AERONET sunphotometer products and backscatter lidar data: Systematic intercomparison over the city of São Paulo, Brazil

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ABSTRACT:

Biomass burning is one of the largest sources of anthropogenic aerosols. Particles from biomass burning can affect the global atmospheric chemistry and the Earth's climate and South America is responsible for 30% of all tropical occurrences. Although São Paulo (Brazil) is approximately 2,000 km away from the main biomass burning sources, the smoke can be transported because the particles, mostly from accumulation mode, can remain in the atmosphere for a week approximately. In this work we looked for signatures of biomass burning smoke transports from the source areas in Amazon and Central Brazilian regions into São Paulo by analyzing the annual evolution of the optical parameters and the relation between the lidar ratio *S* obtained from lidar and AERONET data. Two methods of obtaining *S* and aerosol optical thickness τ_a at 532 from AERONET data are discussed and showed to be compatible to each other. The extinction-to-backscatter ratios from LIDAR were found systematically smaller than those from AERONET data and the seasonal signature within the lidar dataset was not clear.

Keywords: Lidar, AERONET, Aerosol, Sunphotometer.

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1. Introduction

Biomass burning is one of the largest sources of anthropogenic aerosols. Particles from biomass burning can affect the global atmospheric chemistry and the Earth's climate [1-4].

It is known that South America is responsible for 30% of all tropical biomass burnings [2]. In Brazil they occur mostly in the Amazon and Central region during the dry season (June–November) through areas of *cerrado* and forests.

Approximately 40,000 km^2 are burned annually in these regions and through atmospheric transports the smoke can spread out over an area of 4-5 millions of km^2 away from the source of the fires [4]. São Paulo is approximately 2,000 km away from the main biomass burning sources.

Most of the particles from biomass burning is in the accumulation mode, thus being able to remain in the atmosphere for about a week [5,6].

Part of the variability in the atmospheric aerosols size distribution is due to their formation processes and to dynamic processes that happen, like aerosol aging, after the aerosol is formed [3]. In the case of aerosols from biomass burnings, it is known that they undergo rapid aging evolution as they are transported through long distances and Reid *et al* [1] showed that as the aerosols age, changes in their size distribution related to coagulation, condensation, and gas-to-particle conversions processes may happen.

Eck *et al* [3] claim that these variations in aerosol size distribution strongly influence the radiative properties of aerosols such as the scattering phase function $P(\Theta,\lambda)$, single scattering albedo ω_0, and spectral variation of aerosol optical thickness τ_a and thus influence the lidar ratio S. The estimation of which is shown in the next section.

In this work we are looking for signatures of biomass burning smoke transports from the source areas in Amazon and Central Brazilian regions to São Paulo by analyzing the annual evolution of the optical parameters and the relation between the lidar ratio S obtained from LIDAR and AERONET data.

2. Instruments and methods

The lidar system in São Paulo 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 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. 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's field of view (FOV) is variable (0.5-5 mrad) by using a small diaphragm. The lidar is currently used with a fixed FOV of the order of 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 backscattered laser radiation is then sent to a photomultiplier tube (PMT) coupled to a narrow band (1 nm FWHM) interference filter, to assure the reduction of the solar background during daytime operation and to improve the signal-to-noise ratio (SNR) at altitudes greater than 3 km. The PMT output signal is recorded by a dual Analog – Photoncounting system. Data are averaged between 2 to 5 minutes and then summed up over a period of about half an hour, with a typical range resolution of 15 m, which corresponds to a 100 ns temporal resolution. A Raman channel is currently being added to upgrade our system. This will enable us to determine the aerosol extinction and the aerosol backscatter coefficients independently at 355 nm.

The aerosols radiative properties such as the backscattering phase function $P(180º, \lambda)$, the single-scattering albedo $\omega_0(\lambda)$, the Angstrom exponent $\mathring{a}(\lambda)$, and the aerosol optical thickness $\tau_a(\lambda)$ were extracted from AERONET radiometer (CIMEL Electronique 318A) data at 441, 500 (only τ_a), 673, 873 and 1022 nm. The AERONET instrumentation is fully described by Holben *et al* [7] and the parameters previously mentioned were obtained from the instrument which is installed at the roof of the Physics Department at University of São Paulo (USP), near the LIDAR site.

Our current method (lidar) to retrieve the aerosol optical properties is based on the measurements of the aerosol backscatter coefficient (β) at 532 nm, up to an altitude of 5-6 km asl. The determination of the vertical profile of the aerosol backscatter coefficient relies on the lidar inversion technique following the Klett's algorithm as proposed by Klett [8] without considering multiple scattering.

When a quantitative analysis of lidar signals is made it is common to assume a relationship between the aerosol backscatter β and extinction α coefficients to make the lidar equation solvable. Thus we consider a simple range-independent extinction-to-backscatter ratio S although it is known that S might depend on range [8] and also depends on several physical-chemical parameters inherent to the aerosols to be inspected such as aerosol refractive index and particle size [9]. In addition to that, literature shows that S might have a significant dependence on temperature profile and relative humidity [10,11].

To derive the appropriate and "correct" vertical profile of the aerosol backscatter coefficient in the lower troposphere from lidar measurements we use an iterative inversion approach (by "tuning" the S values) based on the inter-comparison between the τ_a values needed to lidar analysis and the τ_a values obtained from AERONET data. We assume the absence of stratospheric aerosols and that the PBL is homogeneously mixed between ground and 300 m height, above which the lidar overlap factor is close to 1. No other assumption about the vertical profile of aerosol backscatter coefficient below 300m is made. When a suitable vertical profile of aerosol backscatter coefficient is achieved we reapply the Klett method, using appropriate S values, to retrieving the final values of the vertical profiles of the backscatter and extinction coefficient at 532 nm (Eq. (4)).

The AERONET radiometer provides the appropriate parameters to obtain τ_a at 532 nm applying the following relation:

$$\tau_a^{lidar}(532) = \tau_a^{aeronet}(500)\left(\frac{532}{500}\right)^{-\mathring{a}}. \qquad (1)$$

This quantity is used in the lidar analysis, where the Angstrom exponent [12] $\mathring{a}$ is derived from the AERONET data at 441 and 673 nm using the following equation:

$$\mathring{a} = -\frac{\log\left(\frac{\tau_a^{aeronet}(440)}{\tau_a^{aeronet}(670)}\right)}{\log\left(\frac{440}{670}\right)}. \qquad (2)$$

The lidar ratio extracted from lidar data is assumed to be range-independent:

$$S = \frac{\alpha_i}{\beta_i}. \qquad (3)$$

The iterative method to obtain the vertical profile of backscatter coefficient from lidar signals, as previously mentioned, consists in forcing τ_a from lidar to be equal to that from AERONET as follows:

$$\tau_a^{lidar} = \sum_{i=1}^{n}\alpha_i(\Delta z)_i = S\sum_{i=1}^{n}\beta_i(\Delta z)_i = \tau_a^{aeronet}, \quad (4)$$

where n is the last atmospheric layer probed by lidar and $(\Delta z)_i$ is the lidar spatial resolution: 15 m or 30 m. After this iterative process the first vertical profile of β is obtained and then the Klett method is re-applied using the appropriate S values to retrieve the final values for the vertical profiles of β and α at 532 nm.

From the phase function and the single-scattering albedo from AERONET products one can obtain S using the following equation:

$$S(\lambda) = \frac{4\pi}{P(\Theta,\lambda)\omega_0(\lambda)}. \qquad (5)$$

Using $P(180º,\lambda)$ and $\omega_0(\lambda)$ data from AERONET at 441nm and 673 nm we used to calculate the S(λ), multiply it by a weight factor (λ/532), take the arithmetic average between them and then use this average as an estimative of S(532nm). The reason why we used the weight factor was by the fact that without it the S values obtained would have extremely high values and very little physical meaning. We are denominating this method as the *standard method*.

In this study we tested an *alternative method* that takes into account the spectral dependence of both $P(180º,\lambda)$ and $\omega_0(\lambda)$ to obtain a wavelength dependent function to calculate S at 532nm by a function and not by an average

3. Results

Figure 1 shows the temporal evolution (2002–2005) of S calculated using the standard and the alternative method for lidar ratio calculated from AERONET dataset from 2002 to 2005. One can see that there is good agreement between the two methods showed by the datasets overlap, with the standard method split up into years.

It is important to observe that for the year of 2005 the AERONET instrument was out for calibration

during approximately 4 months: April through August.

The annual average difference in percentage between the results obtained from alternative and standard method to retrieve the lidar ratio, and their respective standard deviation are given in Table I.

The phase functions from AERONET are available in three models of particles [13]: total, coarse and fine. The spectral dependence of S-calculated using the fine mode phase function-presented a linear interval between 441-673nm within a whole year dataset. However when we verify the spectral dependence of the lidar ratio calculated using total phase function, we note that the interval between 441-673 nm does not show linear behavior always. It is worth to mention that the UV-VIS interval chosen to interpolate the LR (532) not always has a linear behavior unless the proper phase function in Eq. (5) is taken. This should be further explored in a future work but already gives a starting point for a more in depth study in which other quantities should be also taken into account such as relative humidity and size distribution.

We also applied the alternative method to aerosol optical thickness τ_a dataset and it showed good agreement with the standard method which, in this case, is described by Eqs. (1) and (2). Table II shows the annual average difference in percentage between the results obtained from alternative and standard method, for aerosol optical thickness, and their respective standard deviation.

The temporal evolution of τ_a is given in Fig. 2 and one can notice an increase of its values during the dry season indicated by the arrows. Note that these periods are those when τ_a pick values are reached due to poor meteorological condition for aerosol dispersion and transport over the city of São Paulo.

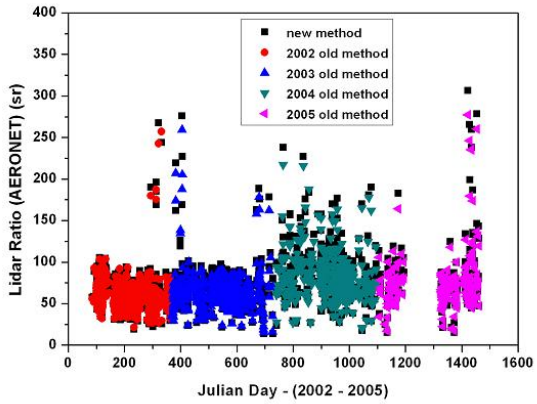

Fig. 1. Standard and alternative method applied to lidar ratio dataset.

Table I
Annual average difference in percentage (standard × alternative method) – Lidar ratio

S	Standard × Alternative (Average)	St.Dev
2002	6.02	3.53
2003	6.58	3.25
2004	6.07	3.25
2005	6.41	3.66

Table II
Annual average difference in percentage (standard × alternative method) – Aerosol optical thickness

τ_a	Standard × Alternative (Average)	St.Dev
2002	2.45	0.56
2003	2.59	0.67
2004	2.21	0.51
2005	2.15	0.51

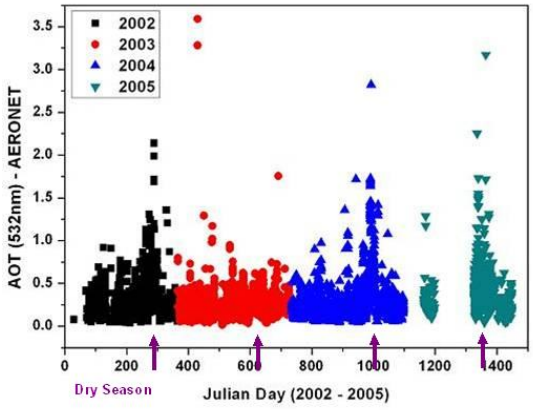

Fig. 2. Temporal evolution of τ_a from 2002 to 2005.

From Figs. 3 and 4 which are histograms plotted by seasons (wet and dry), one can see that the lidar ratio values extracted from lidar are smaller than those from AERONET.

We have tried to find a seasonal signature within São Paulo lidar ratio dataset. As one can see in Figs. 5 and 6, both for AERONET and lidar dataset, it is not clear. We did the same within the Angstrom exponent $å$ dataset but no seasonal signature was found. On the other hand, we could see that the typical values for $å$ range from 1.4 to 2.0 showing that the aerosols are mostly from fine mode. As an example, Fig. 7 shows the 2003 dataset.

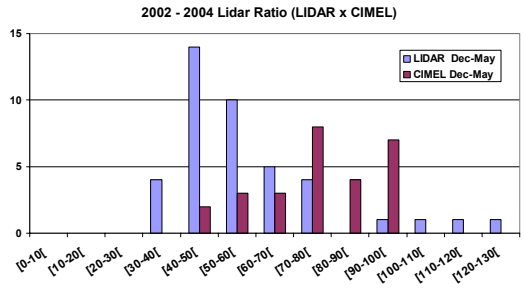

Fig. 3. Histograms of lidar ratio on wet season: lidar and aeronet dataset.

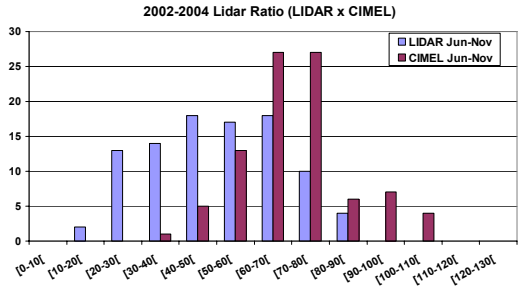

Fig. 4. Histograms of lidar ratio on dry season: lidar and aeronet dataset.

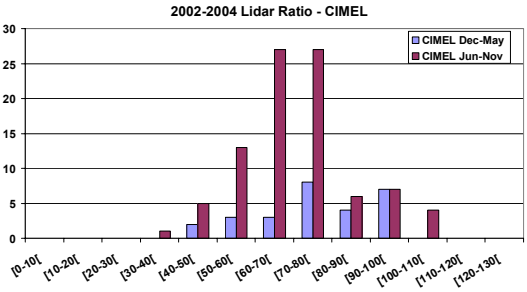

Fig. 5. Lidar ratio from AERONET (2002 to 2004 dataset): looking for seasonal signature.

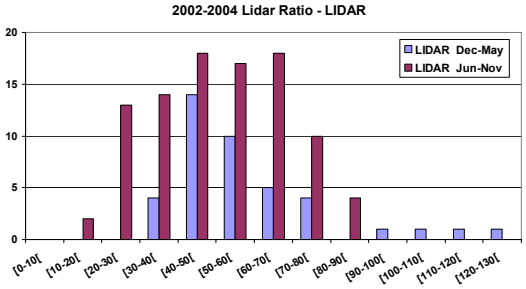

Fig. 6. Lidar ratio from lidar (2002 to 2004 dataset): looking for seasonal signature

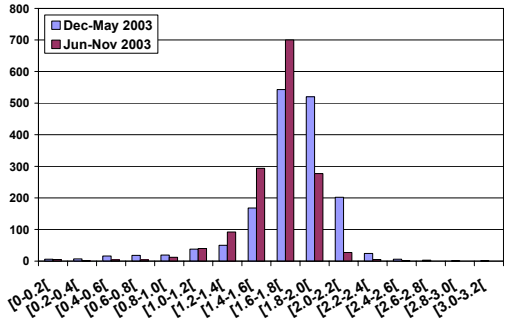

Fig. 7. Angstrom exponent histogram by seasons for 2003 dataset: looking for seasonal signature

4. Conclussions

Both methods, the alternative and standard, show compatible results for aerosol optical thickness τ_a and lidar ratio dataset at 532nm.

The lidar ratios S extracted from lidar dataset are systematically smaller than those extracted from AERONET dataset which might be a consequence of obtaining the τ_a by lidar vertical profiling or column integration, in the case of AERONET. Also, we could consider the vertical profile of aerosol backscatter coefficient below the lidar overlap height using data from auxiliary instruments, a nephelometer for example, to explore the differences that it could bring to our data analysis.

From τ_a dataset we can see an increase of its values during the dry season that is probably indicating transports of particles from biomass burning. Thus, a better understanding of the aerosol aging processes is needed as the transport from remote biomass burning sources shows to be significative. An aerosol optical property tracking method could be implemented by checking the dataset from other AERONET sites on the path of the smoke transport trajectory. Or, alternatively, the use of satellite coverage over the remote areas and São Paulo site could be adopted, e.g. CALIPSO and MODIS.

One still has to investigate if São Paulo is a suitable site for seasonal signatures observations and if maybe the local aerosol could be masking the properties of the incoming biomass burning aerosols and a large statistics should be taken with more data point from other years (2006-2007).

