The Ground-based Lidar Combined with Sun photometer for Aerosol Vertical Profiles and Optical Properties over Beijing

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Abstract. The aerosol extinction-to-backscatter ratio (so called lidar ratio) is an important parameter for inverting LIDAR signals in the lidar equation. It is a complicated function of the aerosol microphysical characteristics. In this paper, we estimate lidar ratio, which ranged from 20 to 80sr, by sun photometer. The correlation between angstrom exponents derived from sun photometer and lidar ratio for columnar mean aerosols were discussed. In this paper, we also present other columnar optical properties of aerosols such as optical depth and Angstrom exponents. The backscattering lidar and sun photometer system has been set up in the city of Beijing to provide the vertical profile of the aerosol backscatter coefficient at 532nm. The measurement has been carried out in 2011.

1. Introduction

Suspended aerosol particles play a significant role in Global Change issues, since they influence the earth’s radiation balance and climate by scattering or absorbing both incoming and outgoing radiation and by acting as cloud condensation nuclei (CCN) [1]. Tropospheric aerosols arise from natural sources, such as airborne dust, sea-spray and volcanoes and also from anthropogenic sources, such as combustion of fossil fuels and biomass burning activities and from gas-to-particles conversion process [2].

The increasing urbanization and industrialization of the East Asia region, in accordance with the intense dust storm events mostly occurring in spring time, lead to continuously increasing particulate matter particularly in the lower troposphere [3]. The air quality in Beijing is drastically affected by both anthropogenic and naturally occurring dust aerosols. Previous research demonstrated that Asian dust particles play significant roles in the climate, as do anthropogenic aerosols [4]. In this study, we investigated the aerosol properties in 2011.

The lidar technique is based on the emission of a collimated laser beam in the atmosphere and on the detection of the backscattered laser light by the suspended atmospheric aerosols and atmospheric molecules. The lidar technique, through its high temporal(from seconds to minutes) and spatial(3-15 m) resolution, is a powerful tool to visualize in real time the structure of the PBL using the aerosols as passive tracers of the atmospheric dynamic processes[5]. The sun photometer data are used to provide the aerosol optical thickness (AOT) at selected wavelength and thus, to derive the Angstrom exponent (AE) [6]. The synergy of Cimel and lidar measurements also acts to minimize the uncertainties of the assumptions made, especially when inverting the lidar signal using Fernald’s technique [7].
In this paper we present a statistical analysis of the aerosol optical properties retrieved over the city of Beijing, using the synergy of lidar and sun photometer measurements performed concomitantly in 2011.

2. Instruments and methodology

Columnar aerosol optical properties and vertical extinction profiles are measured by a sun photometer and a depolarization lidar installed on the roof of a building of Institute of Remote Sensing Applications, Chinese Academy of Sciences (IRSA, CAS) (40.00° N, 116.383°E). Lidar and sun photometer are conducted at IRSA to investigate physic-chemical characteristics of urban aerosols. The geophysical location of IRSA is shown in Figure 1.

![Figure 1. The geographical location of Beijing.](image1)

![Figure 2. The CIMEL sun photometer.](image2)

2.1. Sun photometer

The Cimel sun photometer, the photograph of that is shown in Figure 2, is a kind of equipment with high degree of accuracy which have many advantages such easy taking, easy fixed, automatic scanning, solar energy current supply and automatic data transferring etc. It has been described amply by Holben et al. [6], so just a brief introduction is described here.

The Cimel sun photometer measurements include the radiances in eight spectral channels (340, 380, 440, 500, 675, 870, 1020, and 1640 nm). Direct solar radiation at 15-min intervals and shy radiation at 1-h intervals are recorded. Co-located CIMEL aerosol measurements were performed to determine the AOT values at several wavelengths in the visible spectrum and thus to enable the assessment of the AE values at the same spectral region. The instrument precision and accuracy follow the standard Langley plot method [8]. Calibration methodology of CIMEL sun photometer assures coefficient accuracy between 1 and 3%, nonetheless various instrumental, calibrations, atmospheric, and methodological factors influence the precision and accuracy of optical thickness and effectively the total uncertainty in the AOT retrieved values is less than 8% [9].

2.2. Micropulse Lidar System

Vertical measurements of aerosols and clouds were made using a micropulse lidar system (MPL). The MPL is a compact and eye-safe lidar system capable of determining the range of aerosols and clouds by firing a short pulse of laser light (at 532 nm) and measuring the time of flight from pulse
transmission to reception of a returned signal[10]. The returned signal is a function of time, converted into range using the speed of light, and is proportional to the amount of light backscattered by atmospheric molecules (Rayleigh scattering), aerosols, and clouds [11]. The MPL achieves ANSI eye-safe standards by using low output energies (μJ) [9]. The MPL laser pulse duration is 10ns with a pulse repetition frequency of 2400 Hz and output energies in the μJ range.

2.3. Method
The range and energy-normalized signal of a returned lidar pulse, X(r), can be expressed by

\[ X(r) = C \beta(r) T^2(r) \tag{1} \]

Where C is a calibration constant, which depends upon factors such as transmitted power; receiver cross section; efficiency of the detector and optical system; and correction for the near-range field-of-view problems, \( \beta(r) \) is the volume atmospheric backscattering coefficient, and \( T^2(r) \) represents the total round-trip transmittance to range r, such that[12]

\[ T^2(r) = T_a^2(r) T_m^2(r) = e^{-2 \int (\sigma_a(r') + \sigma_m(r')) dr'} \tag{2} \]

\[ \beta(r) = \beta_a(r) + \beta_m(r) \tag{3} \]

The subscripts a and m represent aerosol and molecular (Rayleigh) atmospheric components, respectively, and \( \sigma \) represents the unit volume extinction coefficient. The backscatter solution to the above nonlinear equation, obtained using a modeled value for the lidar ratio (\( s_a \)), is given by

\[ \beta_a(r) = \frac{X(r) e^{-2(\sigma_a - \sigma_m) \int \beta_m(r') dr'}}{\beta_a(r_c) + \beta_m(r_c)} - \beta_m(r) \tag{4} \]

Where \( r_c \) is a Rayleigh reference calibration range; i.e., where \( \beta(r_c) \approx \beta_m(r_c) \), and

\[ s_a = \frac{\sigma_a(r)}{\beta_a(r)} \text{ and } s_m = \frac{8\pi}{3} \tag{5} \]

The aerosol lidar ratio (LR) can vary widely depending on aerosol size distribution and refractive index [13]. However, in the absence of auxiliary or lidar self-determined transmittance information, must be specified before the vertical profiles of the extinction and backscattering coefficients can be determined [14]. To overcome the uncertainty owing to unknown lidar ratio, the LR obtained from the CIMEL database was used according to the following expression [15]:

\[ \sigma_a = \int_{r_m}^{r_m} Q_e(m,r) \frac{dN(r)}{d\ln r} mr^2 dr \tag{6} \]

\[ \beta_a = \int_{r_m}^{r_m} Q_m(m,r) \frac{dN(r)}{d\ln r} mr^2 dr \tag{7} \]

Where \( Q_e \) is the extinction efficiency, \( Q_m \) is the backscatter efficiency, and \( \frac{dN(r)}{d\ln r} \) is the lognormal size distribution.

In this study, we also used aerosol Angstrom exponent (AE). This parameters is often used to parameterize the wavelength behavior of the aerosol optical depth which obtained from the CIMEL sun photometer [16]; i.e.

\[ \alpha = \frac{-\ln(\lambda_2/\lambda_1)}{\ln(\lambda_1/\lambda_2)} \tag{8} \]

Where \( \lambda_1 \) and \( \lambda_2 \) represent two reference wavelengths, \( \tau \) the aerosol optical depth, and \( \alpha \) the Angstrom exponent. It is also often used to provide basic information on the aerosol size distribution, since its value is related to the relative abundances of coarse and fine modes of the aerosol size distribution [17]. The apparent log linear relationship between two wavelengths does not strictly exist in nature; however, making the selection of reference wavelengths is of some importance if using the parameter to characterize an air mass [18]. Specifically, use of longer wavelength pairs would furnish less information than wavelength pairs spanning more of the visible spectrum. Accordingly, in this paper we use the Angstrom exponent obtained from the AERONET wavelengths of 440 and 870 nm to explore this value [12].

3. Results and discussion
The sun photometer data of 2011 were collected. Figure 3 shows the monthly averaged aerosol optical depth (AOD) values which obtained by sun photometer through one year period. We see that the mean AOD values span from 0.2 to 1.3. August and October recorded higher AOD values than other months. Using LR values retrieved from sun photometer by the method described above, Figure 4 shows 12-month average of LR values. Those LR values suggest a larger extinction-to-backscatter that indicate the presence of biomass burning aerosols in Beijing.

The other aspect we wished to examine was seasonal signature of aerosol properties over Beijing. We highlight this part of the city in four seasons: spring, summer, autumn and winter. For that season we have separated the measured LR mean values for these four seasons and the respective results are shown in Figure 5. Thus, we see that there are, in general, larger LR values in summer and autumn, when compared to these obtained during other seasons. Spring, summer and winter LR distribution shows nearly Gaussian distribution, around the LR value of 40-50 sr and 50-60 sr. However, the autumn LR distribution do not form the Gaussian distribution because of so few data. These findings show that during summer and autumn the LR values are greater, which indicates larger absorption during these periods.

Regarding monthly average of the Angstrom exponent values, we can see AE values range from 1.1 to 1.58, which means that mostly fine particles are found in July, September and December.
Figure 6. 12-month average of Angstrom exponent in 2011.

The dust storm hit Beijing at 10 am in May 1, 2011. We use LR that obtained from sun photometer to improve the accuracy of vertical profile and analyze dust storm on that day. Figure 7 illustrates the dependence of extinction coefficient on observed object altitude. Figure 8 displays vertical aerosol depolarization ratio. Extinction coefficient and Depolarization ratio are small above 2000m. So the dust aerosols dominate below 1500 m.

Figure 7. Aerosol Extinction Coefficient at 532nm on May 1, 2011.

Figure 8. Aerosol Depolarization Ratio at 532nm on May 1, 2011.

4. Conclusions
In this paper, we examined the monthly average of distribution of the AOD, LR and AE values derived by sun photometer data. We also check out the seasonal character of LR. The analysis of these data show an important trend in the monthly signature of the LR which indicate a change of the predominant type of aerosol. LR values are greater in July, which indicates that larger absorption during this period. We analyzed dust storm weather and knew that dust aerosols mainly distribute under 1500m.

In conclusion, Ground-based lidar results are still preliminary and have to be further analyzed. We will found more aerosol vertical profile and analyze seasonal properties.

5. References
[1] Landulfo E, Papayannis A, Artaxo P, Castanho A D A, De Freitas A Z, Souza R F, Vieira N D, Jorge M P M P, Sánchez-Coylllo O R and Moreira D S 2003 Atmos. Chem. Phys. 3 1523–39
[2] Takamura T, Sasano Y and Hayasaka T 1994 Appl. Optics 33 7132–40
[3] Adhikary B, Kulkarni S, Dallura a., Tang Y, Chai T, Leung L R, Qian Y, Chung C E, Ramanathan V and Carmichael G R 2008 Atmos. Environ. 42 8600–15
[4] Li J, Wang Z, Zhuang G, Luo G, Sun Y and Wang Q 2012 Atmos. Chem. Phys. 12 7591–607
[5] Kolgotin A and Müller D 2008 Appl. Optics 47 4472–90
[6] Holben B N, Slutsker T I E I, Tar D, Buis J P, Setzerj I I A, Reagan A, J Y, Nakajima T, Lavenu F, Verm E, Jankowiak I and Smirnozjt A 1998 Remote Sens. Environ. 16 1–16
[7] Klett J D 1985 Appl. Optics 24 1638–43
[8] Campanelli M, Estellès V, Tomasi C, Nakajima T, Malvestuto V and Martinez-Lozano J A 2007 Appl. Optics 46 2688–702
[9] Welton E J, Voss K J, Gordon H R, Maring H, Smirnov A, Holben B, Schmid B, Livingston J M, Russell P B, Durkee P A, Formenti P and Andreae M O 2000 TELLUS B 52 636–51
[10] Spinhirne J, Berkoff T, Welton E and Campbell J 2002 IEEE T. Geosci Remote 3 234-243
[11] Welton E J, Voss K J, Quinn P K, Flatau P J, Markowicz K, Campbell J R, Spinhirne J D, Gordon H R and Johnson J E 2002 J. Geophys. Res. 107 1–13
[12] Cattrall C 2005 J. Geophys. Res. 110 1–13
[13] Particles C 2005 Chin J Laser B 32 1321–4
[14] Kumar Das S, Nee J-B and Chiang C-W 2010 J. Atmos. Sol-Terr Phy. 72 781–8
[15] Pedros R, Estelles V, Sicard M, Gomez-Amo J L, Utrillas M P, Martinez-Lozano J A, Rocadenbosch F, Perez C and Recio J M B 2010 IEEE T. Geosci Remote 48 237–49
[16] Angstrom B A and Eppley T 1964 J. Geophys. Res. 1 64–75
[17] Tesche M, Ansmann A, Müller D, Althausen D, Mattis I, Heese B, Freudenthaler V, Wiegner M, Esselborn M, Pison G and Knippertz P 2009 TELLUS B 61 144–64
[18] Eck T F, Holben B N, Reid J S, Dubovik O, Smirnov A, O’Neill N T, Slutsker I and Kinne S 1999 J. Geophys. Res. 104 31333–49