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**A comparison study
of regional
atmospheric
simulations**

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A comparison study of regional atmospheric simulations with an elastic backscattering Lidar and Sunphotometry in an urban area

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Abstract

We describe a comparison study of aerosol optical thickness (AOT) from numerical simulations using a regional atmospheric model with an elastic backscattering lidar operating at 532 nm and a sunphotometer belonging to the AERONET network at São Paulo (23° S 46° W) city, Brazil, a very populated urban area. The atmospheric model includes an aerosol emission, transport and deposition module coupled to a radiative transfer parameterization, which takes the interaction between aerosol particles and short and long wave radiation into account. A period of one week was taken as case study during the dry season (late August) when intense biomass burning activities occur in remote areas in South America, and meteorological conditions disfavor the pollution dispersion in the city of São Paulo. The situation showed points out how smoke from biomass burning in remote areas is transported to the Southeast part of Brazil and affects the optical atmospheric conditions in São Paulo. The numerical simulations are corroborated by in-situ measurements of Aerosol Optical Thickness.

1 Introduction

In South America every year during the dry season (July to October) occurs a continental scale biomass burning activity (vegetation fires) mainly associated to land use change. A few weeks after the burning season has started, large areas of South America (SA) got covered by dense smoke plumes of aerosol particles and several types of primary and secondary gases. In GOES-8 visible imagery (Prins et al., 1995) an extense regional smoke was observed covering an area of approximately 4 to 5 million km² during the biomass-burning season of 2005. Freitas et al. (2007) described a conceptual model of how the typical South American synoptic systems drive the transport of biomass burning emissions. The general picture is dominated by an anticyclone associated with the South Atlantic Subtropical High (SASH) centered on the Atlantic Ocean and an orographic barrier of the Andes Mountains at West. The smoke

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5 mostly produced on Amazon basin and Central part of Brazil is then normally carried out to West and then turned to Southwest following the East side of Andes. In some cases, this transport is strongly augmented by occurrence of the South America Low Level Jet, a strong low troposphere pole-ward stream at East side of the Andes (Vera et al., 2006; Longo et al., 2006). However the occurrence of others transients systems like a approaching of mid-latitude cold fronts from the South can change this scenario and determines corridors of smoke export towards the Southeast part of Brazil, where the most populated urban areas does exist. In these events, the local air pollution produced by the urban activities gain additional load of pyrogenic and aged aerosols and gases, changing the local air quality and atmospheric optical properties patterns. In this paper we inspect the aerosol transport which can reach areas about 2000 km away from the sources Freitas et al. (2005) and even in a heavy densed urban area as São Paulo these transports can be observed in the lower troposphere. A backscattering LIDAR system located at the outskirts of São Paulo was setup in 2001 and is operational since then (Landulfo et al., 2003). With this system one can profile vertically the aerosol in the atmosphere and extract the optical properties due to the presence of particulate matter. During the so-called dry season which corresponds to the period of June through September the number of these transports into the Metropolitan Area of São Paulo increases drastically. In this case one expects to observe aerosol layers above the Planetary Boundary Layer where less mixing with local sources happen. In order to corroborate these transports we correlated the aerosol layers above the PBL and their optical properties with a regional forecasted calculated model capable of evaluating the concentration of biomass burning products such as: Carbon Monoxide (CO), Particulate Material with a size below 2.5 μm , and meteorological quantities such as temperature, pressure, wind field, etc. In this paper the period of 24 August through 30 August was chosen as a case study for a model validation with a colocated AERONET sunphotometer (SunP) and the LIDAR system (LS). After the selection of these periods a day by day analysis was carried on to obtain: Ångström Exponent (AE), Aerosol Optical Depth (SunP), Extinction-to-Backscatter Ratio (LR) and a synoptic anal-

ysis of this period.

2 Model and numerical simulations description

The numerical simulation described here was performed by using the Coupled Aerosol and Tracer Transport model to the Brazilian developments on the Regional Atmospheric Modeling System (CATT-BRAMS, Freitas et al., 2005, 2007; Longo et al., 2007). Shortly, CATT is an “on-line” transport model fully coupled to the Regional Atmospheric Modeling System (RAMS, Walko et al., 2000) and has been designed to study emission, deposition and transport of gases and aerosols associated with biomass burning in South America. An important characteristic of this modeling system is that the biomass burning emission source is based on the fire counts daily observed by remote sensing (Freitas et al., 2005; Longo et al., 2007), allowing realistic spatial and temporal injection of smoke from fires in the simulated atmosphere. Additionally, CATT-BRAMS includes a radiation scheme that takes into account the interaction between aerosol particles and short and long wave radiation. The consistent description of the smoke and its interaction with short- and long-wave radiation make the CATT-BRAMS model reliable for atmospheric feedback studies of the smoke aerosols (Longo et al., 2006). Model simulations for the 2005 dry season were performed using 2 grids: the coarse grid with 160 km horizontal resolution covering the South American (SA) and African continents and the nested finer grid with a horizontal resolution of 40 km, covering only SA. The vertical resolution for both grids varies telescopically with higher resolution at the surface (150 m) with ratio of 1.07 up to a maximum vertical resolution of 850 m, with the top of the model at 23 km (a total of 42 vertical levels). The soil model is composed of 7 layers with variable resolution, distributed within the first 4 m of soil depth. For the atmospheric initial and boundary conditions, the 6 hourly Brazilian Center for Weather Forecast and Climate Studies (CPTEC) T126 analysis field was used for the model initialization and to provide the necessary boundary condition using the traditional RAMS scheme, the 4DDA (four-dimensional data assimila-

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tion) technique. Initial soil moisture was taken from the (Gevaerd and Freitas, 2006) estimation technique. The soil temperature was initialized assuming a vertically homogeneously field defined by the air temperature closest to the surface from the atmospheric initial data. The biomass burning source emission was defined from remote sensing fire counts. The fire database used a combination of the Geostationary Operational Environmental Satellite – Wildfire Automated Biomass Burning Algorithm (GOES WF_ABBA product <http://cimss.ssec.wisc.edu/goes/burn/wfabba.html>; Prins et al., 1995), the Brazilian National Institute for Space Research fire product, which is based on the Advanced Very High Resolution Radiometer (AVHRR), aboard the NOAA polar orbiting satellites series (<http://www.cptec.inpe.br/queimadas>; Setzer and Pereira, 1991) and the Moderate Resolution Imaging Spectroradiometer (MODIS) fire product (<http://modis-fire.umd.edu>; Giglio et al., 2003). The fire counts were then processed by the emission model and daily emission sources were obtained for CO and PM_{2.5}. During simulation, the emission data is daily ingested in the model to provide the tracer fluxes. Once emitted to the atmosphere, CO and PM_{2.5} are dispersed and transported by the wind in the model providing an useful tool to simulate and forecast its concentration and trends.

3 Experimental setup

3.1 Lidar apparatus

A ground-based elastic Lidar system has been operational in São Paulo since 2001 at the Laboratory of Environmental Laser Applications at the Centre for Laser and Applications (CLA/IPEN) Landulfo et al. (2003, 2005). This system is a single-wavelength backscatter system pointing vertically to the zenith and coaxial mode. The light source used is a commercial Nd:YAG laser (Brilliant by Quantel SA) operating at the second harmonic frequency (SHF), namely at 532 nm, with a fixed repetition rate of 20 Hz. the average emitted power can be selected up to values as high as 3.3 W and peak-power

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of a few MW when the pulse duration is taken into account (around 4 ns). The beam divergence is typically about 0.5 mrad. As a light collector we employ a newtonian telescope with a primary mirror with 30 cm of diameter and focal length $f=30$ cm. The telescope's field of view is variable ranging from 0.5 to 5 mrad by using a small diaphragm.

5 At the present configuration the system has a maximum overlap beginning at 300 m allowing the system to perform up to 8–10 km during daytime (15–25 km nighttime). The backscattered laser radiation is detected by a low-noise photomultiplier (Hamamatsu) coupled to a 1 nm FWHM interference filter to assure the reduction of solar background and improve the signal-to-noise ratio. The PMT output signal is recorded
10 by a transient recorder (Licel GmbH) in both analog and photoncounting modes. Data are averaged every 2 min and summed up in blocks corresponding to about 30 min. The raw resolution applied is 15 m, which corresponds to 100 ns in time.

3.2 Aeronet sunphotometer

The sunphotometer (CIMEL 318A) located at São Paulo is in close range to the Li-
15 dar station. This system belongs to the AERONET network (Holben et al., 1998) and performs aureole and sky radiances measurements in order to retrieve the Aerosol Optical Thickness for aerosols at several wavelengths. The standard measurements are taken in the whole spectral interval, and their number depends on the daytime duration. Besides the AOT, it is possible to obtain also the aerosol size distribution, the
20 phase function, single scattering albedo and extinction-to-backscatter ratio. The sunphotometer like the others in this network is periodically calibrated by a remote computer or locally. This procedure assures an accuracy in the measurements between 1 and 3%. However various instruments, calibration, atmospheric, and methodological factors can influence the precision and accuracy achieved and the total uncertainty in
25 the AOT might reach around 5–10% (Dubovik et al., 2002).

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4 Lidar and aeronet data processing

4.1 Lidar data retrieval

The retrieval of the aerosol optical properties is based on the measurements of the aerosol backscatter coefficient β_{aer} at 532 nm, up to an altitude of 5–6 km. The vertical profile of the aerosol backscatter and extinction coefficients is obtained by the LIDAR inversion technique following the Klett's algorithm Klett (1985). In general, the inversion profile is based on the solution of the so-called LIDAR equation.

$$P(\lambda_L, R) = P_L \left(\frac{c\tau}{2} \right) A_o \xi(\lambda) \zeta(R) R^{-2} \beta(\lambda, R) \times \exp \left[-2 \int_0^R \alpha(\lambda, r) dr \right] \quad (1)$$

where, $P(\lambda_L, R)$ is the lidar signal received from a distance R at the wavelength λ , P_L is emitted laser power, A_o is the telescope receiving area, $\xi(\lambda)$ is the received spectral transmission factor, $\beta(\lambda, R)$ is the atmospheric volume backscattering coefficient, $\zeta(R)$ is the overlap factor between the field-of-view of the telescope and the laser beam, $\alpha(\lambda, R)$ is the extinction coefficient, c is the speed of light and τ is the laser pulse length. In Eq. (1), the α and β coefficients can be separated into two sets, one for the molecular scattering and the other for the particle scattering component. Besides in the inversion technique applied here there is a reference altitude which is used as an upper limit where we consider an aerosol-free region. Moreover, in order to keep this inversion “well” behaved it is common to assume a relation between α and β known also as the Lidar ratio.

$$S_{\text{aer}} = \frac{\alpha_{\text{aer}}}{\beta_{\text{aer}}} \quad (2)$$

The Lidar ratio can be interpreted as the amount of light being absorbed or scattered out of the telescope FOV by the backscattered light due to the influence of the aerosols, therefore it is a microphysical property of the aerosol which depends on the aerosol

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refractive index, size and distribution. Aerosols change their physical-chemical properties in response to relative humidity changes and aging processes which therefore cause a direct impact on their optical properties leading to a wide range of lidar ratio and their interpretation (Anderson et al., 2000; Ackermann, 1998; Dubovik et al., 2002; Cattrall et al., 2005). Also in order to derive the appropriate S_{aer} values of the vertical backscatter and extinction coefficients it is applied an iterative inversion approach by tuning the S_{aer} with the AOT values retrieved by the CIMEL data and comparing with those extracted from the LIDAR data:

$$\text{AOT}_{\text{LIDAR}} = K \times \text{AOT}_{\text{CIMEL}} = \sum_0^{z_{\text{ref}}} \alpha_{\text{LIDAR}}(r) \Delta r, \quad (3)$$

where K is a number between 0 and 1, which might work as a “weight” factor due the fact that the LIDAR overlap is maximum at 300 m and the portion below that might not have been used into account when estimating the aerosol load contribution to the total AOT (Landulfo et al., 2003). Here Δr corresponds to the resolution binning used to calculate the α and β values taken in the whole period show that the maximum AOT values obtained by CATT-BRAMS and measured by the sunphotometer show some large differences which can be understood from three aspects a) the SUNPHOTOMETER data taken is level 1.5 and the level 2.0 after calibration can change somehow the AOT; b) The week during the measurements presented some clouds which are taken into account in the model and c) The grid resolution employed in the model gives an average over an area of 40/40 km. coefficients which in our case is equal to 30 m.

4.2 Sunphotometer data retrieval

The inversion of the solar radiances measured by the CIMEL sunphotometer to retrieve the AOT is based on the Beer-Lambert Law, assuming that the contribution of multiple scattering within the small field of view of the sunphotometer is negligible (Holben et al.,

1998):

$$I_{\lambda} = I_{\lambda}^o \exp\left(-\frac{\tau_{\lambda}}{\mu_s}\right), \quad (4)$$

where I_{λ} and I_{λ}^o are the solar irradiances at the top of the atmosphere and at ground level, respectively, and μ_s is the cosine of the solar zenith angle. τ_{λ} is the total optical thickness from the Rayleigh and aerosol contributions, as well as the ozone and water vapour absorption at 670 nm and 870 nm, respectively. The molecular (Rayleigh) scattering contribution is taken into account to get the aerosol optical thickness values at 532 nm, determined by the relation:

$$\frac{\tau_{532}^{\text{aer}}}{\tau_{500}^{\text{aer}}} = \left(\frac{532}{500}\right)^{-\text{\AA}} \quad (5)$$

where, the Ångström exponent, \AA was derived from the retrieved optical thicknesses in the blue and red channels (440 nm and 670 nm):

$$\text{\AA} = -\frac{\log(\tau_{440}^{\text{aer}}/\tau_{670}^{\text{aer}})}{\log(440/670)}. \quad (6)$$

In general, the Ångström exponent provides information on the aerosol size distribution, and according to the literature different types might bear different ranges for the Ångström exponent: 1.2 to 2.5 (urban-continental aerosols; 1.2 to 2.3 (biomass burning); 0 to 1.6 and 0.9 (desert dust and oceanic). The data are retrieved from the AERONET site and given in three data quality levels: Level 1.0 (unscreened), Level 1.5 (cloud-screened) (Smirnov et al., 2005), and Level 2.0 (cloud-screened and quality-assured).

4.2.1 Results

The CATT-BRAMS simulations have been very useful in assessing the dispersion and transport of biomass burning aerosol over South America. The period of forest fires

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spans from late July through early October (Prins et al., 1995) which might vary due to meteorological conditions. In this work we make comparisons of some of the CATT-BRAMS products, namely AOT (550 nm) and $PM_{2.5}$ over the continent and in special in São Paulo, where we have a backscattering Lidar system and a AERONET sun-
5 photometer running. A period of 7 days in late August 2005 (23 August through 30th) was picked as a case study to observe the model predictions and how the aerosol distribution and impact over the atmospheric optical properties varied during this period. From the CATT-BRAMS simulations we took the AOT (550 nm) in periods of 3 h, starting at 9 a.m. (Local Time) to 6 p.m. for the entire period and it is showed
10 in the supplementary material <http://www.atmos-chem-phys-discuss.net/9/9151/2009/acpd-9-9151-2009-supplement.zip>. Figure 1 illustrates the AOT over the continent in days 23 August, 28 August, 29 August and 30 August. On August 2005 the frequency of precipitation was higher in the eastern part of Northeast Brazil than in the other parts of Amazonia. This increase was associated with the intensification of the trade winds that brought stratiform clouds from the Atlantic Ocean. In the eastern part of southern
15 Brazil the precipitation during the same period were associated with cyclogenesis in the adjoining Atlantic. Although the temperatures were above normal in most parts of the country, two intense cold mass penetrations caused steep falls of temperature in the southern and the western regions of Brazil. Six mid-latitude cold fronts from the South Polar Region, associated with low pressure systems, propagated across the South American territory reaching São Paulo metropolitan area. On 23 August, the fifth cold front developed from a cyclogenesis over Paraguai, Argentina Uruguai and south of Brazil. On the next day, this system moved to North passing over São Paulo and reaching Rio de Janeiro state. The last cold front took place on 28 August and 29 Au-
20 gust over Rio Grande do Sul State and then moved northward reaching São Paulo on 31 August. This synoptic conditions created conditions for the spreading of biomass material almost over a western part of the brazilian territory and cold fronts brought these air masses towards the south-eastern states where the city of São Paulo is included. This procedure not only permitted us to compare the simulations but also to

assess how an influx of biomass burning aerosol could “perturb” the local conditions in a heavy polluted urban area as São Paulo. From the AOT generated figures one can see that an intense activity of forest burning was taking place during the period above mentioned and there was a transport southward into mid-west Brazil, Paraguay and Northeastern Argentina, not affecting the São Paulo area until 27 August when there was an advance over city brought by a cold front, common in this time of the year. It is observed then that on 28 August there was a new cold front forming in the south of the continent where a lot of aerosol concentration is observed and its advance culminates on 30 August when AOT values over 1.5 are observed in the region of São Paulo. Along with those observations, measurements of AOT, AE and Lidar Ratio variations at 532 nm at this period which are presented in a form of a panel in Fig. 2 and the information is summarized in Table 1. The values taken in the whole period show that the maximum AOT values obtained by CATT-BRAMS and measured by the sunphotometer show some large differences which can be understood from three aspects a) the SUNPHOTOMETER data taken is level 1.5 and the level 2.0 after calibration can change somehow the AOT; b) The week during the measurements presented some clouds which are taken into account in the model and c) The grid resolution employed in the model gives an average over an area of 40/40 km. One might see that on days 23 and 30 where the presence of biomass burning transported from remote areas is predicted an steep increase in the AOT, and the largest variations in the AE and LR parameters. As it is expected the high values of LR are a signature of strong absorbing particles (Anderson et al., 2000) and since due transport over a large distance one expects increases in size as result of coagulation, condensation and gas-to-particle conversion (Reid et al., 1998) therefore size distribution can present both coarse and fine modes in equal amounts. Besides the vertical lidar profiles taken during this period one could detect that the incoming air parcels bringing aerosols were about 3–4 km discarding the possibility that aerosol load was only from local sources. The model also generated the $PM_{2.5}$ concentration product shown in Fig. 3 where it can be clearly seen a strong correlation between the particle concentration and AOT values for a period of

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almost ten days beginning on 24 August. That was expected since the coarse mode particles are more prone to be deposited nearby the source and would have a shorter residence time in the atmosphere.

5 Conclusions

We have performed a comparison study of aerosol optical thickness (AOT) from numerical simulations using a regional atmospheric model with an elastic backscattering lidar operating at 532 nm and a sunphotometer belonging to the AERONET network at São Paulo (23° S 46° W) city, Brazil. This synergy proved to be very fruitful in understanding local and regional aerosol transport and its presence at many different layers and also deriving and interpreting the Aerosol Optical Thickness, Ångström exponent and extinction-to-backscattering ratio values, important microphysical quantities to describe the aerosol optical properties. There is a good agreement between the results from the CATT-BRAMS model and the measurements taken during the period in study and any disagreements are believed to be due the grid resolution used in the model, the use of a finer resolution could not be however effective in terms of computational effort and the results achieved. Also the synoptical description gave a good background in comprehension of the transport of biomass burning aerosol from remote areas such as the central-western and Northern regions into the southern and south-eastern parts of Brazil. Such transport was associated with low pressure systems generated by cold fronts originating in the South Polar latitudes. Further efforts should be taken into extending the time series in other years and comparing with other instruments besides the LIDAR system and sunphotometer employed with emphasis on satellite products from MODIS and/or CALIPSO for instance.

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Table 1. Summarized data of the period of this study with the main quantities retrieved by the instrumentation and calculated by CATT-BRAMS. The values taken in the whole period show that the maximum AOT values obtained by CATT-BRAMS and measured by the sunphotometer show some large differences which can be understood from three aspects a) the SUNPHOTOMETER data taken is level 1.5 and the level 2.0 after calibration can change somehow the AOT; b) The week during the measurements presented some clouds which are taken into account in the model and c) The grid resolution employed in the model gives an average over an area of 40/40 km.

Date	MAX AOT Observed	MAX AOT (BRAMS)	AE variation	LR variation
23 Aug 2005	0.25	0.15	1.48–1.67	33–65
24 Aug 2005	0.50	0.30	0.49–0.98	30–33
25 Aug 2005	0.22	0.30	1.42	N/A
26 Aug 2005	1.20	0.70	1.25–1.53	46–55
27 Aug 2005	2.10	0.80	1.45	N/A
28 Aug 2005	0.30	0.80	1.60–1.75	N/A
29 Aug 2005	0.30	0.60	1.50–1.60	33–40
30 Aug 2005	1.70	>1.50	1.55–1.75	39–60

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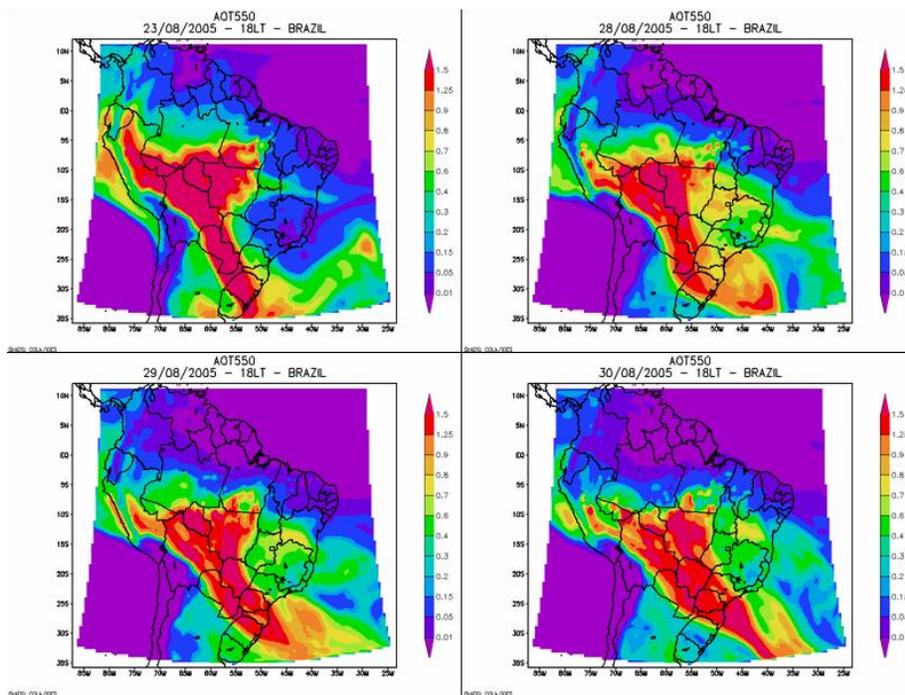


Fig. 1. CATT-BRAMS simulation of Aerosol Optical Thickness at 550 nm for some days over the Brazilian territory and bordering countries.

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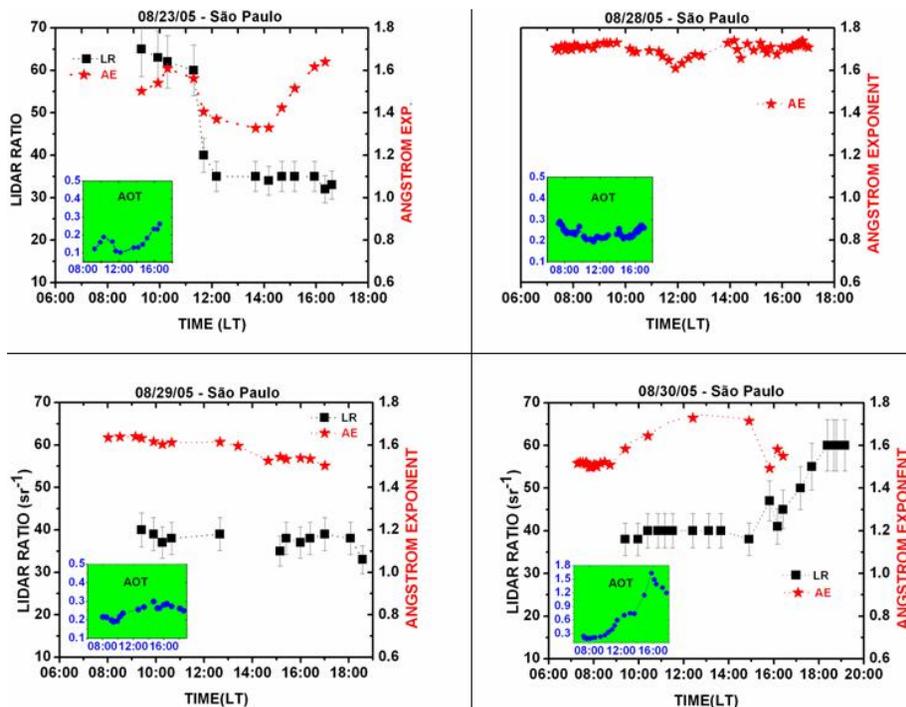


Fig. 2. Aerosol Optical Thickness, Angstrom Exponent and Lidar-Ratio for days 23 August, 28 August, 29 August and 29 August at 532 nm over the city of São Paulo, the AOT and AE were extracted from the sunphotometer and the Lidar-Ratio was retrieved using the Lidar system at IPEN. The features shown in each panel reveal the aerosol micro-physical patterns with and without the biomass burning aerosol influence. The most evident is the increase in the AOT while the other parameters are related to local sources as well.

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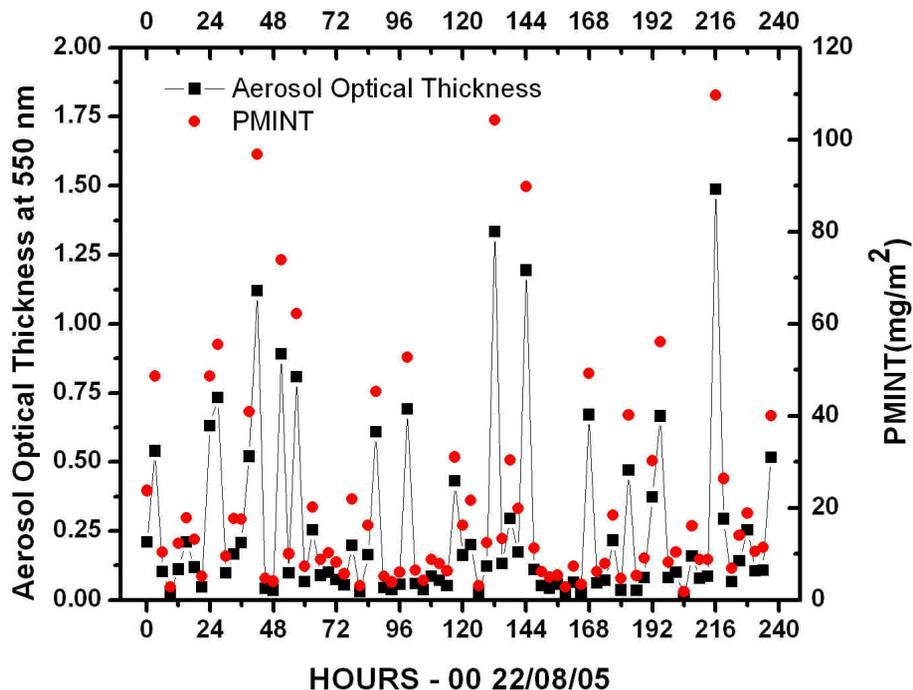


Fig. 3. Aerosol Optical Thickness at 550 nm and PM_{2.5} column integrated concentration during a period of ten days starting on 22 August 2005. There is a direct correlation between these two quantities and the largest values were observed when intense biomass burning aerosol transport took place over the Metropolitan Region of São Paulo.

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