Lidar measurements of tropospheric aerosol and water vapor profiles during the winter season campaigns over the metropolitan area of São Paulo - Brazil.

Fábio J. S. Lopes[a,b], Gregori A. Moreira[b] , Patricia F. Rodrigues[b], Juan Luis Guerrero-Rascado[c,d], Maria F. Andrade[a], Eduardo Landulfo[b]

[a]Instituto de Astronomia, Geofísica e Ciências Atmosféricas (IAG) - Universidade de São Paulo (USP), Rua do Matão 1226, Cidade Universitária, CEP 05508-090, São Paulo-SP, Brasil;
[b]Centro de Lasers e Aplicações (CLA) - Instituto de Pesquisas Energéticas e Nucleares (IPEN-CNEN), Av. Prof. Lineu Prestes 2242, Cidade Universitária, CEP 05508-000, São Paulo-SP, Brasil;
[c]Instituto Interuniversitario de Investigación del Sistema Tierra en Andalucía (IISTA-CEAMA), Av. del Mediterráneo, 18006, Granada, España;
[d]Dpto. Física Aplicada, Universidad de Granada, Fuentenueva s/n, 18071, Granada, España;

ABSTRACT

The so-called Metropolitan Area of São Paulo, one of the largest megacities in the world, faces several problems related to the air quality due the high concentrations of aerosols produced either by local sources or by long-range transporting. Concerned with the elevated concentrations of aerosol and their impact in the air quality and the climate changes inside MASP, a measurement campaign were conducted during the South hemisphere winter of 2012, when the low temperatures and the low level of precipitation contribute to the poor dispersion of aerosols. A Raman Lidar system and air quality monitoring stations from University of São Paulo and Environment Agency of São Paulo State (CETESB) were employed in order to monitor the increasing of aerosol load in the atmosphere. Satellite data, in synergy with HYSPLIT air masses backward trajectories, were applied to track the aerosol from the long-range distanced regions to Metropolitan Area of São Paulo. In the beginning of September 2012, MASP experienced episodes of high air pollution concentration, reaching Aerosol Optical Depth (AOD) values up to 0.89 at 550 nm and particulate matter concentration up to 293 $\mu g/cm^3$. Particle lidar ratio values of 60 to 70 sr retrieved by a Raman Lidar system at 532 nm provided information of the aerosol type, helping to determine the influence of biomass burning advected from large range distance to megacities such as São Paulo.

Keywords: Raman Lidar, CALIPSO, MODIS, AERONET, aerosols, biomass burning, Brazil, particulate matter

1. INTRODUCTION

The Earth's radiation budget is drastically impacted by aerosol and clouds, since their physical and optical properties affect the scattering and absorption processes of incoming solar radiation and also the outcoming longwave terrestrial radiation.[1] Nowadays, aerosols represent a huge challenge for the atmospheric science field that has been searching for understanding the aerosol contributions to the climate change processes with some degree of accuracy.[2] The challenges come from the fact that aerosols can influence in the climate change processes in different ways. In a direct manner, they can act to warm or either cool the atmosphere, and as an indirect manner, they can act as a cloud condensation nuclei (CCN) affecting the concentration, size and lifetime of clouds.[3–5] Since aerosols affect climate processes on both local and global scales, representing a large source of uncertainties in the prediction of climate changes, cities with population higher than 10 million of

Further author information: (Send correspondence to Fabio Lopes)
E-mail: fabiolopes@usp.br, Telephone: 55 11 3133-9372

Lidar Technologies, Techniques, and Measurements for Atmospheric Remote Sensing X, edited by Upendra N. Singh, Gelsomina Pappalardo, Proc. of SPIE Vol. 9246, 92460H
 · doi: 10.1117/12.2067374

inhabitants, and thus with different sources of pollution, can represent a key role in the global process of climate change.[6] One of five largest cities in the world, the Metropolitan Area of São Paulo (MASP) has more than 20 million of inhabitants. Considered the richest and the most developed region of Brazil, MASP has several sources of particulate matter pollution, the mainly one comes from the automotive fleet, achieving the amount higher than 8 million of vehicles, of which 84.9% are light-duty vehicles, 5.8% are heavy-duty vehicles, and 9.3% are motorcycles.[7] This fleet can be considered unique since most of the vehicles are fueled by ethanol or by a gasoline-ethanol mixture.[8] This large automotive fleet contributes to degrade of air quality at MASP, especially during the winter season when a high-pressure semi static regime over the São Paulo city is often observed.[9,10] This event becomes highly favorable for air pollutant accumulation, especially during episodes of intense temperature inversions, occurring typically at very low altitudes, less than 1000 m.[11] During this period the particulate matter concentration index can achieve values higher than those recommended by Environment Pollution Agency (EPA), causing several health problems on the population and increasing the morbidity and mortality due to respiratory or diseases.[12,13] The air quality index and particulate matter concentration in the MASP is provided by São Paulo Sanitation Technology Company (CETESB), which has 26 air quality stations and is responsible for monitoring and controlling the air quality environment through Environmental Protection Agency (EPA)-certified.[14] The air quality network provides near-real time air quality data report based on hourly averages that are available in a web platform. Hourly air quality reports take into account several pollutants such as sulfur dioxide, ozone, nitrogen dioxide, carbon monoxide, sulfur monoxide, and particulate matter, both $PM_{2.5}$ and PM_{10}. Besides of local pollution sources, in certain periods of the year, mainly during the winter station, from July to September, MASP suffers from the advection of aerosols transported from long-range distance areas in the North and Central-Western portion of Brazil, and also from different areas of South American Continent. As part of the Megacities Project NUANCE-SPS (NARROWING THE UNCERTAINTIES ON AEROSOL AND CLIMATE CHANGES IN SAO PAULO STATE), which comprises the study of aerosol particles in the atmosphere, addressing their sources, their evolution in the atmosphere and the potential impact on the climate and human health, the present study intends to explore aerosol optical properties, their vertical distribution and particulate matter concentration employing remote sensing ground-based instruments, and also to track the long-range transport of aerosols and to identify their optical properties and their type using satellite data. An episode of increasing of AOD and PM_{10} concentration related to a biomass burning transportation event detected in the beginning of September 2012 using a Raman Lidar system and long-range tracked using HYSPLIT air masses trajectories in synergy with Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and AQUA satellite retrievals is presented.

2. INSTRUMENTS

A biaxial mode single wavelength elastic and Raman Lidar system (MSP-Lidar II) installed at the Nuclear and Energy Research Institute (IPEN) was employed to measure independently profiles of the particle extinction and backscatter coefficients and, thus, the respective particle extinction-to-backscatter ratio at 532 nm.[15] A frequency-doubled Nd:YAG laser (CFR200) is used as the light source. It emits pulses energy of 120 mJ nominal at the 532 nm, with a repetition rate of 20 Hz and pulse duration of 9.2 ns. The light beam is expanded by a factor of 3, in order to reduce the divergence of the expanded beam less than 0.2 mrad. The laser beam is vertically directed to the atmosphere and the backscattered radiation is collected with a Cassegrain telescope that has a primary mirror diameter of 200 mm and a focal length of 800 mm. The receiver field of view is set to 1.25 mrad, and thus the complete overlap of laser beam and the telescope field of view is observed at altitudes higher than 300 m above the Lidar system, which limits the minimum range of our measurements. After separating and passing the respective interference filters, the photons elastically backscattered at the 532 nm wavelength and the photons inelastically (Raman) scattered by nitrogen molecules at 607 nm are detected with photomultiplier tubes (PMTs, Hamamatsu type R9880U-110). The bandwidth of the filters in 532 and 607 nm channels are 0.5 and 1 nm, respectively. LICEL receiving electronics has provision to operate both in analog and photon counting mode and to record data in 12-bit resolution. Data are averaged every 2 min, with a typical height resolution of 7.5 m. Since Raman signal is too weak to be detected under bright daytime conditions, measurements are proceed only during night-time, when the return signal no longer suffers from the

solar background interference.[16,17] In addition, the Raman signal is amplified and acquired by a photon counting mode. Since 2008 the MSP-Lidar II system is part of LALINET (http://lalinet.org), that is a coordinated lidar network focused on the vertically-resolved monitoring of the particle optical properties distribution over Latin America.[18]

The CALIPSO satellite was launched in April 2006 and flies in a 705 km sun-synchronous polar orbit with an equator-crossing time of about 13:30 local solar time, covering the whole globe in a repeat cycle of 16 days.[19] The primary instrument aboard CALIPSO is the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), a two-wavelength laser (532 nm and 1064 nm) operating at a pulse repetition rate of 20.16 Hz.[20] The CALIOP data products are assembled from the backscattered signals measured by the receiver system and are divided in two categories: level 1 products and level 2 products. Level 1 products are composed of calibrated and geolocated profiles of the attenuated backscatter signal and are separated into the total attenuated backscatter profile at 1064 nm, the total attenuated backscatter profile at 532 nm (i.e., the sum of parallel and perpendicular signals) and the perpendicular attenuated backscatter signal at 532 nm.[19,21] The level 2 products are derived from the level 1 products and three different level 2 products are distributed according to the layer products, profile products and the vertical feature mask (VMF). The set of CALIPSO algorithms uses an aerosol classification scheme to assign each aerosol layer to one of the six aerosol types, namely dust, biomass burning, clean continental, polluted continental, marine, and polluted dust.[22] Several validation studies were conducted to show the accuracy of the CALIPSO aerosol classification scheme,[23–26] including in the South America region.[27]

The Moderate Resolution Imaging Spectrometer (MODIS) sensor is on board the polar orbiting satellites AQUA launched in 2002. The sensor was the first designed to obtain global observations of aerosols with moderate resolution (between 250 m and 1000 m depending on the wavelength used). MODIS has 36 spectral bands between 0.4 and 14.5 $\mu\,m$, allowing the generation of several products related to aerosol, such as aerosol optical depth over the ocean and land with a resolution of 10x10 km (at nadir), and the size and type distribution over oceans and type of aerosol over the continent.[28,29] In this study 550 nm AOD product from aerosol Level 2 were used.

The AErosol RObotic NETwork (AERONET)[30] is an international system of ground-based sun photometers that provides automatic sun and sky scanning measurements. Using direct sun measurements, AERONET provides both AOD and the Ångström Exponent (Å), which gives the wavelength dependence of the AOD. By using multiangular and multispectral measurements of atmospheric radiance and applying a flexible inversion algorithm,[31] the AERONET data can also provide several additional aerosol optical and microphysical parameters, such as size distributions, single-scattering albedo and refractive index. The operating principle of this system is to acquire aureole and sky radiance observations using a large number of solar scattering angles through a constant aerosol profile, and thus retrieve the aerosol size distribution, the phase function and the AOD.

3. RESULTS AND DISCUSSION

A measurement campaign was coordinated during the Southern hemisphere winter season, from July to September 2012. The period considered is the dry season at the Southeastern part of Brazil, where MASP is located. During the winter/dry season MASP can experience episodes of strong stable layer between the boundary layer and the free troposphere. This stable capping inversion can trap pollutants and avoid their dispersion, contributing to episodes of high concentration of particulate matter. However, in this region, high pollution episodes can also be intensified by the transport of aerosol biomas s burning from different parts of Brazil and South America continent.

As a first step, coarse mode particulate matter (PM_{10}) concentrations from the CETESB air quality stations, AQUA/MODIS and CALIPSO/CALIOP AOD retrievals for cloud-free days during the campaign period are derived. The CETESB air quality station installed at Ibirapuera Park, at 8 km from MSP-Lidar II system, registered mean values of PM_{10} concentrations of $41 \pm 28\,\mu g/m^3$, $41 \pm 25\,\mu g/m^3$ and $54 \pm 49\,\mu g/m^3$, for July, August and September, respectively. All these mean values are higher than the particulate matter standards recommended by U.S. Environmental Protection Agency (http://www.epa.gov/airquality/particlepollution/) and also by World Health Organization.[32] The means values of AOD retrieved from AQUA/MODIS for July, August

and September, respectively, are 0.15 ± 0.09, 0.15 ± 0.06 and 0.38 ± 0.16. These results show a large increasing in the particulate matter concentration on September 2012, as can also be seen in the temporal distribution of PM_{10} concentrations and AOD values retrieved by MODIS and CALIOP systems, presented in figure 1. The same figure shows in the first half of September an evident increasing in AOD values retrieved by MODIS and CALIOP systems, both in agreement to the increasing of PM_{10} concentrations.

A linear correlation between MODIS AOD retrievals and daily mean PM_{10} observations from Ibirapuera Station is derived using only cloud-free days. A reasonably correlation of $R = 0.60$ are found for this period, with a slope of $110.87\,\mu g/m^3$ and intersection value of $30.67\,\mu g/m^3$ within 30 cases analyzed, depicted in figure 2. These results show a good correlation between different instruments used to monitoring the air pollution conditions within the Metropolitan area of São Paulo.

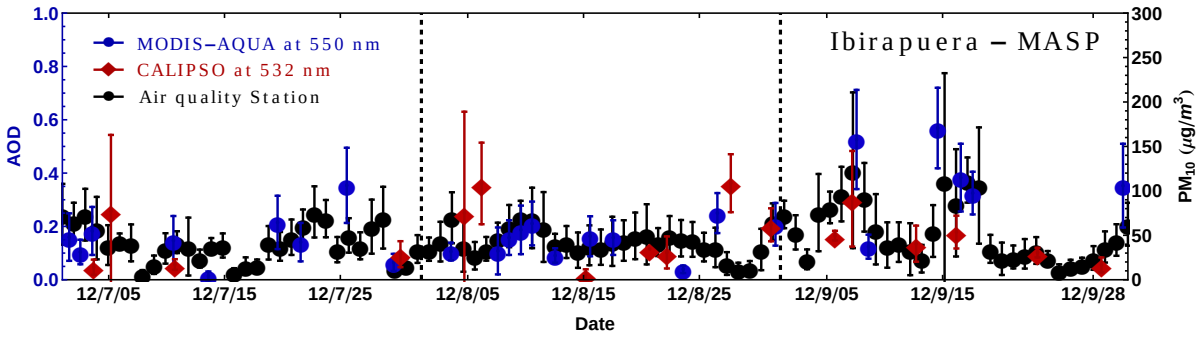

Figure 1. Temporal distribution of AOD values from MODIS and CALIOP systems and PM_{10} concentration from Ibirapuera CETESB station at MASP, for the period of July to September of 2012.

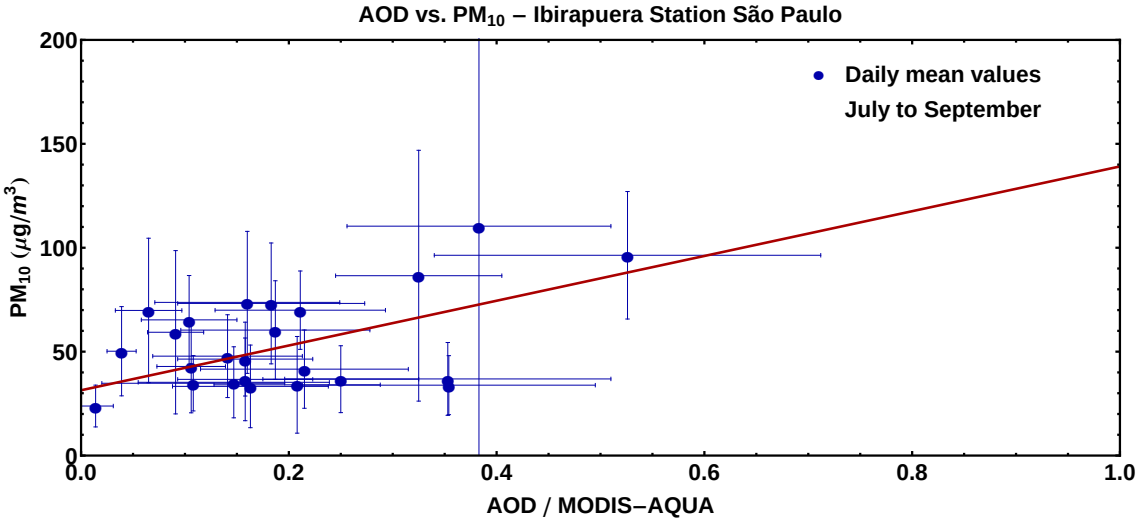

Figure 2. Scatterplot correlation between AQUA/MODIS AOD retrievals and CETESB air quality station PM_{10} concentration for cloud-free cases during July to September 2012 measurement campaign at MASP.

The large increasing of PM_{10} and also the AOD values in September may be much more associated with aerosols transported from long-range distance location to MASP than to a local episode of pollution. In order to better understand the increasing of particulate matter concentration at MASP, different analysis using several tools have been employed. HYSPLIT trajectory model[33] was used to calculate backward trajectories and derive information

from where, when and which altitude aerosols layers were transported to MASP. Five-days back-trajectories of air-masses starting at the MSP-Lidar II coordinates ($Lat : 23.56° S$ and $Long : 46.74° W$) were calculated, using the GDAS database from Global Data Assimilation System, for six different altitudes ranging from 1000 to 4000 m above ground level (a.g.l.). The back-trajectories starting at 12, 15, 18 and 21 UTC and with altitude level from 1000 to 2500 m a.g.l. came originally from North and North-Western direction. For all initial hours, the air masses trajectories at altitude level from 3000 to 4000 m a.g.l. came from Central-Western part of Brazilian territory, and thus it can be expected that biomass burning aerosols were advected from this source region to MASP, as depicted in figure 3.

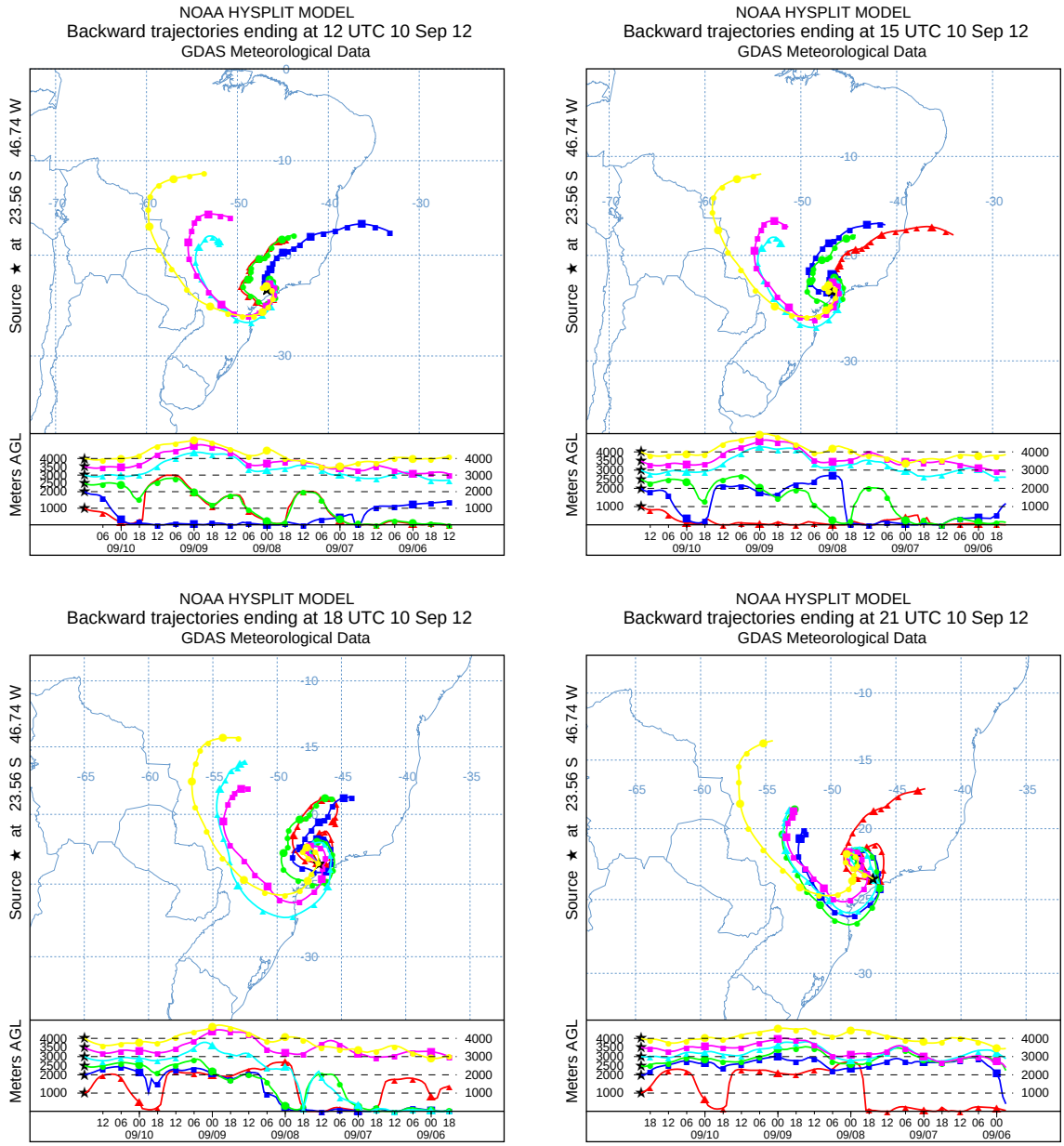

Figure 3. Five-day backward trajectories ending at MASP at 12, 15, 18 and 21 UTC, at different levels 1000, 2000, 2500, 3000,3500, 4000 m a.g.l.) on September 10^{th} 2012 at MSP-Lidar II measurement site.

According to the National Institute for Space Research INPE (http://sigma.cptec.inpe.br/queimadas/estatisticas.php), the total of fire focus registered in 2012 was 193,838; increasing approximately 32% comparing with the previous year. From the total number of focus fire, more than 62% of cases occurred only during July, August and September, with monthly occurrences of 13,508; 46,289 and 62,099; respectively. Figure 4 depicts the number of focus fire cases during the whole year of 2012 and the large increasing during the mentioned period.

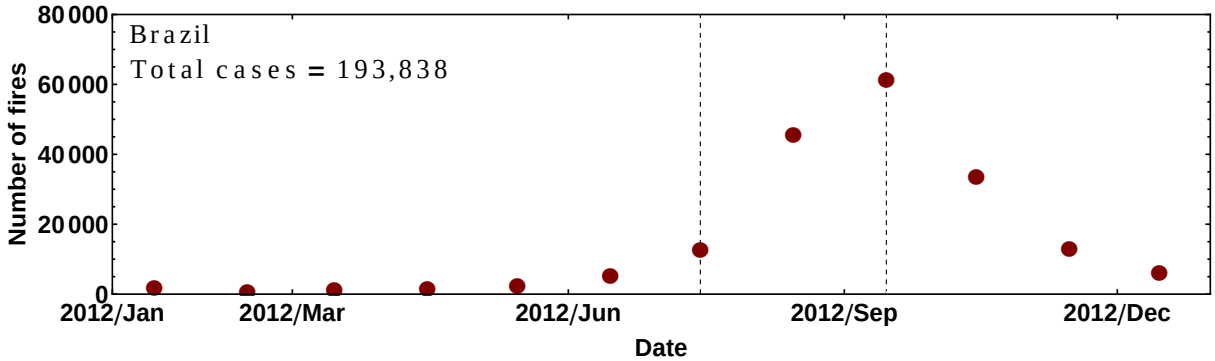

Figure 4. Temporal distribution of the number of focus fire cases in the Brazilian territory during the year of 2012 retrieved by the National Institute for Space Research-IPEN. The peak with the large number of focus fire was achieved in September.

It is well known that high concentrations of biomass burning aerosol particles, produced mainly in the Amazon basin and the Brazilian Central-Western region, can be detected due fire activities in the tropical forest, savanna and pasture during the dry season,[34] and a portion of the biomass burning aerosol can be transported from long-range distances and it can be detected over São Paulo State and over Metropolitan Area of São Paulo.[35,36] By taking it into account, AERONET Level 2 data from Cuiabá-Miranda Station were employed to investigate the optical properties of aerosols over the Central-Western region of Brazil during the period of this measurement campaign. The Cuiabá-Miranda station ($Lat : 15.73^\circ\ S$ and $Long : 56.02^\circ\ W$) is located at the same region where the air masses trajectories has initiated in the HYSPLIT calculation presented in figure 3. During the mentioned period the mean AOD and Ångström Exponent values retrieved at Cuiabá-Miranda station were 0.22 ± 0.24 and 1.32 ± 0.27. From this total, 23% of the cases lying down in the sector II, with AOD and Ångström Exponent values higher than their respective median values, which correspond to fine mode (high Ångström Exponent values) and high absorption (high values of AOD) aerosol types, as shown in figure 5. The sector II can be associated to the predominance of biomass burning aerosols in the atmosphere as the large Ångström Exponent values corresponds to small sized particles and the large AOD correspond to strong absorbing aerosols.[37] The temporal distribution of AOD retrieved at the same AERONET station shows a large increasing of aerosol quantity at the end of August and beginning of September. AOD values retrieved by MODIS/AQUA and CALIOP sensors show good agreement between the three instruments, as depicted in figure 6.

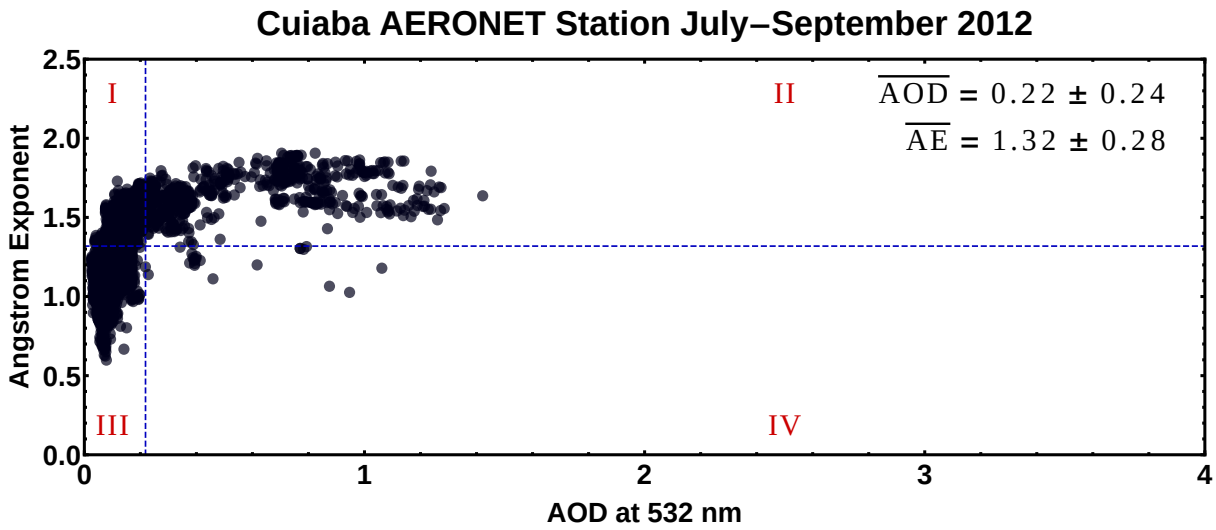

Figure 5. Scatterplot of Aerosol Optical Depth at 532 nm vs. Ångström Exponent calculated in the range of 440-675 nm for July to September 2012 retrieved by Cuiabá-Miranda AERONET station. The four distinctive sectors are related to different types and sizes of aerosol according to the AOD and Ångström Exponent values.

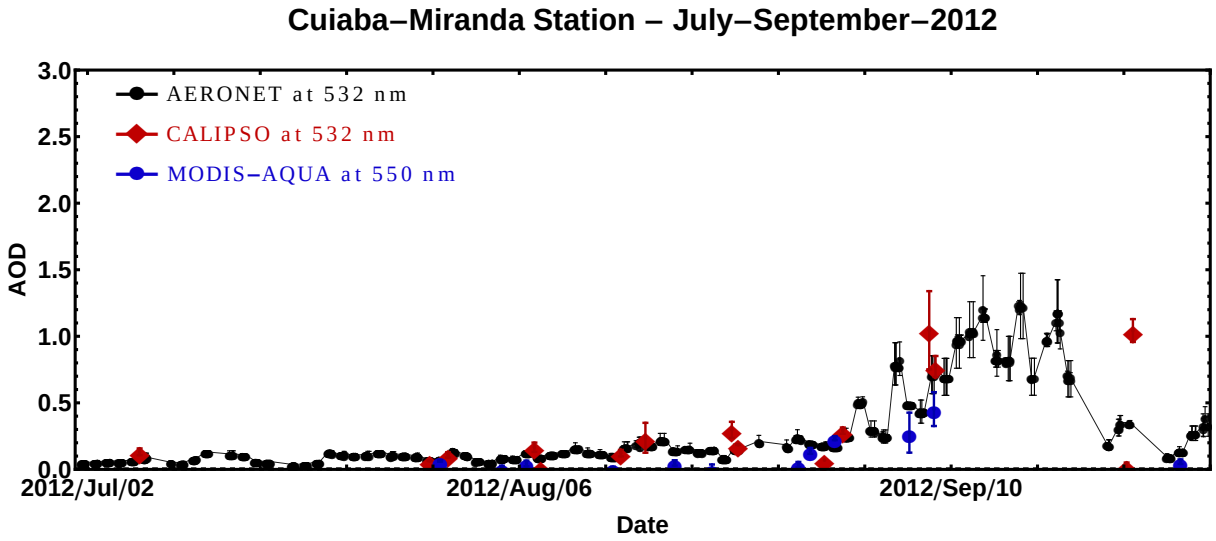

Figure 6. Temporal distribution of AOD retrived by Cuiabá-Miranda AERONET station, and from MODIS/AQUA and CALIOP sensors during the period of July to September 2012, for cloud-free days. The error bars take into account variations from the daily average values.

Some studies indicate that a bi-modal lognormal function is the most appropriate model for aerosol particle size distributions,[38,39] and it can represents several types of aerosols. Level 2 inversion data from AERONET were employed to derived the lognormal size distribution of aerosol for the measurement campaign period. As can be seen in figure 7, the log-normal distribution considerably changes during this period. Mostly of aerosols can be found in the coarse mode range distribution in July and August, however the scenario surprisingly changes in September, when the larger portion of aerosol were in fine mode range distribution. It represents a strong evidence of mostly of aerosols detected were derived from biomass burning events,[40] which can be corroborated

with the extinction-to-backscatter ratio (CALIPSO lidar ratio - S_{caliop}) values assigned by CALIPSO satellite and also, the extinction-to-backscatter ratio (AERONET lidar ratio - $S_{aeronet}$) calculated employed by the single scattering albedo ($\omega(\lambda)$) and the 180° phase function ($P(180°)$) from inversion data from AERONET using the following equation,

$$S_{aeronet} = \frac{4\,\pi}{\omega(\lambda)\,P(180°)}. \tag{1}$$

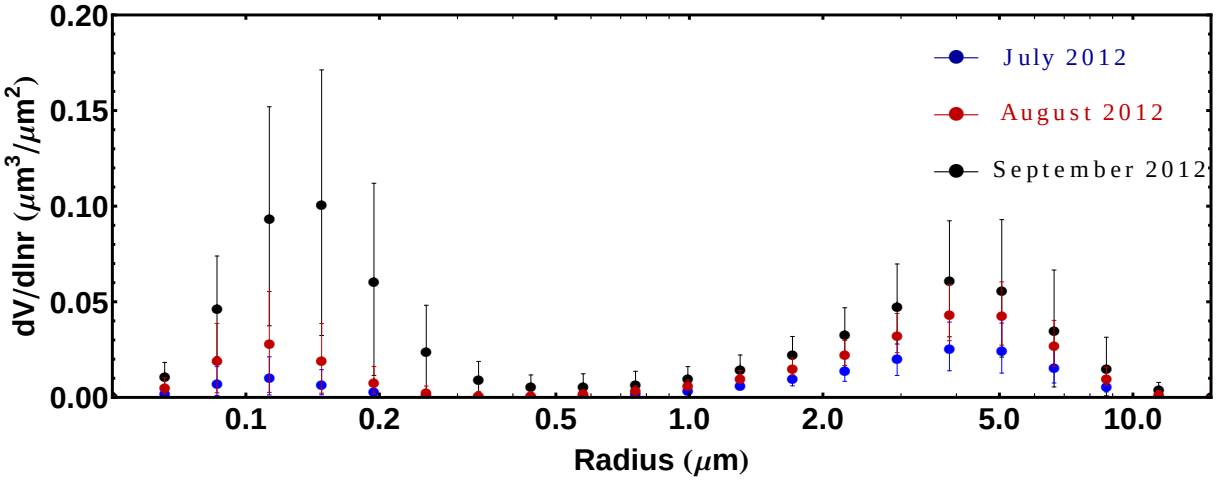

Figure 7. Monthly mean lognormal size distribution retrieved by Cuiaba-Miranda AERONET station during the period of July to September of 2012, for cloud-free days. The error bars take into account variations from the average values during the measuring period.

CALIOP lidar ratio values vary from 40 to 55 sr from July to August, while AERONET lidar ratio vary mostly between 55 to 70 sr, presented in figure 8. According to CALIOP lidar ratio chart, this values can be associate to dust and polluted dust aerosol type.[22] From the middle of August to the end of September CALIOP lidar ratio values is assigned as 70 sr, and classified as biomass burning aerosol for layers above the boundary layer and polluted continental for low altitude layers. Moreover, the AERONET lidar ratio vary from 60 to 75 sr. It is important to note that in the beginning of September, lidar ratio from CALIOP and AERONET, both provide values of 70 sr which can be mostly related to biomass burning aerosol type.[37] Mean values of Saer and Scaliop for the whole period are $57.7 \pm 12.6\,sr$ and $59.1 \pm 10.6\,sr$, respectively, showing a very good agreement, which is expected according to the CALIOP-AERONET validation study conducted in South American region.[27]

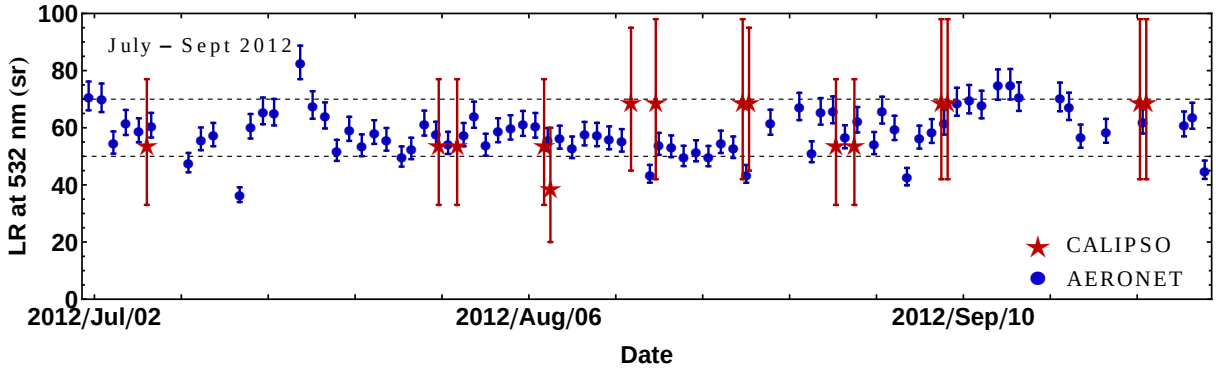

Figure 8. Particle lidar ratio temporal distribution calculated by employing level 2 AERONET inversion data and CALIOP assigned values for Cuiabá-Miranda AERONET station during the period of July to September 2012. The error bars take into account variations from the daily average values for AERONET and the assigned standard deviation for the CALIOP lidar ratio .

Mesurements of aerosol vertical distribution was conducted for several days during the campaign, however, in this study we will focus in a Lidar Raman measurement on September 10^{th}, when the air masses trajectories arrived at MASP according to HYSPLIT analysis presented in figure 3. The time evolution of Lidar range corrected signal for this specific day, depicted on figure 9, shows a planetary boundary layer (PBL) loaded by large quantity of aerosols, verified by the color red which represents large backscattered signals detected by MSP-lidar II. PBL heights were calculated applying two differents methods, Wavelet Covariance Transform (WCT) and the gradient method.[41–44] The mean PBL height during the whole period were 572 m a.g.l obtained by the Gradient method, and 970 m a.g.l. according to the WCT method. The range corrected signal also shows a significant quantity of aerosols load in the free troposphere. A portion of these aerosols aloft above the PBL might have been transported from the Central-Western region of Brazil to MASP according to the HYSPLIT air masses trajectories on figure 3.

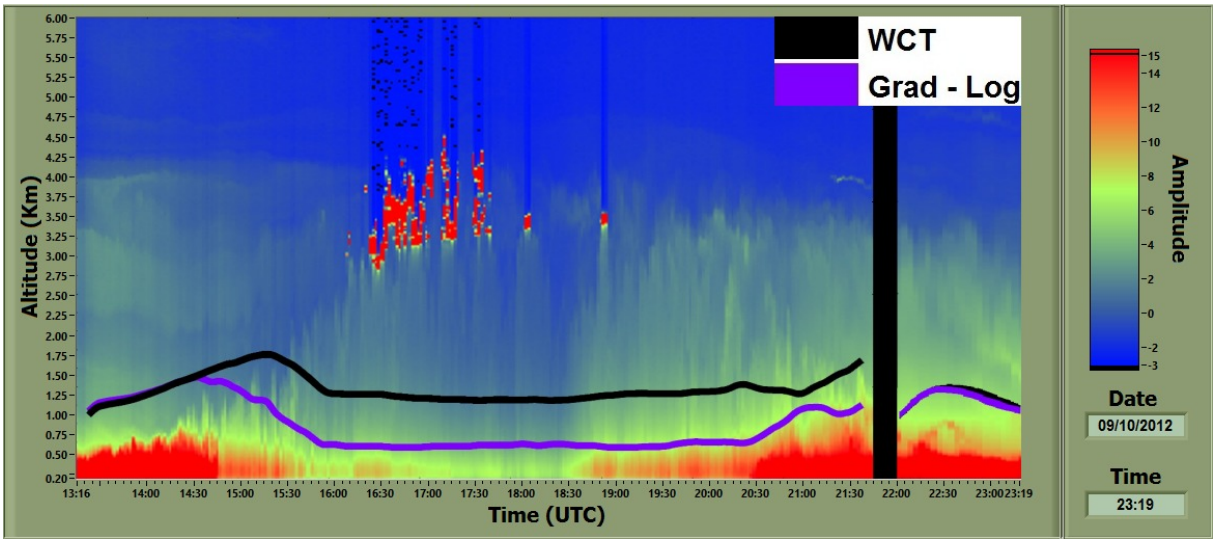

Figure 9. MSP-Lidar II range corrected signal and the Planetary boundary layer altitude retrieved by WCT and gradient method for measurement on September 10^{th}, 2012.

For this specific day, Lidar measurements were conducted since 13:00 UTC to around 23:20 UTC. Figure 10 shows the particle backscatter, extinction and Lidar ratio profiles at 532 nm for September 10^{th} from 21:52 to 23:03 UTC measured at MASP. Raman backscatter and extinction profiles show aerosol layers above the PBL. Large quantities of aerosol are detected up to 3000 m a.g.l. and smooth aerosol layers are detected between 5000 to 6000 m. Particle Lidar ratio was derived using independent retrieval of backscatter and extinction profiles. The Lidar ratio profile from 900 m to around 4000 m a.g.l. ranging from 60 to 100 sr. Mean Lidar ratio values for this altitude region and for altitudes between 5500 to 6000 m a.g.l. are $77 \pm 19\,sr$ and $79 \pm 22\,sr$, respectively. Figure 3 depicted HYSPLIT backward trajectories coming from the Central-Western region of Brazil and arriving over MASP on 21 UTC at altitudes ranging from 2000 to 4000 meters a.g.l., in turn, the Lidar ratio profile for this period time presents Lidar ratio values of 60-70 sr, which are in agreement with Lidar ratio values for biomass burning aerosol retrieved by Cuiabá-Miranda AERONET station and also CALIOP sensor (figure 8). The Lidar ratio values retrieved by MSP-Lidar II are in agreement with lidar ratio values for biomass burning aerosol obtained in other studies.[22, 45, 46]

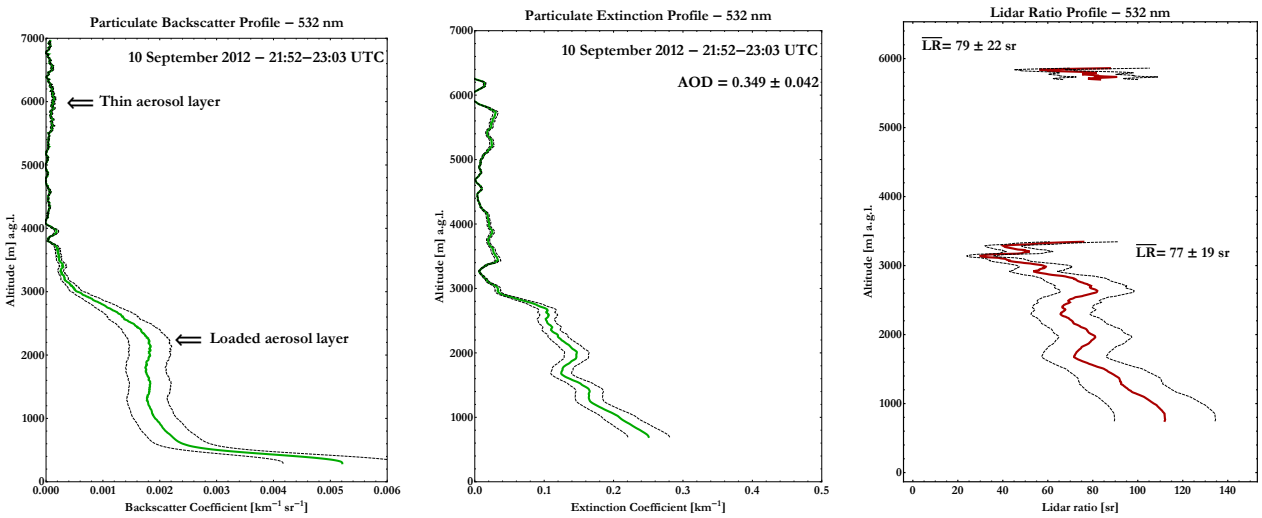

Figure 10. Vertical profiles of aerosol extinction and backscatter coefficients, and Lidar ratio at 532 nm retrieved by Raman measurements during night-time on September 10^{th} at MASP. The error bars were calculated considering the effect of signal noise in the final retrieval.

4. CONCLUSIONS

During July to September of 2012, a measuring campaign had been carried out in Metropolitan area of São Paulo, using a ground-based Raman Lidar system, air quality stations, AQUA and CALIPSO satellites data in order to monitor the particulate matter concentrations and AOD and identify any extreme pollution case. Results showed a large increasing of PM_{10} concentrations and also AOD retrieved from MODIS and CALIOP system on the month of September of 2012. Ground-based AERONET sunphotometer installed at Cuiabá-Miranda Station in the Central-Western region of Brazil in synergy with CALIOP and MODIS have shown a large increasing of AOD in the atmosphere on the end of August and beginning of September. Lidar ratio retrieved by AERONET inversion data and also by CALIPSO layer products showed a predominance of biomass burning aerosol type in this region, with can be corroborated by the increasing number of focus fire detected all over the Brazilian territory. Air masses backward trajectories obtained by HYSPLIT model suggested that biomass burning aerosols were advected to MASP on the beginning of September in several altitudes, ranging from 2000 to 4000 meters a.g.l.. Aerosol layers in the free troposphere were detected by the MSP-Lidar II according to the particle backscatter and extinction profiles. Independent Lidar ratio profile values between 60

to 70 sr verified the presence of biomass burning over MASP. This study demonstrates the powerful combination between ground-based and satellite remote sensing instruments and also air masses modeling to investigate the transport of aerosol from long-range pollution sources which can affect the air quality in megacities such as São Paulo.

Acknowledgments

This work was supported by FAPESP (Fundação da Amparo à Pesquisa do Estado de São Paulo) through the Posdoctoral project 2011/14365-5 and the thematic project 2008/58104-8; in a collaboration between the Institute of Astronomy, Geophysics and Atmospheric Sciences (IAG) of the University of São Paulo (USP) and Nuclear and Energy Research Institute (IPEN), and by the University of Granada through the contract "Plan Propio. Programa 9. Convocatoria 2013". The authors would like to acknowledge the Center for Lasers and Applications for supporting the project, the entire CALIPSO team for their substantial contributions and for the data obtained from the NASA Langley Research Center, specially Ali Omar and Mark Vaughan. They also acknowledge the team of AERONET sunphotometer network and Paulo Artaxo, the PI of AERONET Cuiabá-Miranda site, and NOAA Air Resources Laboratory for providing the HYSPLIT transport and dispersion model

REFERENCES

1. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. L. Miller, ***Climate Change 2007: The Physical Science Basis***, Cambridge University, New York and United Kingdom, 1st ed., 2007.
2. O. Boucher, D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S. Satheesh, S. Sherwood, B. Stevens, and X. Zhang, "**Clouds and Aerosols**," in ***Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change***, T. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley, eds., Cambridge University Press, United Kingdom and New York, 2013.
3. R. J. Charlson, S. E. Schwartz, J. M. Hales, R. D. Cess, J. C. Jr., J. E. Hansen, and D. J. Hofmann, "Climate forcing by anthropogenic aerosols," ***Science*** **225**, pp. 423–430, 1992.
4. T. L. Anderson, R. J. Charlson, M. Winker, J. A. Ogren, and K. Holmén, "Mesoscale Variations of Tropospheric Aerosols," ***Journal of Atmospheric Sciences*** **60**, pp. 119–136, 2003b.
5. T. L. Anderson, R. J. Charlson, S. E. Schwartz, R. Knutti, O. Boucher, H. Rodhe, and J. Heintzenberg, "Climate forcing by aerosols - a hazy picture," ***Atmospheric Sciences*** **300**(5622), pp. 1103–1104, 2003.
6. T. Zhu, M. Melamed, D. Parrish, M. Gauss, L. G. Klenner, M. Lawrence, A. Konare, and C. Liousse, ***WMO/IGAC Impacts of megacities on air pollution and climate***, World Meteorological Organization, Switzerland, 2012.
7. CETESB, "**Qualidade do ar no Estado de São Paulo**," tech. rep., Companhia Ambiental do Estado de São Paul -CETESB, 2011.
8. L. D. Martins, M. F. Andrade, E. D. Freitas, A. Pretto, L. Gatti, E. L. Albuquerque, E.Tomaz, M. L. Guardani, M. H. R. B. Martins, and O. M. A. Junior, "Emission factors for gas-powered vehicles traveling through road tunnels in São Paulo city, Brazil," ***Environ. Sci. Technol.*** **40**(21), pp. 6722–6729, 2006.
9. O. R. Sánchez-Ccoyllo, R. Y. Ynoue, L. D. Martins, R. Astolfo, R. M. Miranda, E. D. Freitas, A. S. Borges, A. Fornaro, H. Freitas, A. Moreira, and M. F. Andrade, "Vehicular particulate matter emissions in road tunnels in são Paulo, Brazil.," ***Environ. Monit. Assess.*** **149**(1-4), pp. 241–249, 2006.
10. M. F. de Andrade, R. M. de Miranda, A. Fornaro, A. Kerr, B. Oyama, P. A. de Andre, and P. Saldiva, "Vehicle emissions and $PM_{2.5}$ mass concentrations in six brazilian cities," ***Air Qual. Atmos. Health*** **5**, pp. 79–88, 2012.

11. E. Landulfo, F. J. S. Lopes, G. L. Mariano, A. S. Torres, W. C. de Jesus, W. M. Nakaema, M. Jorge, and R. Mariani, "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," ***J. Air & Waste Manage. Assoc.*** **60**, pp. 386–392, 2010.
12. F. R. Silva, U. P. Santos, P. Saldiva, L. F. A. Loureno, and S. Miraglia, "Health risks and economic costs of absenteeism due to air pollution in São Paulo, Brazil," ***Aerosol Air. Qual. Res.*** **12**(5), pp. 826–833, 2012.
13. D. Veronez, L. Kulay, P. Saldiva, and S. Miraglia, "A cost-benefit evaluation of the air quality and health impacts in São Paulo, Brazil," ***J. Environ. Prot.*** **3**(9A), pp. 1161–1166, 2012.
14. CETESB, ***Qualidade do ar no Estado de São Paulo***. Companhia Ambiental do Estado de São Paulo-CETESB, 2013.
15. E. Landulfo, M. P. M. P. Jorge, G. Held, R. Guardani, J. Steffens, S. A. F. Pinto, I. R. Andre, G. Garcia, F. J. S. Lopes, and G. L. M. R. F. da Costa; P. F. Rodrigues, "Lidar observation campaign of sugar cane fires and industrial emissions in the State of São Paulo, Brazil," in ***Proc. SPIE, Lidar Technologies, Techniques, and Measurements for Atmospheric Remote Sensing VI***, **7832**, 2010.
16. A. Ansmann, M. Riebesell, and C. Weitkamp, "Measurement of atmospheric aerosol extinction profiles with a Raman lidar," ***Opt. Lett.*** **15**(13), pp. 746–748, 1990.
17. W. Whiteman, "Examination of the traditional raman lidar technique," ***Appl. Opt.*** **42**(15), pp. 2571–2592, 2003.
18. J. L. Guerrero-Rascado, E. Landulfo, J. C. Antuña, H. M. J. Barbosa, B. Barja, A. E. Bastidas, A. E. Bedoya, R. F. da Costa, R. Estevan, R. N. Forno, D. A. Gouveia, C. Jimnez, E. G. Larroza, F. J. S. Lopes, E. Montilla-Rosero, G. A. Moreira, W. M. Nakaema, D. Nisperuza, L. Otero, S. Papandrea, E. Pawelko, E. J. Quel, P. Ristori, P. F. Rodrigues, J. Salvador, M. F. Sánchez, and A. Silva, "Towards an instrumental harmonization in the framework of LALINET: dataset of technical specifications," in ***Proc. SPIE, Lidar Technologies, Techniques, and Measurements for Atmospheric Remote Sensing X***, in press.
19. D. M. Winker, M. A. Vaughan, A. Omar, Y. Hu, K. A. Powell, Z. Liu, W. H. Hunt, and S. A. Young, "Overview of the CALIPSO mission and CALIOP data processing algorithms," ***J. Atmos. Oceanic Technol.*** **26**, pp. 2310–2323, 2009.
20. W. H. Hunt, D. M. Winker, M. A. Vaughan, K. A. Powell, P. L. Lucker, and C. Weimer, "CALIPSO Lidar Description and Performance Assessment," ***J. Atmos. Oceanic Technol.*** **26**, pp. 1214–1228, 2009.
21. C. A. Hostetler, Z. Liu, J. Reagan, M. A. Vaughan, D. M. Winker, M. Osborn, W. H. Hunt, K. A. Powell, and C. Trepte, "**CALIOP Algorithm Theoretical Basis Document - Calibration and Level 1 data products**," *Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations* **PC-SCI-201**, pp. 1–66, 2006.
22. A. H. Omar, D. M. Winker, C. Kittaka, M. A. Vaughan, Z. Liu, Y. Hu, C. R. Trepte, R. R. Rogers, R. A. Ferrare, K. Lee, R. E. Kuehn, and C. A. Hostetler, "The CALIPSO automated aerosol classification and Lidar Ratio Selection Algorithm," ***J. Atmos. Oceanic Technol.*** **26**, pp. 1994–2014, 2009.
23. R. E. Mamouri, V. Amiridis, A. Papayannis, E. Giannakaki, G. Tsaknakis, and D. S. Balis, "Validation of CALIPSO space-borne-derived attenuated backscatter coefficient profiles using a ground-based lidar in Athens, Greece," ***Atmos. Meas. Tech.*** **2**, pp. 513–522, 2009.
24. R. R. Rogers, C. A. Hostetler, J. Hair, R. A. Ferrare, Z. Liu, M. D. Obland, D. B. Harper, A. L. Cook, K. A. Powell, M. A. Vaughan, and D. M. Winker, "Assessment of the CALIPSO Lidar 532 nm attenuated backscatter calibration using the NASA LaRC airborne High Spectral Resolution Lidar," ***Atmos. Chem. Phys.*** **11**, pp. 1295–1311, 2011.
25. S. P. Burton, R. A. Ferrare, M. A. Vaughan, A. H. Omar, R. R. Rogers, C. A. Hostetler, and J. W. Hair, "Aerosol classification from airborne HSRL and comparisons with the CALIPSO vertical feature mask," ***Atmos. Meas. Tech.*** **6**, pp. 1397–1412, 2013.
26. R. R. Rogers, M. A. Vaughan, C. A. Hostetler, S. P. Burton, R. A. Ferrare, S. A. Young, J. W. Hair, M. D. Obland, D. B. Harper, A. L. Cook, and D. M. Winker, "Looking through the haze: evaluating the CALIPSO level 2 aerosol optical depth using airborne high spectral resolution lidar data," ***Atmos. Meas. Tech. Discuss.*** **7**, pp. 6141–6204, 2014.

27. F. J. S. Lopes, E. Landulfo, and M. A. Vaughan, "Evaluating CALIPSO's 532 nm lidar ratio selection algorithm using AERONET sun photometers in Brazil," ***Atmos. Meas. Tech.*** **6**, pp. 3281–3299, 2013.
28. R. C. Levy, L. A. Remer, J. V. Martins, Y. J. Kaufman, A. Plana-Fattori, J. Redemann, and B. Wenny, "Evaluation of the modis aerosol retrievals over ocean and land during CLAMS.," ***J. Atmos. Sci.*** **62**, p. 974992, 2005.
29. L. A. Remer, Y. J. K. D. Tanré, S. Mattoo, D. A. Chu, J. V. Martins, R. R. Li, C. Ichoku, R. C. Levy, R. G. Kleidman, T. F. Eck, E. Vermote, and B. N. Holben, "The MODIS aerosol algorithm, products, and validation," ***J. Atmos. Sci.*** **62**(4), pp. 947–973, 2005.
30. B. N. Holben, T. F. Eck, I. Slutsker, D. Tanré, J. P. Buis, A. Setzer, E. Vermote, J. A. Reagan, Y. J. Kaufman, T. Nakajima, F. Lavenu, I. Jankowiak, and A. Smirnov, "Aeronet - A Federal Instrument Network and Data Archive for Aerosol Characterization," ***Remote Sens. Environ.*** **66**, pp. 1–16, 1998.
31. O. Dubovik and M. D. King, "A flexible inversion algorithm for retrieval of aerosol optical properties from sun and sky radiance measurements," ***J. Geophys. Res.*** **105**(D16), pp. 20673–20696, 2000.
32. W. H. Organization, ***WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide - Summary of risk assessment***, World Health Organization press, Switzerland, 2012.
33. R. R. Draxler and G. D. Hess, "An overview of the HYSPLIT 4 modeling system of trajectories, dispersion, and deposition," ***Australian Meteorological Magazine*** **47**, pp. 295–308, 1998.
34. S. R. Freitas, K. M. Longo, M. A. F. S. Dias, P. L. S. Dias, R. C. E. Prins, P. Artaxo, G. A. Grell, and F. S. Recuero, "Monitoring the transport of biomass burning emissions in South America," ***Environ. Fluid Mech.*** **5**, pp. 135–167, 2005.
35. E. Landulfo and F. J. S. Lopes, "Initial approach in biomass burning aerosol transport tracking with CALIPSO and MODIS satellites, sunphotometer and a backscatter lidar system in Brazil," in ***Proceedings of SPIE***, **7479**, 2009.
36. F. J. S. Lopes, G. Held, W. M. Nakaema, P. F. Rodrigues, J. M.Bassan, and E. Landulfo, "Initial approach in biomass burning aerosol transport tracking with CALIPSO and MODIS satellites, sunphotometer and a backscatter lidar system in Brazil," in ***Proceedings of SPIE - Lidar Technologies, Techniques, and Measurements for Atmospheric Remote Sensing V***, **7479**, 2009.
37. D. Müller, A. Ansmann, I. Mattis, M. Tesche, U. Wandinger, D. Althausen, and G. Pisani, "Aerosol-type-dependent Lidar ratios observed with Raman Lidar," ***J. Geophys. Res.*** **112**, p. D16202, 2007.
38. L. A. Remer and Y. J. Kaufman, "Dynamic aerosol model: Urban/industrial aerosol.," ***J. Geophys. Res.*** **103**(D12), pp. 13859–13871, 1998.
39. O. Dubovik, B. Holben, T. F. Eck, A. Smirnov, Y. J. Kaufman, M. D. King, D. Tanré, and I. Slutsker, "Variability of absorption and optical properties of key aerosol types observed in worldwide locations," ***Bull. Amer. Meteor. Soc.*** **59**, pp. 590–608, 2002.
40. O. Dubovik, A. Smirnov, B. N. Holben, M. D. king, Y. J. Kaufman, T. F. Eck, and I. Slutsker, "Accuracy assessments of aerosol optical properties retrieved from aerosol robotic network (AERONET) sun and sky radiance measurements," ***J. Geophys. Res.*** **105**(D8), pp. 9791–9806, 2000.
41. A. Lammert and J. Bösenberg, "Determination of the convective boundary layer height with laser remote sensing," ***Bound.- Lay. Meteorol.*** **119**, p. 159170, 2006.
42. H. Baars, A. Ansmann, R. Engelmann, and D. Althausen, "Continuous monitoring of the boundary-layer top with lidar," ***Atmos. Chem. Phys.*** **8**, pp. 7281–7296, 2005.
43. G. A. Moreira, R. Bourayou, F. J. S. Lopes, T. A. Albuquerque, N. C. R. Jr, G. Held, and E. Landulfo, "Automatic methods to detect the top of atmospheric boundary layer," in ***Proc. SPIE, Lidar Technologies, Techniques, and Measurements for Atmospheric Remote Sensing IX***, **8894**, 2013.
44. G. A. Moreira, F. J. S. Lopes, J. L. Guerrero-Rascado, M. J. Granados-Muñoz, R. Bourayou, and E. Landulfo, "Comparison between two algorithms based on different wavelets to obtain the planetary boundary layer height," in ***Proc. SPIE, Lidar Technologies, Techniques, and Measurements for Atmospheric Remote Sensing X***, in press.

45. U. Wandinger, D. Müller, C. Böckmann, D. Althausen, V. Matthias, J. Bösenberg, V. Weiß, M. Fiebig, M. Wendisch, A. Stohl, and A. Ansmann, "Optical and microphysical characterization of biomass-burning and industrial-pollution aerosols from multiwavelength lidar and aircraft measurements," ***J. Geophys. Res.*** **107**(D21), pp. 2571–2592, 2003.
46. C. Cattrall, J. Reagan, K. Thome, and O. Dubovik, "Variability of aerosol and spectral lidar and backscatter and extinction ratios of key aerosol types derived from selected Aerosol Robotic Network locations," ***J. Geophys. Res.*** **110**, p. D10S11, 2005.