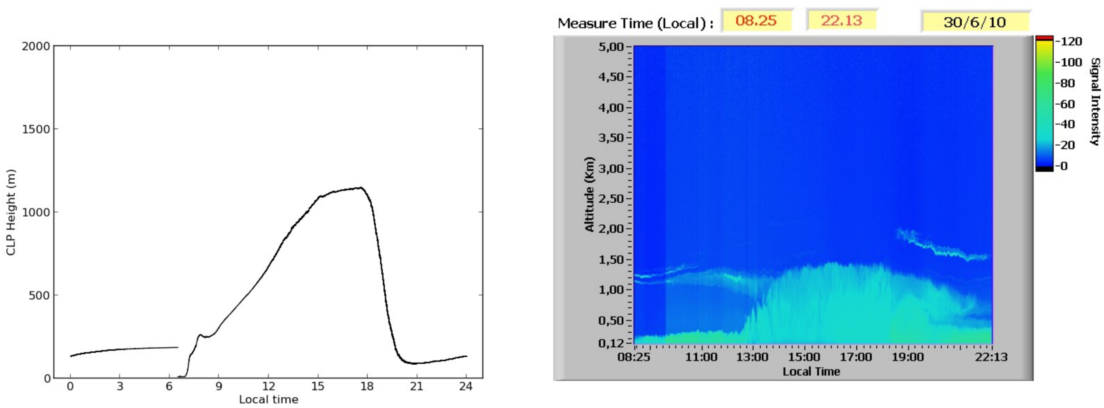

**(a)** **(b)**

**Figure 2:** Vertical profiles of **(a)** potential temperature, specific humidity and **(b)** wind speed. The solid lines represent the averages of interpolated radiosondes (with their uncertainty bars). The points represent the profile in the experiment started at 6:30 LT and at 9:00 LT (local time).

## 3 – RESULTS

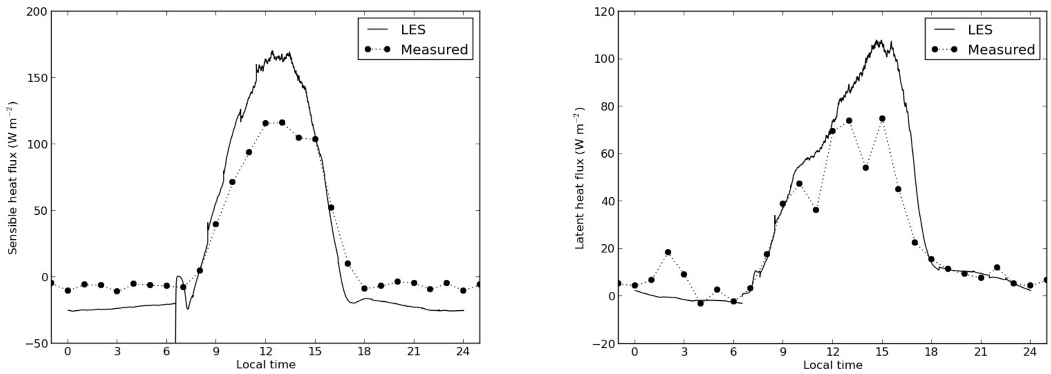
The PBL height evolution in the experiment can be seen in Figure 3. At the end of convective regime, the PBL has reached a maximum height of 1149 m. The night period is characterized by a stable boundary layer (SBL) with about 180 m of extension. This result is consistent with estimates by LIDAR at the Institute of Nuclear and Energy Research, USP (Figure 3b).

The surface fluxes are presented in Figure 4 for June of 2010. They correspond to monthly averaged values taken with sample frequency of 10 Hz at the University of São Paulo *campus*.




**(a)** **(b)**

**Figure 3:** Diurnal evolution of **(a)** the PBL height in the LES model experiment and **(b)** the aerosol layer observed with LIDAR on June 30, 2010 (Landulfo *et al.*, 2010).

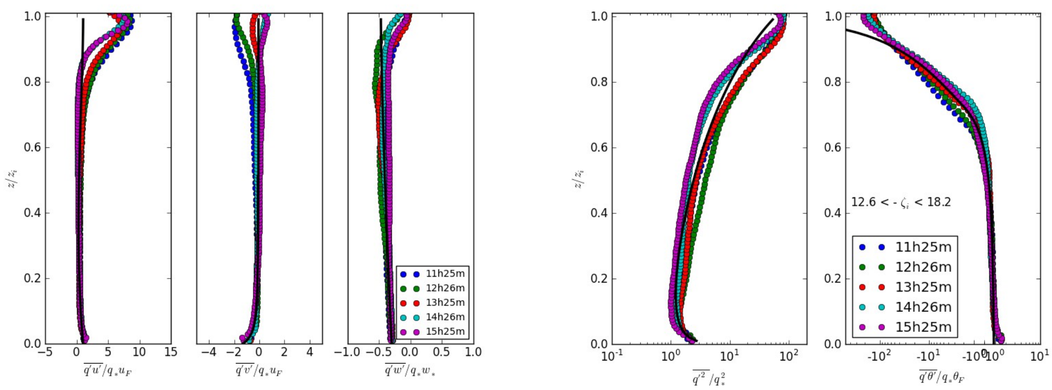



**(a)** **(b)**

**Figure 4:** Comparison of diurnal cycles in the experiment (solid line) and measured in the micrometeorological platform of IAG-USP (hourly averages for June 2010) of **(a)** sensible heat flux and **(b)** latent heat flux.

For the sensible heat flux, the model shows a tendency to overestimate the absolute value of the measured flux, this overestimation being approximately of 50% during the day. At night, the LES model generates a negative sensible heat flux of about 20 W m$^{-2}$ against a practically null observed flux. As for the latent heat flux, the major discrepancies, which occur during the afternoon, are related to the increasing values of specific humidity at surface (Figure 1b) caused by the arrival of the sea breeze. Because there's no humidity entering or leaving the numerical domain, the model accounts for this increase in humidity by generating a vertical flux that's not real. The additional latent heat flux (of order 30-50 W m$^{-2}$) can be interpreted as the rate of increase of humidity caused by the entrance of the sea breeze in the MRSP.

Following the ideas presented in Sorbjan (1986), the vertical profiles of variance and covariance of specific humidity, potential temperature and wind components simulated numerically during




**(a)** **(b)**

**Figure 5:** LES vertical profiles on free convective regime for **(a)** $\overline{q'u'}, \overline{q'v'}, \overline{q'w'}$, **(b)** $\overline{q'^2}$ and $\overline{q'\theta'}$ normalized by $\theta_F$, $u_F$, $w_*$ e $q_*$.

the convective regime were normalized in terms of characteristic scales of Mixed-Layer ($w_*$ for convective velocity), Free Convection ($u_F$ for velocity, $\theta_F$ for potential temperature*)* and Monin-Obukhov Similarity Theory ($q_*$, specific humidity). The normalized profiles are indicated in Figure 5. The interpolated expressions for the curves are listed in Table 1. Future observations are needed to verify the validity of these profiles.

**Table 1:** Dimensionless profiles (and adjusted $R^2$ coefficients) of variance and covariance of specific humidity, wind speed component and potential temperature simulated by LES model during convective regime ($12.6 < -\zeta_i < 18.2$) in the MRSP. These expressions where obtained considering just points in the first 80% portion of the mixed-layer.

| | | |
|---|---|---|
| $\overline{q'u'}/q_* u_F = \phi_{qu}(z/z_i)$ | $\phi_{qu}(z/z_i) = 1.04 - 4.5(z/z_i)(1 - z/z_i)^{1.76}$ | $R^2 = 0.32$ |
| $\overline{q'v'}/q_* u_F = \phi_{qv}(z/z_i)$ | $\phi_{qv}(z/z_i) = -1.3(1 + z/z_i)^4 (1 + 17z/z_i)^{-2}$ | $R^2 = 0.50$ |
| $\overline{q'w'}/q_* w_* = \phi_{qw}(z/z_i)$ | $\phi_{qw}(z/z_i) = -0.47 + 0.17(1 - z/z_i)^{1.4}$ | $R^2 = 0.52$ |
| $\overline{q'^2}/q_*^2 = \phi_{qq}(z/z_i)$ | $\phi_{qq}(z/z_i) = 0.35(z/z_i)^{-0.44}(1 - \alpha z/z_i)^{-3.2}$ | $R^2 = 0.74$ |
| $\overline{q'\theta'}/q_* \theta_F = \phi_{q\theta}(z/z_i)$ | $\phi_{q\theta}(z/z_i) = 0.96 - 0.09(1 - z/z_i)^{-2.7}$ | $R^2 = 0.86$ |

## 4 – CONCLUSIONS

With mean profiles as initial conditions and averaged measurements at surface as forcings, a simulation of 24 hours with LES model was performed to represent the general conditions of the PBL of the MRSP in winter conditions. In this experiment, a well-developed mixed layer reached a maximum height of 1149 m at 18:00 LT, and a SBL of about 180 m during the night.

Comparisons of profiles and fluxes estimated in the experiment with observational data showed that the model is able to reproduce what is observed on clear-sky days in the MRSP. Furthermore, it was observed that the profiles of variances and covariances involving moisture fluctuations could be expressed in terms of similarity scales already present in the literature.

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