

Study of the Properties of Aerosols and the Air Quality Index Using a Backscatter Lidar System and Aeronet Sunphotometer in the City of São Paulo, Brazil

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ABSTRACT

Between the months of July and September of 2007 during the so-called Brazilian dry season, an aerosol profiling campaign was carried out with a backscatter(ing) lidar system in the city of São Paulo, Brazil. The main goal of this campaign was to observe the aerosol load in the troposphere (up to 10 km) and its daily behavior to check for air dispersion conditions, planetary boundary, and mixed layer height daily evolution. Lidar analysis provided aerosol optical properties in the visible range (532 nm) and quantities such as aerosol backscatter(ing) and extinction coefficients in conjunction with the aerosol optical thickness provided by a collocated AERONET Sunphotometer. Altogether 61 days were used in the dataset, which were compared with air quality indexation from the local air quality monitoring and management agency.

INTRODUCTION

Air quality assessment at a local or regional scale is required for various purposes, including emission control, air quality forecasts, and implementation of legislation.

IMPLICATIONS

The knowledge of air pollution emission and the air quality indexing in megacities is extremely important for determining the impacts in the environment and health of the population. The objective of this paper is to quantify and to make some comparisons with the air quality in the area of São Paulo using a multi-instrumental approach to provide a better understanding of air quality, therefore promoting orientation and support to public policies in questions related to management and control of air pollution.

The dispersion of pollutants depends mostly on atmospheric turbulence, but turbulence measurements are not always routinely performed by meteorological services.¹

As is well known, the impact on the environment due to anthropogenic activities extends to regional and global levels, and the air pollution in megacities remains one of the most important problems inherited from the 20th century. For instance, the metropolitan area of São Paulo (MASP) is among the five largest metropolitan areas in the world and is one of the most populated with approximately 18 million inhabitants, wherein human activities have made an enormous impact on the area's air quality and on the population's health.² Large areas such as MASP suffer from the influence of many different sources of particulate matter such as heavy industries, refineries, chemical manufacturing, cement, sulfuric acid, petrochemical plants, and the automotive fleet; in the case of MASP, the vehicle fleet is already over 6 million units. Regarding its topography, the city of São Paulo is located on a plateau at approximately 800 m above sea level (ASL) and is surrounded by mountains of approximately 1200 m ASL, which is a relevant factor for the poor dispersion conditions of the pollutants.

During the summer season, precipitation increases and many cold fronts generate meteorological instabilities that favor pollution dispersion. These periods can extend over the autumn months of May and June. When winter begins, a high-pressure semistatic regime over the São Paulo area is generally observed. This event becomes highly favorable for air pollutant accumulation, especially during episodes of intense temperature inversions, occurring typically less than 1000 m, or in critical events even less than 200 m, above the metropolitan area.^{3,4} Because of the importance of meteorological conditions in determining the transport, diffusion,

transformation, and removal of air pollutants, some meteorological measurements and analyses are synchronously conducted while the air pollution field observations are performed.⁵

To better address the air quality issue in São Paulo, a multi-instrument approach with ground-based sensors was used that included a backscatter(ing) lidar (light detection and ranging) system,⁶ a CIMEL sunphotometer belonging to the AERONET Network,⁷ and radiosonde data from the local weather service that is launched on a daily basis. These data are also used by the local environmental agency to derive dispersion conditions affecting air quality.⁸ A backscatter(ing) lidar can provide information on the planetary boundary layer (PBL) mixed layer depth, entrainment zones and convective cells structure, aerosol distribution, clear air layering, cloud-top altitudes, cloud statistics, atmospheric transport processes, and other inferences of air motion.^{9–12} The sunphotometer data were used to provide aerosol optical thickness (AOT) values at selected wavelengths and thus to derive the Angström exponent values over São Paulo, which are good indicators of particle size distribution. The synergy of CIMEL and lidar measurements also acts in minimizing the uncertainties of the assumptions made, especially when inverting the lidar signal, using Klett's technique.¹³ The air quality index (AQI) in the state of São Paulo is provided by CETESB (Companhia de Tecnologia de Saneamento Ambiental), which has 23 air quality stations, as seen in Figure 1, and is responsible for monitoring and controlling the air quality environment through Environmental Protection Agency (EPA)-certified stations scattered over MASP.

The thermal structure of the atmospheric boundary layer and the height of the mixing layer are essential quantities when assessing the air quality and vertical dispersion of air pollutants because they determine and limit the rate and range of the vertical dispersion of volatile substances that are formed or emitted near the ground. Because it is usually assumed that most aerosol particles that are responsible for the optical depth of the atmosphere are confined within the mixing layer, somewhere between 1500 and 2000 m, the knowledge of the depth of

the mixing layer can also be used to convert optical depths measured from satellites into near-surface air quality information.¹⁴ Comparisons with the pollution level data that were available were also performed to establish a more representative average of the indices from four neighboring stations.

METHODOLOGY

A ground-based elastic backscatter lidar system was recently developed at the Instituto de Pesquisas Energéticas e Nucleares (IPEN), located in a suburban area of the city of São Paulo (23°33' south, 46°44' west)¹⁵. Figure 1 shows the location of the lidar station and the air quality stations. The lidar system is a single-wavelength backscatter system pointing vertically to the zenith and operating in the coaxial mode. The light source is based on a commercial Nd:YAG laser (Brilliant-Quantel SA) operating at the second harmonic frequency (i.e., 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. The emitted laser pulses have a divergence of less than 0.5 mrad. A 30-cm diameter telescope (focal length $[f] = 1.3$ m) is used to collect the backscattered laser light. The telescope field of view (FOV) is adjusted using a small diaphragm. The lidar is currently used with a fixed FOV of approximately 1 mrad, which, according to geometrical calculations, permits a full overlap between the telescope FOV and the laser beam at heights greater than 300 m above the lidar system. The retrieval of aerosol optical properties with the lidar system 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 is determined using the lidar inversion technique proposed by Klett. For altitude below the overlap region, it is considered that 10% of the AERONET AOT is confined, and a more detailed study is presently being conducted.

One other straightforward data retrieval is the height from the PBL. Because this system monitors the various aerosol layer (AL) altitudes, one can assume that those higher AL altitudes correspond, within a margin of confidence, to the PBL altitude. Lidar data could be very useful for determining the PBL altitude, which provides

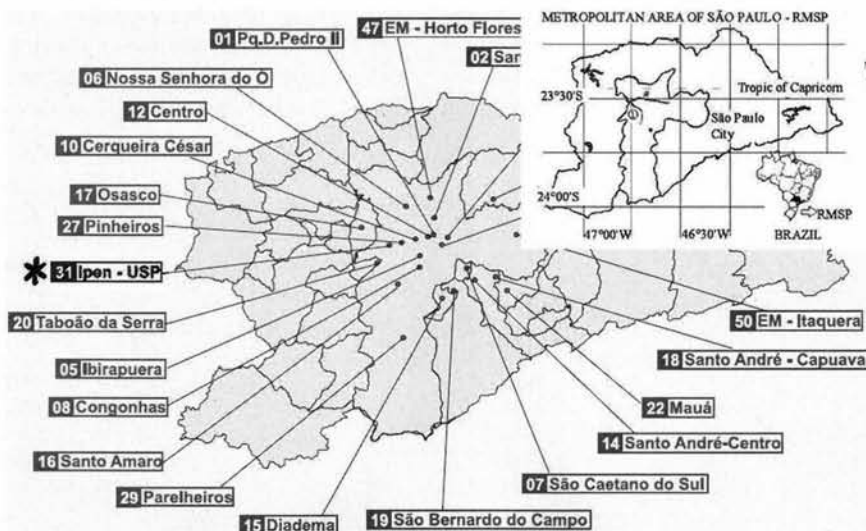


Figure 1. MASP and the air quality stations of CETESB. IPEN's location is highlighted.

important information in investigating pollution dispersion and prediction of air pollution enhancement episodes. One more accurate method is to take the first derivative of the range-corrected lidar signal.^{16,17}

In addition to the lidar measurements, aerosol measurements with the CIMEL sunphotometer were performed to determine the AOT values at several wavelengths in the visible spectrum and thus to enable the assessment of the aerosol extinction values in the same spectral region. The principal operation of the CIMEL sunphotometer instrument is to acquire aureole and sky radiance measurements. The standard measurements are taken 15 min apart to allow for checking for cloud contamination.⁷ The inversion of the solar radiances measured by the CIMEL sunphotometer to retrieve the AOT values¹³ is based on the Beer-Lambert law, assuming that the contribution of multiple scattering within the small FOV of the sunphotometer is negligible. The molecular (Rayleigh) scattering contribution is taken into account to retrieve the AOT values at 532 nm. The methodology used to derive the AOT from the CIMEL sunphotometer, and the extinction-to-backscatter(ing) ratio (LR) values are described in Landulfo et al.¹⁵

The radiosonde launched from sounding base Marte Civil (SBMT)⁸ is located approximately 10 km from the lidar system and its data were taken every day at 9:00 a.m. local time. These data allow one to establish the structure of the atmosphere to approximately 4000 m in altitude and from them it is possible to achieve the main thermal inversion present at a given date and to compare its main features with those provided by the lidar profiles. Some information in the calculation can also be used to obtain the atmospheric optical properties such as the backscatter coefficient. Because in some instances the mixed layer could be below the overlap height from the lidar system and for validation purposes, the radiosonde data were used to retrieve the minimum PBL height.¹⁸

CETESB has 29 air quality stations, 23 of these are in MASP. This network provides a daily air quality data report^{18,19} based on a 24-hr average that is available daily. These daily air quality reports take into account the following pollutants: sulfur dioxide, inhalable particulate, smoke (soot), ozone, and nitrogen dioxide. The AQI is obtained by a segmented linear function in which the inflection points are the air quality standards. Also from this function each pollutant is assigned a dimensional

number referred to a scale. For report presentation purposes, the highest index among the pollutants is presented. If the AQI average is between 0 and 50, the condition of the air quality is considered good (G); when between 51 and 100, it is considered fair (F); and when between 101 and 200 air quality is considered inadequate (I). The equipment used for these pollutants are based on automatic air quality stations that use equivalent methods certified by the U.S. Environmental Protection Agency. The related AQI is published according to the worst occurrence in the day for ozone, the worst values in the last 4 hr for nitrogen dioxide, an 8-hr average for carbon monoxide, and a daily average for sulfur dioxide and inhalable particulate. Although different systems reside in distinct places around the city, mainly because of operational reasons, the most unified way would be to extract the quantity that best describes the overall aspect of the atmospheric conditions and/or air quality; namely, the PBL height for the lidar and radiosonde launchings and the AQI in the case of the air quality stations.

In Table 1 a summary of the equipment, their locations, and the retrieved information from each one is shown. Table 2 summarizes the optical atmospheric parameters, the PBL heights, and sunphotometer data.

RESULTS

In the months of July, August, and September the lidar system at IPEN was used to make daily measures of 4–8 hr, except in those days that precipitation occurred. The September period was marked by the constant occurrence of the South Atlantic subtropical anticyclone, which helped in the transport of humidity from the Atlantic Ocean to the continental area during the first half of the month. Because of this, there was an occurrence of predominant wind from the north to northeast over the city of São Paulo, and in some cases the wind direction changed to the east. From the 15th day on, because of the incoming cold front the predominant wind direction changed from the south to southeast. Therefore, the predominant air mass during this period was maritime because of the predominance of the anticyclonic circulation throughout the atmospheric profile over the country. This favored subsidence inhibiting cloud formation and development as well as precipitation in a large part of Brazil. In addition, the anticyclone circulation presence

Table 1. Summary of the equipment and their retrieved data.

Equipment	Latitude (°)	Longitude (°)	Elevation (m ASL)	Retrieved Information
Lidar	-23.561	-46.739	840	β_{aer} , LR, PBL top
Sunphotometer AERONET	-23.561	-46.735	840	AOT, AE
Radiosonde	-23.505	-46.637	724	Minimum PBL height
CETESB station-IPEN/USP	-23.566	-46.737	840	AQI (NO, NO ₂ , NO _x , CO, O ₃ , concentrations)
CETESB station-Pinheiros	-23.561	-46.701	730	AQI (PM ₁₀ , NO, NO ₂ , NO _x , CO, O ₃ , concentrations)
CETESB station-Taboão da Serra	-23.609	-46.757	753	AQI (PM ₁₀ , NO, NO ₂ , NO _x , CO, concentrations)
CETESB station-Osasco	-23.526	-46.792	725	AQI (PM ₁₀ , NO, NO ₂ , NO _x , CO, concentration)

Notes: NO = nitric oxide, NO₂ = nitrogen dioxide, NO_x = oxides of nitrogen, CO = carbon monoxide, O₃ = ozone, PM₁₀ = particulate matter <10 μm in aerodynamic diameter, USP = University of São Paulo.

Table 2. Atmospheric parameters obtained from CETESB stations, radiosonde, the lidar system, and the AERONET sunphotometer.

Date	Lidar PBL Top (m)	Radiosonde PBL Top (m)	AQI	AE	AOT	LR
September 7, 2007	2000	1900	100	1.61 (4)	0.29 (10)	43 (33)
September 20, 2007	2400	2200	125	1.53 (4)	0.62 (8)	46 (15)
September 22, 2007	2000	2050	140	1.37 (8)	0.75 (26)	60 (6)

Notes: Numbers in parentheses indicate standard deviation.

throughout the country subsided the inhibition of cloud formation and therefore the occurrence of rain.

This kind of meteorology strongly enhances the chances of poor air dispersion and therefore poor air quality. In total, it was possible to have 61 days of measurements altogether; however, for the sake of summarizing the overall bad air quality condition three cases from September were chosen to analyze the dispersion conditions of aerosols in the PBL and to correlate with the AQI and all systems involved in the campaign. In concomitance, these measurements were coordinated with the CETESB in such a way that their dispersion data for air quality "nowcasting" purposes were obtained. Every day a report was produced in which a lidar range corrected signal plot was generated, giving special attention to the PBL evolution for the day and other features observed in the plot, such as higher layer presence (above 3 km) as an indication of aerosol transport, cloud observations, low and high altitudes, and entrainment features likely due to seabreeze influence because São Paulo is not far from the sea shore (~90 km).

Figure 2 presents the daily PBL maximum and an average between minimum heights extracted from the lidar plots and the radiosonde mixing layer altitude retrieved by the meteorological service and the AQI from three neighboring stations. The days shown in the plot are those in which the lidar system was running and it was possible to observe interesting features (e.g., slightly staggered behavior in the maximum PBL height and in the AQI data), one indication being when an AQI maximum with a peak in PBL height is reached. One can

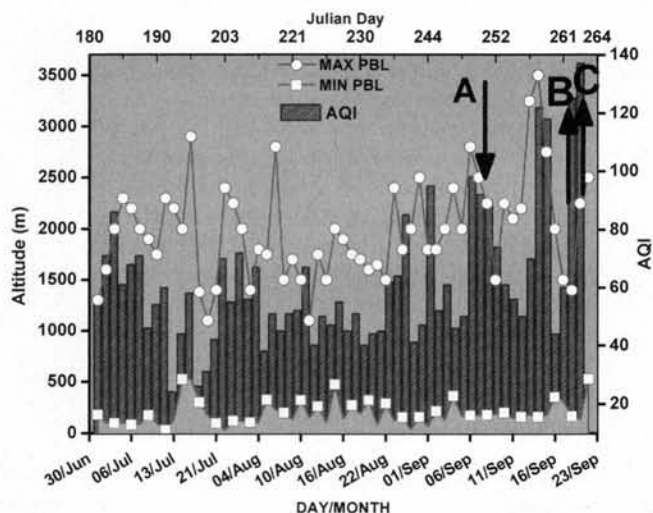


Figure 2. Daily variation of PBL heights by lidar, radiosonde, and AQI. Arrows A, B, and C indicate the case studies explored in this paper.

understand that when the PBL reaches its maximum values good dispersion conditions are present; notably, in the examples given in the plot the AQI worst cases with inadequate air quality are those when maximum PBL height values were larger.

Figure 3 shows the range-corrected lidar signal for each day. In this plot, the PBL daily variation and changes in the layer structure due meteorological conditions can be observed.

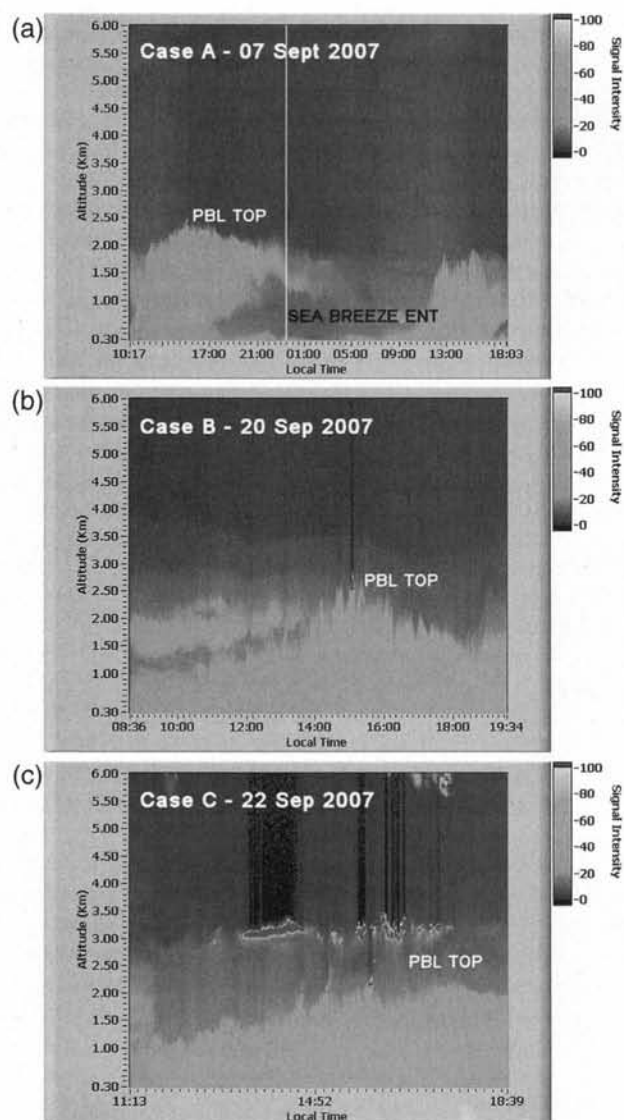


Figure 3. Range-corrected lidar signal for cases A, B, and C (panels a, b, and c, respectively). Daily PBL height behavior and ALs can be identified.

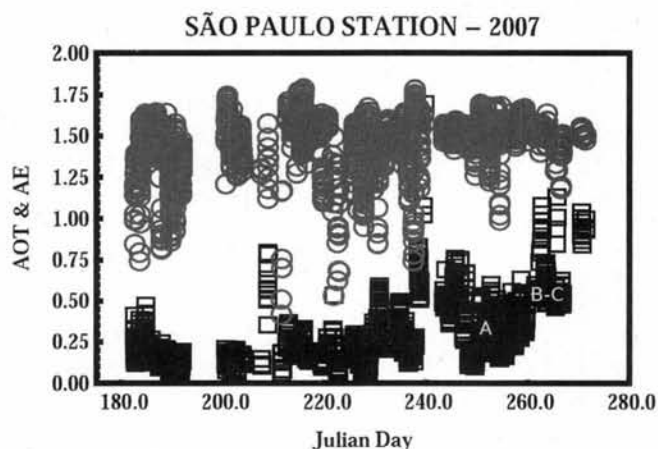


Figure 4. AOT and AE values for the whole campaign. Case studies are identified by their respective letters (A, B, and C).

Figures 4–6 depict the aerosol optical and microphysical properties for the entire campaign period from July 1 through September 23 (also expressed in Julian days, i.e., 182–275). These data were extracted from the AERONET sunphotometer site corresponding to São Paulo and are given in individual points taken every 15 min. These types of data are available after pre- and post-field calibrations were applied, automatically cloud-cleared, and manually inspected by the AERONET data processing personnel.

Figure 4 continuously shows the AOT (squares) and AE (circles) for each day (Julian) in the period. The gaps where data are missing were those when cloudy conditions were predominant. The letters A, B, and C in the plot indicate the case study days. Figures 5a–5c correspond individually to each case study and can be understood as a “zoom” of the previous plot for each specific date. In each panel, one can observe two band-shaped areas that correspond to the median values taken for the entire period, and the absolute median variance for each line limits its width. In the study presented here, the median was chosen rather than the average because a Pearson’s coefficient analysis showed that the skewness coefficients²⁰ for AOT and AE were 1.67 and –1.62, respectively; therefore, the median value has more statistical meaning. However, for each individual case study the AOT and AE daily averages are given because the number of measurements each day is smaller than that for the whole period of the campaign.

The correlation between AE and AOT can be visually inspected in Figure 6. The crosshair bands have the same properties as in the previous plot. In general, for those days when the AE values were below the median horizontal line the type of aerosol corresponds to a coarse-mode aerosol and above this line corresponds to a finer type of aerosol. Following the same reasoning, the AOT values lying to the left of median vertical line correspond to low radiation-absorbing types of aerosols whereas those values on the right bear strong absorbing optical properties. In this fashion, the plot was split into four different regions (I, II, III, and IV) to present the aerosol optical properties and retrieved AQI in a systematic fashion. Finally, for each case the LR was obtained from the lidar measurements.

Case A

Figure 3a shows the lidar data obtained on September 7 and 8, 2007, demonstrating the PBL top at approximately 2000 m. Figure 2, arrow A, shows and an AQI value of approximately 100; thus, there was a predominance of poor air quality conditions. One particular aspect is that September 7 was a national holiday in the country, and one would expect better air quality conditions because the traffic was not as intense as on a typical working day. By late afternoon on the same day a seabreeze front entered that clearly diminished the aerosol load up to 1.5 km; however, the AQI remained the same on the following days. In Figure 4 it is difficult to distinguish any noticeable feature on this day from the whole campaign

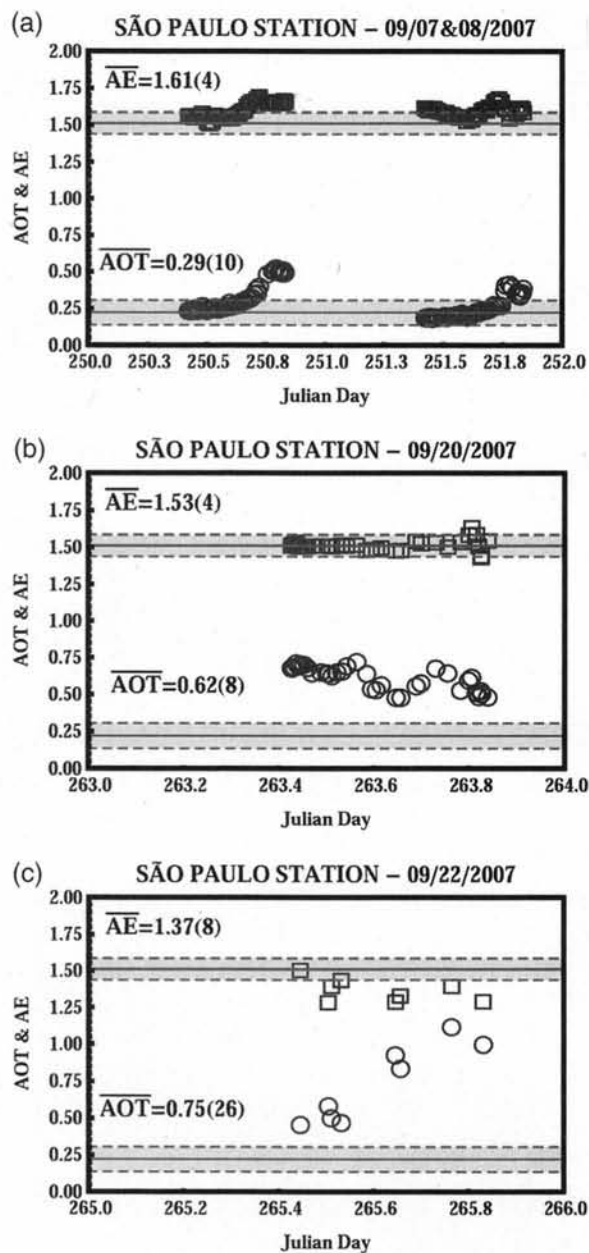


Figure 5. AOT and AE panel displays of cases A, B, and C (panels a, b, and c, respectively) with band-shaped areas limited by whole-period AOT and AE medians and their respective absolute median deviations. The values given are the mean (standard deviation) for each specific day.

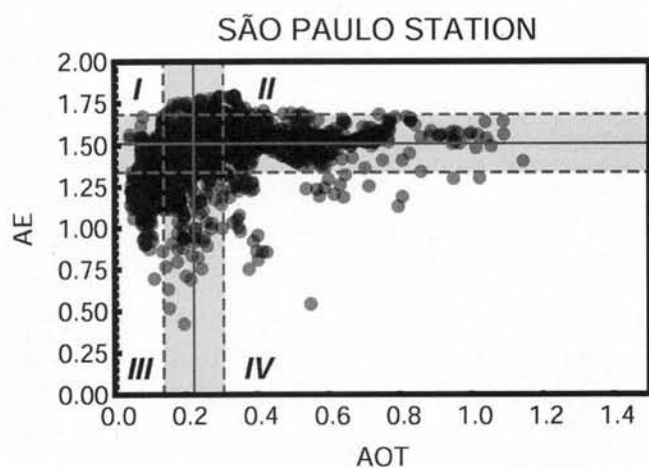


Figure 6. AE vs. AOT values for the São Paulo station in 2007 for the whole campaign period. This plot is split into distinct areas for the purpose of a systematic aerosol optical property characterization. The vertical and horizontal band-shaped areas are limited by the AOT and AET median values \pm their respective absolute median deviations.

period; however, Figure 5 shows in detail an increase in the AE values and AOT toward the end of each day. This variation could be associated with a change in the type of aerosol and its size. Furthermore, with the entrance of a seabreeze front a lot of moisture was brought to the region and interacted with the aerosols previously present in the observing area. The average AOT, AE pair values are equal to 0.29 (10), 1.61 (4) (number in parentheses represents the standard deviation). For these two days the AOT, AE pair would lie mostly in region II of Figure 6, corresponding to finer aerosols and a mildly absorbing AL.

The LR value found for the 2-day period was 43 (33), which is typical for an urban site such as São Paulo.²¹ However, the high standard deviation is an indication of high variability in this optical property; hence, the seabreeze effect noticed toward the end of September 7 should have played a definite role. In any case, long-range aerosol transport is not discarded and is therefore representative of the influence of higher altitude layers. A detailed study on this subject is currently under revision and should be addressed in another article.

Case B

Figure 3b shows the lidar data taken during September 20, 2007. It is possible to observe the PBL top at approximately 2400 m, and according to Figure 2, arrow B, there is a poor AQI of approximately 125. It is important to mention that the highest PBL value of approximately 3500 m occurred on September 14, which is a strong indication of improvement in the air quality dispersion conditions. However, the AQI was still high (~ 100), and indeed the air quality improved after then until September 19 and 20. In this process the maximum PBL height decreased down to 1000 m, therefore worsening the air dispersion conditions.

In Figures 4 and 5, a significant increase in the AOT value is noted; in fact, it reaches an average of 0.62 (8), whereas the AE remained at a typical value of 1.53 (4). These values would put the AOT, AE pair in regions II and

IV in Figure 6, and one might claim that the poor air quality conditions were related to the strongly absorbing AL for this day.

As observed with case A, the LR value of 46 (15) is representative for this type of region, but with less variability. This fact strongly supports that the air condition for the day is only due to the absorbing AL and its AOT value.

Case C

Figure 3c represents the lidar data corresponding to September 22, 2007. The PBL maximum height is 2000 m and a higher layer at 3000 m is also observed. This layer could also originate from an aerosol transport event that brought some moisture, which is evident by the formation of clouds around 2:00 p.m. local time. In Figure 2, arrow C, the AQI is the highest of the three cases shown at approximately 140. Despite the PBL high altitude, the air quality conditions are the poorest so far for this period and might be attributed to an incoming front into the city of São Paulo that "trapped" the pollutants because of the meteorological conditions.

In Figure 4, the increase in AOT values is very pronounced, along with a decrease in the AE values, which stayed around the median value in the previous cases. The AOT, AE pair average values are equal to 0.75 (26), 1.37 (8) and are clearly away from their corresponding median band-shaped areas as seen in Figure 5. According to Figure 6, these values would belong to region IV in the plot, therefore characterizing the ALs with mainly coarse, highly absorbing aerosols.

The LR value of 60 (6) is the highest among the case studies and could be typical of a highly polluted area and/or for biomass burning aerosol types that could have been transported into the São Paulo area. In effect, the poor air quality condition could be the result of different processes acting together, bringing it down to the lowest level of the whole period.

SUMMARY

This paper presents some results of a 3-month campaign of lidar measurements coordinated with sunphotometer measurements and daily reports from the local environmental agency. It was possible to observe the PBL daily variation and corresponding AQI values, making it possible to identify potential air dispersion conditions. With the lidar it was possible to realize the influence of meteorological conditions on the AL structure, and with the aid of a colocated sunphotometer, the AL optical properties were retrieved in a statistical analysis and by a systematic characterization. The methodology applied gives a more complete understanding of the relation between aerosol optical properties and direct air quality measurements, and a careful statistical analysis showed possible seasonal and more time-localized trends. To extend knowledge and to improve the database, more campaigns should be carried out, not only to improve data quality in a statistical way but also to verify seasonal trends in a fully equipment-related parametric data retrieval study.

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