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INVESTIGATION OF THE TRANSPORT OF POLLUTANTS FROM THE METROPOLITAN AREA OF SÃO PAULO AND FROM THE INDUSTRIAL CITY OF CUBATÃO TO NEARBY AREAS

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Abstract: The mesoscale meteorological model BRAMS and the Lagrangian dispersion model SPRAY were used to discuss the transport of pollutant inside, between, and nearby the Metropolitan Area of São Paulo and Mogi Valley, at an industrial town from Cubatão city. The acceptable agreement between simulated and measured data showed the models skill to represent meteorology and air pollution dispersion in these areas. Two winter episodes were studied and, in general, the local emissions dominated the local air quality levels, although transport was significant to some localized places.

Key words: *São Paulo air Pollution, Cubatão air pollution, Dispersion Modeling, SPRAY, BRAMS*

INTRODUCTION

The Metropolitan Area of São Paulo (MASP) has more than 20 million inhabitants and above 7 million vehicles. In the coast, 40 km farther, there are a strong industrial city, named Cubatão, with 23 big industrial plants and tenths of small and middle size ones. In the winter of 2006 an experiment was conduced in these areas, collecting the fine and coarse atmospheric aerosol in four stations, every 12h, for one week (Gioia, S., 2006). One stations was in a small city, Juquitiba, a remote border area of the MASP, rounded by native vegetation, other was slightly more inside the MASP area, another in an almost central point of the MASP, and the lat one at the industrial area of Cubatão. Samples was analyzed by PIXE and ID-TIMS, respectively to identify chemical elements (atomic number>10) and Pb isotopes concentrations and ratios, to characterize the aerosol, to study they sources and to get some information of pollutant transport among the sampled areas. In the present work, we used the mesoscale atmospheric model BRAMS and SPRAY, a Lagrangian Stochastic Model (LSM), to improve the discussion about pollutant dispersion in and around the area of this experiment. An inventory of the particulate emitted by five fertilizer plants from Cubatão, and, of the CO emitted by the vehicular fleet from MASP, was used in the simulations, providing reliable concentrations values and images for the pollutant transport during two winter episodes for PM_{10}.

METHODS

The modeling system BRAMS & SPRAY

The LSM SPRAY basis and development (ENEL, ICG/CNR, and Arianet) are described by Tinarelli et al. 1994 and 2000, among other references. It uses the generalized Langevin equation to simulate the dispersion of inert gases; the key input is the Eulerian PDF of the turbulent velocities, used in the corresponding Fokker-Planck equation to determine the value of the drift coefficient of the Langevin equation. In this work, for instance, the Gram-Charlier PDF truncated to the third order moment was used in the vertical, and in the horizontal direction the PDF was Gaussian.

The meteorological parameters needed by SPRAY were provided by BRAMS (Brazilian developments on the Regional Atmospheric Modelling System-RAMS), version 4.2 (Fazenda et al. 2007). It is a shared development of ATMET, IME/USP, IAG/USP, and CPTEC/INPE, with the aims of provide a new RAMS version, improved for tropics. Historical development and theoretical basis for BRAMS is well described in BRAMS, 2013.

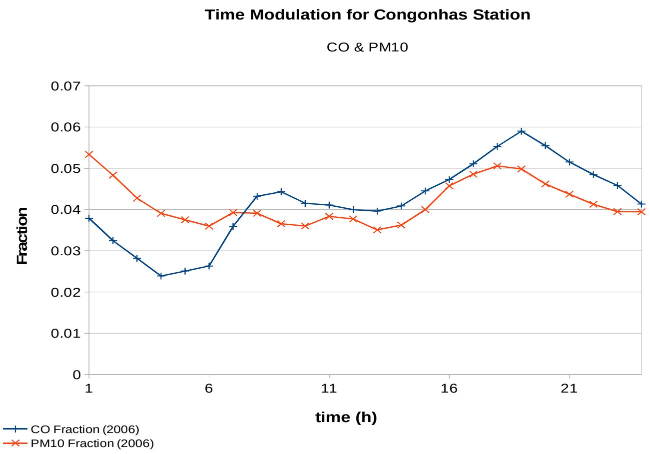

Figure 1. Time modulation for CO and PM_{10} concentrations at Congonhas' Station in 2006. They showed a good correlation. An assumption used in the work was that CO to PM_{10} ratio at Congonhas (40.7) was a first approximation of this vehicular emission ratio at MASP.

Table 1. Resolution and boundary conditions for simulation areas

Grid	Grid center (lat/Lon)	Grid resolution (m)	Grid area (Km x Km)	Latitude limits (deg)	Longitude limits (deg)
1	23.077^{0}S / 46.345^{0}E	12000	456 x 456	20.985^{0}S - 25.141^{0}S	48.579^{0}W - 44.049^{0}W
2	23.293^{0}S / 46.342^{0}E	3000	403 x 360	22.231^{0}S - 24.344^{0}S	47.713^{0}W - 44.949^{0}W
3	23.714^{0}S / 46.615^{0}E	1000	346 x 267	23.284^{0}S - 24.143^{0}S	47.199^{0}W - 46.028^{0}W

Table 2. Meteorological and/or CO measuring Stations

Station Number	Station Name	Latitude (S, Degree)	Longitude (W, Degree)
1	Ibirapuera	23.591	46.629
2	Cubatão Centro	23.879	46.418
3	Cubatão Vale do Mogi	23.832	46.37
4	Cubatão Vila Parisi	23.849	46.388
5	Pinheiros	23.561	46.702
6	Santo Amaro	23.655	46.71
7	São Caetano	23.617	46.556
8	São José dos Campos	23.187	45.871
9	Osasco	23.527	46.792
10	Sorocaba	23.502	47.479
11	Santo André	23.646	46.536
12	Pedro II	23.544	46.66
13	Taboão da Serra	23.609	46.758
14	IAG	23.649	46.625

BRAMS uses a two ways nesting procedure, allowing coherence between large to small grids data processing. Three nested grids were used in this case (Table-1) to simulate meteorological parameters in the areas studied, between days 23 and 29 August 2006. The model was initialized with CPTEC (Centro de Previsão de Tempo e Estudos Climáticos, a Brazilian Weather Forecast Center) global files (time resolution of 12h, and Lat-Lon resolution of 0.9375º, with 28 vertical levels).

SPRAY simulated the dispersion of the CO emitted by the MASP's vehicular fleet using the meteorological data from Grid-2 (3 km resolution). In the other hand, the transport of PM_{10} emitted by 5 Fertilizer Plants at Cubatão, a complex terrain area, was analyzed using the better resolution (1 km) of Grid-1 (sources' position and emission rates at Kerr et all., 2000). The CO vehicular area emission at MASP, with 5 km² resolution, was estimated considering the fleet composition and traffic flow, estimated by Kerr, A., et al., 2005, for the year 2000 at MASP (a total of $1.69x10^6$ $t.y^{-1}$). A reduction factor of 1.5 was applied considering 2000 to 2006 CO concentrations ratio at Congonhas' station (CETESB, 2001 and 2007). The time modulation of CO concentrations was also associated to the pattern observed at this station in the year 2006 (Figure 1). An assumption was that this station is representative of the vehicular CO emission, because it is very close to a typical high traffic MASP avenue. In the same way, the CO to PM_{10} average ratio at this station in 2006 (40.7) was taken as representing, in a first approximation, the vehicular CO to PM_{10} concentration ratio at MASP in this year.

Arianet provided GAP (Grid Adaptator) and SurfPro softwares to adapt the simulated BRAMS' meteorological data grid for SPRAY and, added to USGS landuse data, evaluate also the turbulence information to be used by SPRAY

RESULTS AND ANALYSIS

Statistical comparisons for Meteorological and Pollutants dispersion simulations

Table 2 shows the position of 13 stations from the São Paulo State environmental agency (CETESB, 2007), measuring air pollutants and/or meteorological parameters, and one meteorological station from the Institute of Astronomy, Geophysics and Atmospheric Sciences of the University of São Paulo – IAG. Meteorological and/or CO data comparisons were performed in every station were these data are available with acceptable number of miss values.

Tables 3 to 5 show the comparisons between observed and simulated values for wind, temperature, and relative humidity. The columns "**r**" report the observed to simulated data correlation (index "**u**" and "**v**" indicate the two horizontal wind components) and "P" is the significance level of the correlation; the σ are standard deviations (index "**o**" and "**s**", refer to observed and simulated data, respectively), and σ(u,v) is equal to $(\sigma_u^2+\sigma_v^2)^{-0.5}$, accounting for both, u and v, standard deviations; RMSE is the Root Mean Square Error (RMSVE is used for vector variables); N is the number of compared points.

Table 3. Comparisons between observed and simulated horizontal wind at 10 m (N from 120 to 167)

Station	σ_s (u,v) ($m.s^{-1}$)	σ_o (u,v) ($m.s^{-1}$)	RMSVE ($m.s^{-1}$)	r_u	r_v	P (for the worse r)
1	2.25	1.90	1.65	0.5590	0.8214	<0.001
3	2.98	3.16	3.12	0.2317	0.7439	<0.005
4	2.57	2.54	2.73	0.2448	0.6354	<0.005
5	2.29	2.18	1.61	0.6739	0.8279	<0.001
6	2.49	2.42	1.43	0.7896	0.8667	<0.001
7	2.64	1.95	2.10	0.6968	0.7640	<0.001
8	2.25	1.90	1.65	0.5590	0.8214	<0.001
9	2.75	2.12	1.66	0.7359	0.8595	<0.001
10	2.37	2.11	1.93	0.5099	0.8006	<0.001
14	2.60	2.46	2.79	0.4452	0.4608	<0.001

Table 4. Relative Humidity – Comparison between measured and simulated values (N=167)

Station	σ_s (%)	σ_o (%)	RMSE (%)	r	P	<RH>o (%)	<RH>s (%)
1	28	20	17	0.81	<0.001	72.4	67.3
2	17	11	30	0.43	<0.001	86.2	61.1
5	28	21	19	0.85	<0.001	58.0	67.0
7	26	22	17	0.88	<0.001	71.4	66.9
14	26	24	16	0.77	<0.001	71.0	67.8

Table 5. Air Temperature - Comparison between measured and simulated values (N=167)

Station	σ_s (^{0}C)	σ_o (^{0}C)	RMSE (^{0}C)	r	P	$\langle T \rangle_o$ (^{0}C)	$\langle T \rangle_s$ (^{0}C)
1	7.1	5.3	3.8	0.86	<0.001	18.9	17.4
2	6.6	6.6	3.6	0.78	<0.001	17.4	17.2
5	7.3	6.8	3.7	0.87	<0.001	18.8	17.6
7	4.3	4.8	3.0	0.8	<0.001	17.4	17.2
14	6.5	7.1	3.4	0.89	<0.001	18.9	17.3

Horizontal wind at 10 m are correlated at high level of significance, while RMSVE and **σ_s (u,v)** values are lower or similar to the observed **σ_s (u,v)**, all indicating a good BRAMS skill for simulating the 10 m wind. The same could be inferred for humidity and temperature in tables 4 and 5, except for humidity at station 2, probably because this station is settled at the ground of the Mogi Valley, which walls are steep, and fast growing from sea level till 600 to 1200 m heights, limiting the Model's ability to capture such variability.

Comparisons between simulated and observed CO concentrations (Table 6) show correlations with good significance level (stations 5, 7, 11and 13), while RMSE and σ_s are less or not much higher than σ_o for stations 7, 11 and 13. Finally, the ratio of simulated to observed CO averages in the last stations differs by less than 37%, corroborating to qualify their good data agreement. Stations 5 and 12 showed acceptable significance level for the data correlation, although the other parameters do not show fair results. Data for station 1, otherwise, showed high discrepancies, being the simulated average CO concentration 3.51 times greater than the observed values, probably because this station is settled in a large park inside the MASP, and the model resolution was not able to capture the dilution produced by the park.

The two selected images of simulations at Figure 2 show the significative amount of pollutant transported down (from São Paulo), and up the mountain range (from Cubatão) following the shore line.

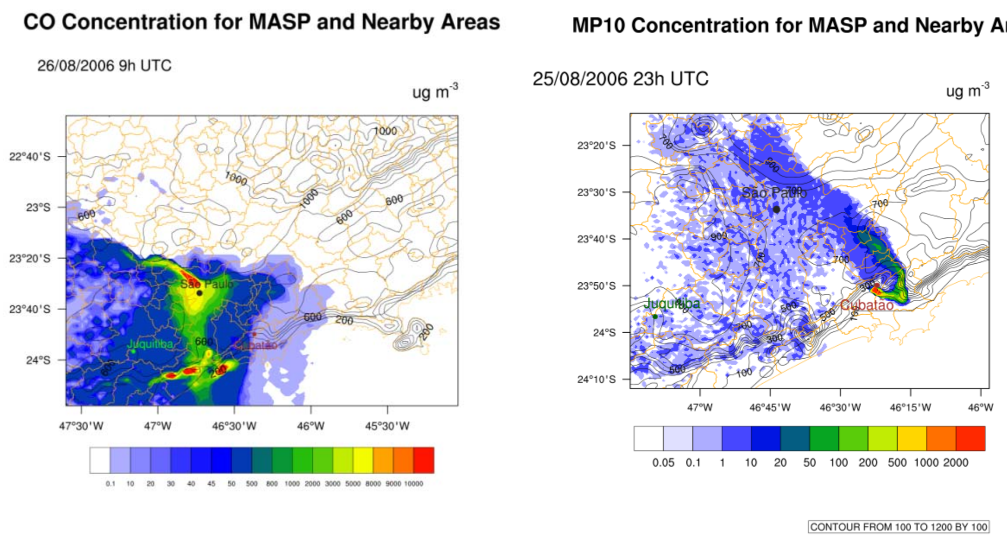

Figure 2. CO transport and concentration related with two episodes.

Although not exceeding the 8h standard ($10x10^3 \mu g.m^{-3}$ or 9.0 ppm) the CO plume contours show the CO transport, with 1 h values relatively high in remote and forested areas of the MASP.

Table 6. CO concentrations - Comparison between observed and simulated values (N from 53 to 93)

Station	σ_s ($x10^2\ \mu g.m^{-3}$)	σ_o ($x10^2\ \mu g.m^{-3}$)	RMSE	r	P	$<CO>_o$ ($x10^2\ \mu g.m^{-3}$)	$<CO>_s$ ($x10^2\ \mu g.m^{-3}$)	N	s/o
1	35.4	7.81	45.5	0.30	<0,002	13.4	46.9	91	3.51
5	36.7	14.0	42.2	0.37	<0,001	22.7	49.9	93	2.2
7	12.6	17.1	11.8	0.77	<0,001	19.9	17.0	53	0.86
11	7.7	8.90	8.7	0.54	<0,001	13.8	10.7	91	0.78
12	48.3	11.8	68.5	0.27	<0,01	15.2	65.2	75	4.28
13	25.7	19.6	27.5	0.30	<0,01	22.8	31.4	84	1.37

Table 7. PM_{10} exceedance of World Health Organization daily guide lines (50 $\mu g.m^{-3}$, WHO, 2005).

City	Measure period	Start date	Finish date	$<PM_{10}>$ ($\mu g.m^{-3}$)
Cubatão	daytime	25/08/2006	25/08/2006	107
São Paulo	daytime	25/08/2006	25/08/2006	57
Cubatão	night time	25/08/2006	26/08/2006	73
Juquitiba	night time	25/08/2006	26/08/2006	81
São Paulo	night time	25/08/2006	26/08/2006	84

CONCLUSION

The Couple BRAMS/SPRAY meteorological and diffusion simulation modeling systems was able to simulate reliable concentration fields for vehicular CO emitted in the MASP, as well as the PM_{10} emitted by fertilizer plants at Cubatão. Pollutant transport between some zones of these areas, highly populated and comporting forested reserves may arrive to significant intensity.

In the next steps of this work, this dispersion simulations system, chemical analysis of the measured PM_{10}, and receptor modeling will be put together to better understand the sources' role and air pollution transport among these areas.

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