Ground and satellite-based measurements of aerosols during heavy haze events

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Abstracts

Many large cities in eastern and southwestern China have been experiencing heavy haze events over the past 30 years. However, the aerosol properties of these events are still insufficiently understood. In this work, heavy haze events occurring around Beijing in 2007 is investigated by using ground- and satellite-based measurements. Retrieval of atmospheric aerosol characteristics from satellite data (i.e., aerosol remote sensing) is founded in the multiple light scattering theory and achieved by radiative transfer simulation. In the case of heavy haze events, which are associated with dense concentrations of aerosols in the atmosphere, the radiative transfer problem is solved by the method of successive order of scattering in this paper.

Keywords: Atmospheric Aerosol, Radiation Simulation, Successive Order of Scattering, MODIS

1. INTRODUCTION

Atmospheric aerosols directly affect the radiation budget of Earth's atmosphere through sunlight scattering and absorption. Aerosols also play an important indirect role. For example, they contribute to cloud particle formation and cloud density by acting as condensation nuclei. Thus, the observation of aerosols is vital. Various research institutions are performing observations of terrestrial atmospheric radiation. Furthermore, ground-based measurement of particulate matter (PM) concentrations is also carried out all over the world. PM_x refers to the mass of particles with an aerodynamic diameter lower than x μm; 10 and 2.5 are typical values for x. The concentration of small particles, $PM_{2.5}$, is known to be closely related to human health.

It is well known that $PM_{2.5}$ has recently attracted increased attention since Chinese air pollution problems were publicized at the beginning of 2013. The problem with $PM_{2.5}$ in China was reported by news agencies in Japan. The genesis of this incident was that PM measurement instruments were installed on the roof of U.S. Embassy in Beijing in spring of 2008. On 1 November 2010, the U.S. Embassy started using Twitter to broadcast the $PM_{2.5}$ observations. The air quality reported by the U.S. Embassy differed considerably from that released by the Beijing Environmental Protection Agency. This disparity immediately became a topic of discussion on the Internet and attracted the interest of the world.

Atmospheric particle monitoring from the ground is, however, limited. Satellite remote sensing has been found to be an effective alternative, with Wang and Christopher using MODIS data from the Terra/Aqua satellites [1], Kacenelenbogen et al. using ADEOS-2/POLDER data [2], and Aaron van Donkelaar et al. using MODIS/MISR data [3].

This research reports on observations of the heavy haze events in Beijing by ground equipment and satellite. Retrieval of atmospheric aerosol characteristics from satellite data (i.e., aerosol remote sensing) is predicated on the light scattering theory. A multiple scattering simulation is calculated by solving a radiative transfer process; this process is based on Rayleigh and Mie scattering. The aerosol optical characteristics are estimated from comparison between light scattering simulation and satellite data, and so precise calculations in the multiple scattering process are important. For optically very thick atmospheres, lengthy computation times become a problem. In such cases, it is necessary to develop practical and efficient algorithms for obtaining aerosol characteristics from satellite data during aerosol events, which represent excessive loading of aerosols in the atmosphere. The radiative transfer calculations for the optically semi-infinite atmosphere model are performed by the successive order of scattering method (MSOS) [4]. This paper also introduces computer code for radiative simulation and an algorithm for retrieval of aerosol characteristics from atmospheric images.

2. GROUND-BASED MEASUREMENTS

NASA's atmospheric aerosol observation network, AERONET, was deployed on a global scale starting in 1993; it has used observation of direct solar radiation and atmospheric scattering to derive important data on optical thicknesses, Ångström exponents, size distributions, and complex refraction indices of aerosols [5].

Kinki University has performed airglow observations by using a Sun/Sky-Radiometer (CE-318; Cimel) at AERONET stations established in Shirahama, Higashi-Osaka, and Noto (Fig. 1) [6]. The radiometer was calibrated according to a standard AERONET procedure [7]. In addition, observations of PM concentrations PM_{10} and $PM_{2.5}$ by SPM-613D (Kimoto Electric) were started on 15 March 2004 at the same site (AERONET in Higashi-Osaka) [6].

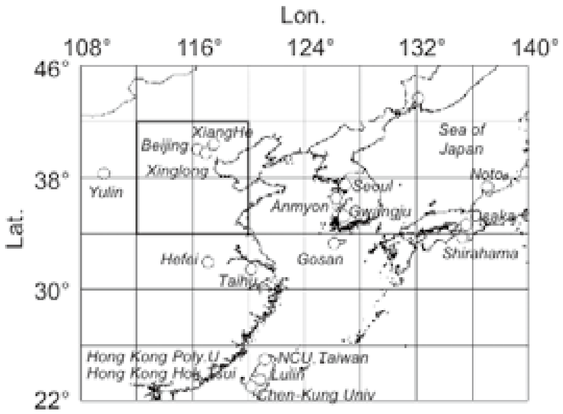

Figure 1. Geographical positions of NASA/AERONET sites in Asia.

Figure 2 presents the monthly averages of aerosol optical thickness (AOT) at a wavelength of 0.55 μm and $PM_{2.5}$ over Beijing (black circles) and Higashi-Osaka (white circles) from 1 February 2010 to 30 June 2013. AOT is an important aerosol parameter that can be derived from the transmittance measured by direct sun photometry.

The following results are inferred from Fig. 2.

1. $PM_{2.5}$ and AOT over Beijing are very high compared with Osaka.
2. AOT is increasing each month.
3. $PM_{2.5}$ over Beijing has peaks in January, February, and June. The values are 6- to 8-fold the limits set by environmental standards in Japan (yearly mean value below 15 μg/m^3).
4. The peaks in January, February, and June in Beijing are caused by haze events.

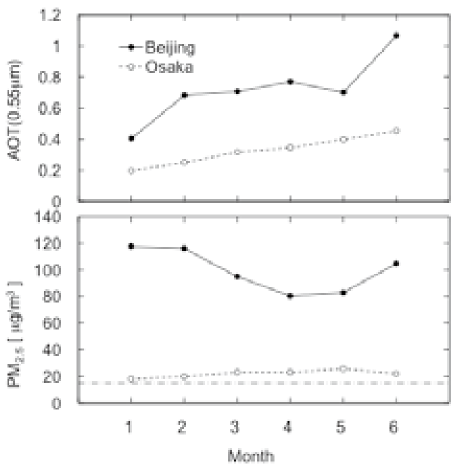

Figure 2. Monthly averages of atmospheric particles over Beijing (black circles) and Higashi-Osaka (white circles) from 1 February 2010 to 30 June 2013. The upper panel shows aerosol optical thickness at a wavelength of 0.55 μm and the lower panel shows $PM_{2.5}$ concentrations.

Table 1 shows monthly changes in $PM_{2.5}$ during January, February, and June for every year in Beijing and Osaka. Although Osaka is stable, the change in Beijing is marked. Moreover, the value in January rises every year. In June, fine particles are more prevalent in large areas of China compared with in January and February. This result shows the influence of the heavy haze events, such as forest fires and field burning, that occur in southeastern China.

This paper introduces a method of estimating the aerosol properties during heavy haze events from ground and satellite data.

Table 1. Monthly change of $PM_{2.5}$ in January, February, and June of each year in Beijing and Osaka

Year	$PM_{2.5}$ [μg/m^3]					
	Beijing			Osaka		
	Jan.	Feb.	Jun.	Jan.	Feb.	Jun.
2010		152	174	23	15	23
2011	43	209	108	14	25	23
2012	111	136	96	18	20	19
2013	199	174	107	18	18	23

3. AEROSOL RETRIEVAL IN HEAVY HAZE EVENTS

Aerosol properties are estimated by comparing satellite data with the results of light scattering simulations [8]. Figure 3 shows an overview of the aerosol retrieval process.

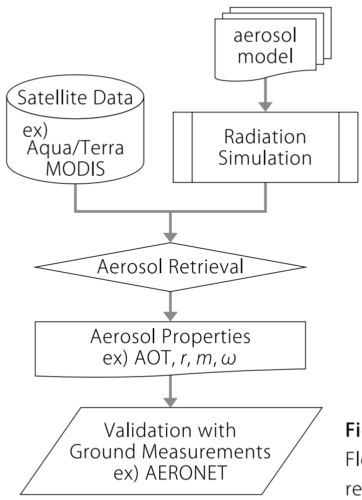

Figure 3. Flow of aerosol retrieval.

It is known that the large increase in the optical thickness of the atmosphere during heavy haze events can be detected by sun/sky photometry from the surface. However, satellite-based observations are also feasible for monitoring atmospheric aerosols during such events. For this, the atmosphere is assumed to be optically semi-infinite, and unlike in the finite model, radiative transfer calculations are computed on the basis of Mie scattering results. Results of the calculation are stored in a database (MSDB), and optimum aerosol properties are estimated in comparison with satellite data. In the model, spherical parameters are assumed and aerosol parameters are described by the complex refractive index (m = n - ki), size distribution, and aerosol optical thickness. Six aerosol types are proposed from the long-range data of NASA/AERONET [9]. The size distribution of aerosol classified into these six categories (Desert Dust: DD; Biomass Burning: BB; Rural, Continental Pollution: CP; Polluted Marine: PM; Dirty Pollution: DP) from AERONET data has two modes for small (f: fine) and large (c: coarse) particles. A bimodal log-normal distribution is assumed (see Eq. (1)).

$$\frac{dV}{d\ln r}=\frac{V_f}{\sqrt{2\pi}\ln\sigma_f}\exp\left[-\frac{(\ln r-\ln r_f)^2}{2\ln^2\sigma_f}\right]+\frac{V_c}{\sqrt{2\pi}\ln\sigma_c}\exp\left[-\frac{(\ln r-\ln r_c)^2}{2\ln^2\sigma_c}\right], \quad (1)$$

Here, the left-hand term is the volume particle size distribution ($0.05 \le r \le 15\mu$m). Parameters V_f, r_f, and σ_f are the volume concentration, mode radius, and standard deviation of fine mode particles, respectively; the corresponding parameters for coarse mode particles are V_c, r_c, and σ_c. The complex refractive index of each type is also given. Lee and Kim classified air aerosol into six categories from the AERONET data on the East Asia region [10]. From global data, Yulin classified some sites as Desert Dust or Biomass Burning, and Anmyon and Shirahama classified some sites as Continental Pollution (Fig. 1)[9]. Other sites in the Asian region are not classified. Figure 4 shows the sizes of aerosol distribution sites according to type both globally and in the Asian region. The sites in the Asian region have a higher volume concentration than seen in global data. The sites in the Asian region are classified as belong to the small particle group (from Ct-1 to Ct-4) or the large particle group (Ct-5 and Ct-6), as seen in Figure 5. The fine particle fraction (ff) defined as ff = Vf / (Vf+Vc) in Eq. (1), is particularly high for Ct-2. For analyzing aerosols of only heavy haze events in the Asian region, it is more appropriate to use the Asian region's size distribution. In this research, Ct-2, BB, and CP types are adopted, and ff of size distribution is used a parameter for calculation.

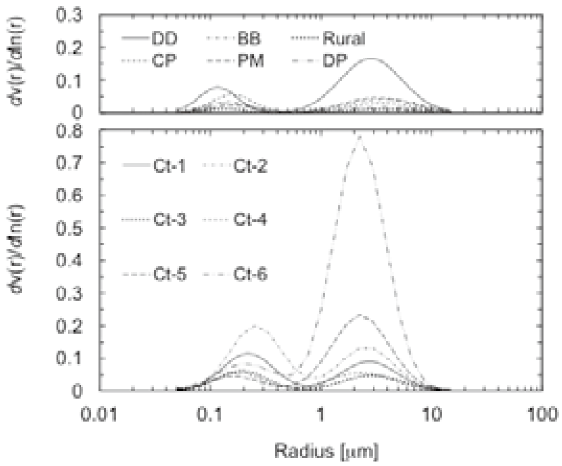

Figure 4. Size distribution for six aerosol types in the global (upper) and Asian (lower) regions, from AERONET data.

The radiative transfer equation takes the following form:

$$\mu\frac{dI}{d\tau}=I-\frac{\omega}{4\pi}\int P(\Omega,\Omega')I(\tau,\Omega')d\Omega', \quad (2)$$

where τ represents the optical depth of the atmosphere, ω is the single scattering albedo, I is the specific intensity in the direction of Ω; Ω is given by $\Omega=(\mu,\ \phi)$, $d\Omega = d\mu\, d\phi$ where μ is the cosine of the zenith angle θ (i.e., $\mu = \cos\theta$) and ϕ is the azimuth angle, and $P(\Omega,\ \Omega')$ is the phase function for single scattering. Simulation values equivalent to satellite data are acquired by solving Eq. (2) with boundary conditions at the top (τ =0) and bottom ($\tau = \tau^*$) of the atmosphere and calculating the upwelling radiance at the top of the atmosphere. The intensity of the upward radiation at level τ (I (0, +Ω)) takes the following form:

$$I(0,+\Omega)=\frac{\mu_0}{4}R(\Omega,\Omega_0)F. \quad (3)$$

Here, the function R denotes this upwelling radiance. I (0, +Ω) is considered to be the case where πF enters into the top of the atmosphere from -Ω_0.

In this research, upwelling radiance R is efficiently calculated in the optically very thick atmospheric model of aerosol events by MSOS [4]. If aerosol optical thickness at wavelength 0.55 μm is larger than 4, the value of a reflective function is treated as a steady value. In other words, the atmosphere of AOT(0.55 μm) > 4 is an optically semi-infinite atmosphere. By MSOS, a reflective function is calculated by using the sum of an infinite series of the following formula:

$$R(\Omega,\Omega_0)=\sum_{n=1}^{\infty}\omega^n R^*(n:\Omega,\Omega_0), \quad (4)$$

where n is the number of scatterings, and R^* (n: Ω, Ω_0) is the reflective function after scattering n times within the atmosphere. The radiation field reflected from the optically semi-infinite atmosphere is calculated from Eq. (4) by using the first order, second order, and nth order reflective functions.

In practice, the convergence of Eq. (4) is very slow when ω is very close to 1. To overcome this problem, the asymptotic form of R is proposed for higher-order scattering [11, 12]. Figure 5 shows the reflection function versus number of scatterings (n) for Ct-2 aerosol models at λ = 0.55 μm. A solid line and a thick solid line show, respectively, R and R' (the asymptotic form). Here, 30 times was adopted as the number of scatterings. The efficiency of numerical computation of Eq. (4) is thereby increased.

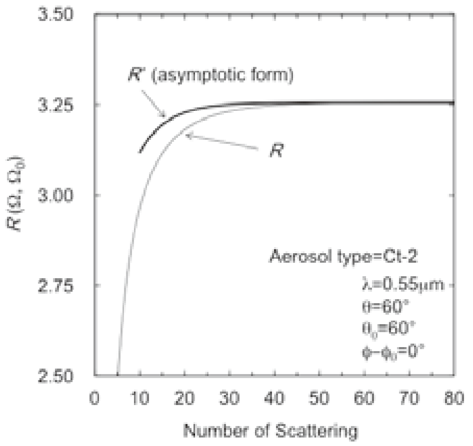

Figure 5. Reflection function versus number of scatterings (*n*) for Ct-2 aerosol models at $\lambda = 0.55$ μm.

4. RESULTS

Figure 6 shows Terra/MODIS measurements over Beijing on 12 June 2007. The left image is a color composite image with RGB = (0.65 μm, 0.55 μm, 0.46 μm), where the symbols □ and ◎ denote the AERONET Beijing site and the test area (S1–S5) for aerosol retrieval, respectively. Small dots represent hot spots, which seem to indicate agricultural biomass burning [13]. This image shows the transportation of dense air pockets of heavy haze from the southeast area, where agricultural biomass burning is typical during this season, toward the northwest direction. The right image shows AOT(0.55 μm) (image: MYD04_L2 Collection 5.1). The value of AOT(0.55 μm) at test sites (S1–S5) is more than 4.0.

Figure 7 shows the results of comparing MODIS data from 12 June 2007 (black circles) with simulated values (solid lines) at wavelengths 0.46 and 0.55 μm; the symbols ●, ○, □, ×, and ■ indicate MODIS data. Simulated values of BB, CP, and Ct-2 are calculated by using ff values from 0.2 to 0.9, and the complex refractive indices and size distributions shown in Fig. 5 and Table 2. Simulated values for BB agree well with satellite data. Simulated values for Beijing are calculated by using the size distribution of BB type (see Fig. 4) and the Level-2 complex refractive-index data observed at the AERONET Beijing site and shown in Table 2. Simulated values for Beijing fit satellite data better than values calculated by other models do. The complex refractive index varied from m(0.55 μm) =1.530 - 0.0145*i* to 1.530 - 0.0155*i*. The data from the S4 and S5 sites, which are near the AERONET Beijing site, are reproducible by simulation using the complex refractive index from the Beijing site. In contrast, the data from the S1–S3 sites, which are distant from the Beijing site, are reproducible by increasing the imaginary part of the complex refractive index from the Beijing site. That is, the aerosol near the source of soot shows increased absorption. For size distribution, the BB type fit the data better than the Asian type Ct-2 did. However, for 12 June 2010, Ct-2 is better [14]. Correspondingly, AOT on 12 June 2007 is higher than AOT on 12 June 2010; for high rates of soot, the particulate size differs.

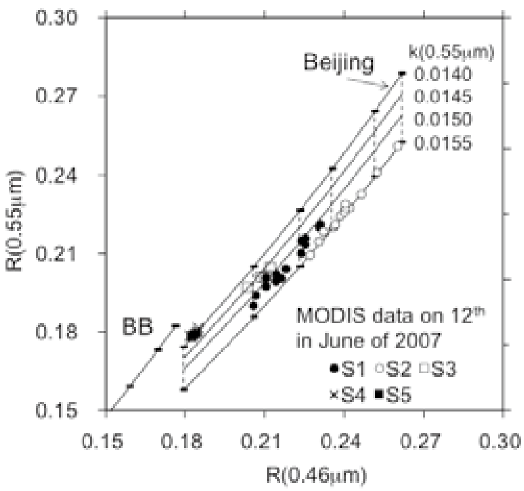

Figure 7. Terra/MODIS data for 12 June 2007 and simulated values of reflectance for aerosol models with fine fraction (ff) and complex refractive indices (m) (refer to Table 2) in a two-channel diagram at wavelengths of 0.46 and 0.55 μm.

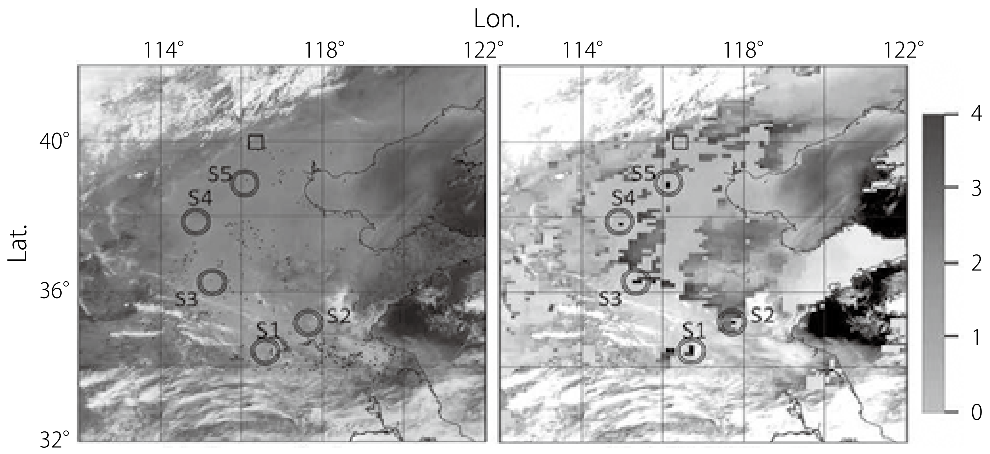

Figure. 6
Terra/MODIS measurements over Beijing on 12 June 2007. The left and right images are a color composite image and AOT(0.55 μm), respectively (MYD04_L2 Collection 5.1). The symbols □ and ◎ denote the AERONET Beijing site and the test area for aerosol measurement, respectively.

Table 2. Complex refractive indices of aerosol types over AERONET Beijing site.

Aerosol type	Complex refractive indices (m(λ)=n(λ)-k(λ)*i*)			
	0.46 μm		0.55 μm	
	n	k	n	k
CP	1.415	0.006	1.410	0.006
BB	1.510	0.025	1.520	0.025
Ct-2	1.479	0.010	1.480	0.009
AERONET Beijing	1.524	0.015	1.530	0.014

5. SUMMARY

First, a comparison of air quality in Higashi-Osaka and in Beijing from February 2010 to June 2013 was carried out. Month-to-month, both cities had large differences in June. Moreover, the air quality of Beijing during winter is getting worse each year. Next, an estimation of the optical aerosol properties of heavy haze events of 12 June 2007 was carried out by using ground and satellite observational data. In that case, high-concentration soot was carried to Beijing from the southern part of China. The aerosols in the areas near the source of soot showed that high absorption. The aerosols near the source of soot had higher absorption than the aerosols over Beijing did. It is highly likely that large-scale aerosol events will continue to occur around Beijing. There are many potential applications for the radiative simulation according to MSOS that was introduced in this paper.

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