Relationship between AOT and PM based on multi-measurements and model simulations

Makiko Nakata[a], Itaru Sano[b] and Sonoyo Mukai[b]
[a]Faculty of Sociology, [b]Graduate School of Science and Technology, Kinki University,
3-4-1 Kowakae, Higashi-Osaka, 577-8502, Japan

Abstract

The suspending particulate matter ($PM_{2.5}$) is a typical indicator of small particles in the atmosphere. Accordingly in order to monitor the air quality, sampling of $PM_{2.5}$ has been widely undertaken over the world, especially in the urban cities. On the other hand, it is known that the sun photometry provides us with the aerosol information, e.g. aerosol optical thickness (AOT), aerosol size information and so on. Simultaneous measurements of $PM_{2.5}$ and the AOT have been performed at a NASA/AERONET (Aerosol Robotics Network) site in urban city of Higashi-Osaka in Japan since March 2004, and successfully provided a linear correlation between $PM_{2.5}$ and AOT in separately considering with several cases, e.g. usual, anthropogenic aerosols, dust aerosols and so on. This fact suggests that the vertical distribution also should be taken into account separately for each aerosol type. In this work, vertical profiles of atmospheric aerosols are considered based on combination use of photometric data with AERONET, LIDAR (Light Detection and Ranging) measurements and model simulations.

Keywords : Aerosols, PM, Aerosol optical depth, LIDAR

1. INTRODUCTION

It is well known that the increasing emissions of anthropogenic aerosols associated with continuing economic growth in Asia are causing serious air pollution and climate change. $PM_{2.5}$ is sampling widely over the world due to monitoring the air quality. Also our group monitors $PM_{2.5}$ in Japan at Higashi-Osaka and Noto sites[1]. Among these sites, the simultaneous measurements by the sun photometry have been undertaken. The sun photometry provides us with the aerosol information. The world wide NASA/AERONET data are most available as the ground-based sun-photometric products[2, 3]. Our group has also managed several AERONET stations as Shirahama since 2000, Higashi-Osaka since 2002, and Noto since 2003 in Japan. Furthermore a standard instrument of NIES/LIDAR network[4], Mie scattering lidar instrument, has been set up since April in 2008 at the Higashi-Osaka site.

Smirnov et al. have showed that the relation of total column aerosol optical thickness and PM_{10} in-situ measurements over the Barbados Island[5]. Wang and Christopher investigate the relation between satellite based MODIS-AOT and in-situ $PM_{2.5}$ measurements in the Alabama, USA, and obtained good correlation for monthly even hourly $PM_{2.5}$ measurements[6]. Mukai et al. also investigates the relation in the 2nd large city, Osaka, in Japan[7]. The results showed that a linear correlation definitely exists between AOT and $PM_{2.5}$, and the value of correlation coefficient for whole data were lower than that in separately considering with two cases as anthropogenic and dust aerosols. This result looks to be showing a fact that the atmospheric situation during Asian Dust events, i.e., high AOT and low $PM_{2.5}$, may be different from that as usual. In other words, the vertical distribution of atmospheric aerosols, namely the height of boundary layer, plays a sufficient role on the relationship between AOT and $PM_{2.5}$. Especially our study site, Osaka AERONET station, is surrounded by mountains, and hence the height of boundary layer could have a strong influence upon the correlation between AOT and $PM_{2.5}$[8]. The precise relationship between AOT and $PM_{2.5}$ is desired. In this work, new LIDAR extinction data are examined to improve the correlation of AOT and $PM_{2.5}$ under boundary layer atmosphere.

*nakata@socio.kindai.ac.jp

2. MEASUREMENTS

2.1 AERONET data

The data supplied by the Cimel instrument were analyzed with a standard AERONET processing system[9,10]. It provides us with AOT and the Ångström exponent (α). The resolution of the AOT is better than 0.01 in all observation wavelengths, and cloud screening of the obtained data was performed before aerosol retrieval[11]. AOT is the basic parameter describing atmospheric aerosols and indicates the degree of opacity (and hence the concentration of the aerosol particles) in the atmosphere[12]. Some aerosol events show the characteristic feature of dust events of a high AOT and a low α but almost always the detection of rather high values of α indicates contamination by small anthropogenic particles. Figure 1 indicates the AOT at Higashi-Osaka from 2004 to 2010. It shows that high AOT due to dust event is observed frequently in spring.

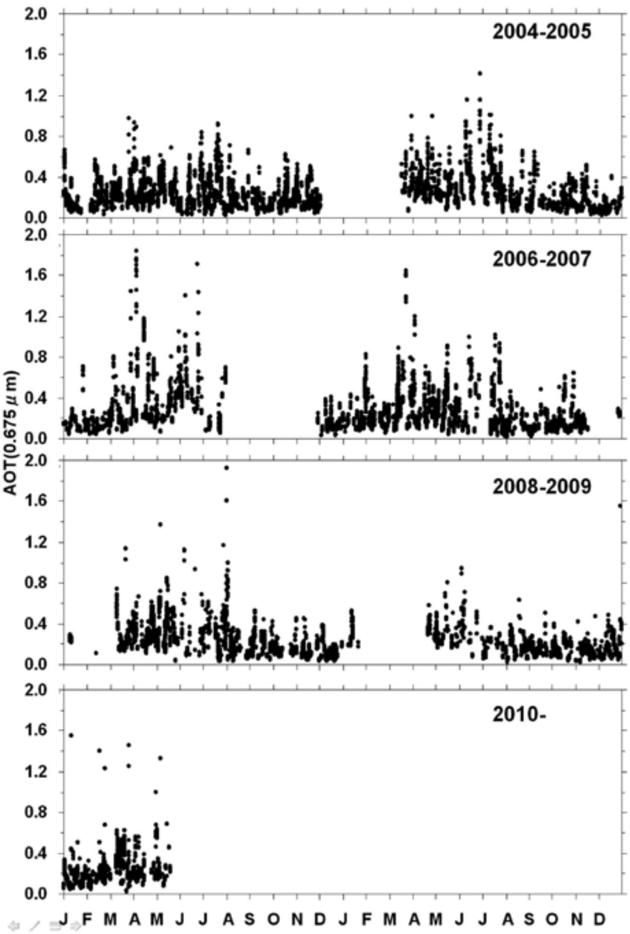

Figure 1. AOT at a wavelength of 0.675 μm at the Higashi-Osaka site from AERONET data obtained from 2004 to 2010.

The aerosol properties at Higashi-Osaka were classified by applying a standard statistics software package (SPSS; Statistical Package for the Social Sciences) to the AERONET data shown in Fig.1. The number of clusters and classification variables were chosen arbitrarily for use with SPSS. The AOT at a wavelength of 0.675 μ m and the α were examined as the classification variables. With these two input variables, SPSS gave the three aerosol clusters shown in Fig. 2 as scatter diagrams of the AOT against α. Cluster-1 appears to represent a clear atmosphere with small AOT values. Cluster-1 can be attributed to the background aerosols at Higashi-Osaka. Namely, the atmosphere over Higashi-Osaka isusually covered with these small particles even on ordinary days. Cluster-2 is associated with large values of α and the AOT, and hence represents a typical aerosol event involving small aerosols. Cluster-3 shows a dust event with a large AOT and a small α .

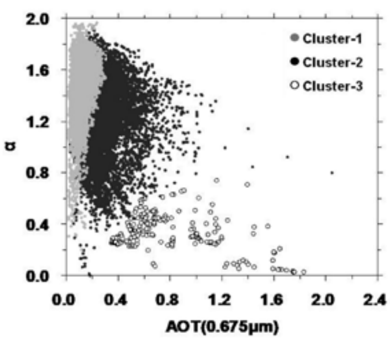

Figure 2. Scatter diagrams of α against the AOT at wavelength of 0.675μm for three clusters of aerosols obtained by SPSS classification for aerosol data during the same period as in Fig.1.

◆ 2.2 PM sampling

An SPM sampler (SPM-613D, Kimoto Electric, Japan) set up at the same AERONET site on the roof of a building at Kinki University (about 50 m above sea level) can measure the concentrations of various SPMs (e.g., PM_{10} and $PM_{2.5}$) separately, as well as optical black carbon (OBC). The SPM sampler makes it possible to determine the relationship between aerosol properties and the particulate mass concentration, since it can separate the contributions of fine particles ($PM_{2.5}$) and coarse particles(PM_C) (defined as the difference between PM_{10} and $PM_{2.5}$), both of which are abundant when the column AOT is high during dust events. PM_C is generally a better indicator of dust events than $PM_{2.5}$ due to soil dust particles being large. However, it is also well known that the size of dust particles decreases during long transportation on a westerly wind, with the resulting dust storm containing fine anthropogenic particles[13]. Accordingly, the $PM_{2.5}$ concentration corresponds well to both anthropogenic and dust aerosols. Therefore, $PM_{2.5}$ data are used for analyzing the correlation between aerosols and PM even in dust events. Figure 3 shows hourly $PM_{2.5}$ and PM_C data obtained during the same period as in Figs. 1 and 2.

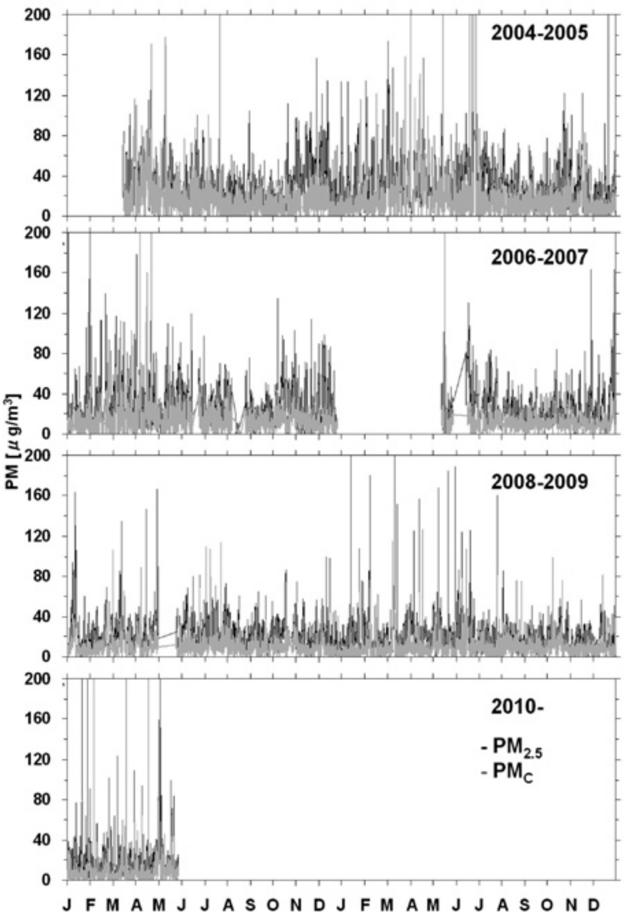

Figure 3. $PM_{2.5}$ and PM_C measurements during the same period and the same site as in Fig.1.

2.3 LIDAR data

Figure 4 presents the measurements with a Mie scattering LIDAR instrument, which is a part of LIDAR network governed with NIES (National Institute for Environmental Studies) , at Higashi-Osaka from April in 2008 to June in 2010. The NIES/LIDAR uses the second harmonics (0.532μm) of a flashlamp-pumped Nd:YAG laser as alight source. It is very interesting to mention that the LIDAR provides the vertical distribution of atmospheric aerosols and the total depolarization ratio of perpendicular component to parallel one of the backscattering intensity[4]. The values of LIDAR extinction at a wavelength of 0.532μm are shown in Fig.4a, where the open and filled circles denote the accumulate values from altitude (h) of 0 to 6 km (expressed by $Ext_{0\text{-}6km}$) and those from 0 to 0.9km ($Ext_{surface}$), respectively. Note that LIDAR signal is rather weak in the higher atmosphere with h > 6km, in other words LIDAR data seem to be saturated around 6km. Therefore 6km is pretended to be top of atmosphere with respect to LIDAR measurements. The ratio is available as below.

$$R(h) = \frac{\int_0^{h} Ext(0.532\,(m)\,dz}{\int_0^{6km} Ext(0.532\,(m)\,dz} \tag{1}$$

The values of R(0.9km) in Fig.4b represent the efficiency factor of extinction by aerosols within the near surface layer against that with total atmosphere.

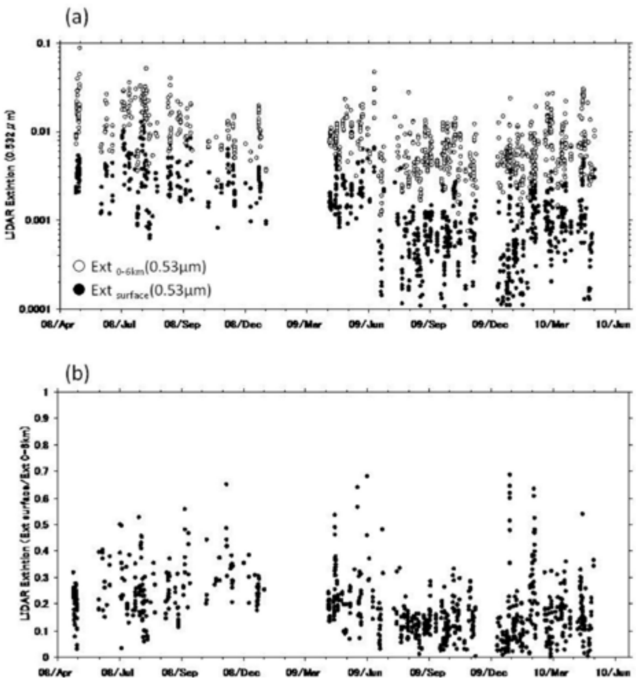

Figure 4. LIDAR extinction at a wavelength of 0.532μm from April of 2008 to June of 2010. In Fig. 4a, $Ext_{0\text{-}6km}$ and $Ext_{surface}$ represent the accumulate values from altitude of 0 to 6 km and those from 0 to 0.9km, respectively. Fig. 4b shows the ratio R(0.9km) of $Ext_{surface}$ to $Ext_{0\text{-}6km}$.

3. RELATIONSHIP BETWEEN MULTI-MEASUREMENTS

3.1 Correlation between AOT and PM

Figure 5 shows scatter diagrams of $PM_{2.5}$ versus AOT(0.675 μm) for Cluster-1 plus Cluster-2 and Cluster-3 defined in Fig.2. The squares in Fig. 5 show a 10-bin data set, because the 10-bin method is a useful procedure for increasing the accuracy of correlation coefficients[14]. However, the number of data points for Cluster-3 was insufficient for applying the 10-bin method. Therefore, the regression line was calculated using the entire data for $PM_{2.5}$ and AOT in Fig. 5b.

Furthermore, correlation between PM2.5 and $AOT_{surface}$ was plotted in Fig. 5d. $AOT_{surface}$ represents the near surface (from the surface to the height of 0.9km) aerosol optical thickness estimated by Eqs. (2).

$$AOT_{surface} = R(0.9\text{km}) \times AOT \tag{2}$$

The figures show linear correlation between $PM_{2.5}$ and AOT is different by aerosol type. This fact suggests that the vertical distribution also should be taken into account separately for each aerosol type. The comparison between Fig.5c and Fig.5d shows that the correlation between $PM_{2.5}$ and AOT has been improved under consideration of near surface aerosol optical thickness ($AOT_{surface}$).

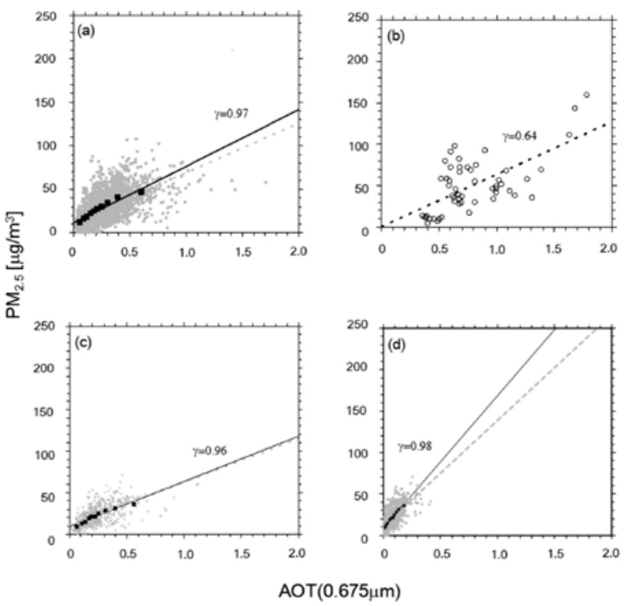

Figure 5. (a) Scatter diagram of $PM_{2.5}$ versus AOT(0.675 μm) for Cluster-1+Cluster-2 during the same period as in Fig.1, (b) Same as (a) but for Cluster-3, (c) Same as (a) but during the same period as in Fig.4., (d) Same as (c) but using $AOT_{surface}$ (0.675 μm).

3.2 Vertical distribution of aerosol

In this section, vertical profiles of atmospheric aerosols are considered using model simulation. Figure 6 presents the simulated results for the vertical distribution of the annual mean aerosol mass concentration at Higashi-Osaka based on a three-dimensional aerosol-transport–radiation model, SPRINTARS[15], which is driven by GCM that was developed by CCSR (Center for Climate Systems Research), NIES, and FRCGC (Frontier Research Center for Global Change)[16]. The model includes carbonaceous, sulfate, mineral dust, and sea salt aerosols. The black and gray lines represent the mass concentrations of mineral dust and anthropogenic (carbonaceous plus sulfate) aerosols, respectively. Note that the error bars represent the standard deviations generated in our model simulations. The pie chart in Fig.6 shows the relative contributions of the two aerosol types. It shows that the two aerosol types exhibit different vertical profiles. The concentrations of anthropogenic aerosols are maximal at the surface and rapidly decrease with height. In particular, carbonaceous and sulfuric aerosols are concentrated in the boundary layer. In contrast, mineral dust is distributed almost uniformly from the surface to the higher atmosphere, with a moderate peak at a height of 2–4 km. The simulated vertical profile of aerosol is consistent with LIDAR measurement.

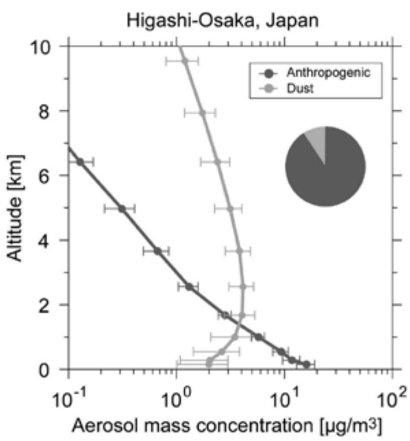

Figure 6. Simulated results of the vertical distribution of the annual mean aerosol mass concentration and its standard deviation at Higashi-Osaka.

4. SUMMARY

The mass concentration of $PM_{2.5}$ is known as an index of air quality. In order to investigate the relationship between $PM_{2.5}$ and AOT, both measurements have been simultaneously done at Kinki University Campus, Higashi-Osaka, Japan since March in 2004[7]. Furthermore LIDAR instrument has joined since April in 2008 at the same site. It provided a linear correlation between $PM_{2.5}$ and AOT in separately considering with several cases. Especially, a stronger linear correlation exists between $PM_{2.5}$ and $AOT_{surface}$. This fact suggests that the vertical distribution is helpful information to estimate $PM_{2.5}$ from column AOT. These results show that combining radiometric aerosol information (including space-based data) with surface-level particulate mass data and LIDAR vertical profile measurements is a useful approach for improving our understanding of air quality and the atmospheric environment.

ACKNOWLEDGEMENTS

The authors thank NASA/AERONET and NIES/LIDAR teams for providing data. This work was supported in part by Global Change Observation Mission – Climate (GCOM-C) by JAXA and the Greenhouse Gases Observing Satellite (GOSAT) Science Project by NIES.

REFERENCES

[1] Mukai, S., Sano, I. and Holben, B. N., “Aerosol properties over Japan by sun/sky photometry,” Water, Air and Soil Pollution 5, 133-143 (2005) [doi:10.1007/s11267-005-0731-2].

[2] Holben, B.N., Eck, T.F., Slutsker, I., Tanré, D., Buis, J.P., Setzer, A., Vermote, E., Reagan, J.A., Kaufman, Y., Nakajima, T., Lavenu, F., Jankowiak, I., and Smirnov, A., “AERONET - A federated instrument network and data archive for aerosol characterization,” Rem. Sens. Environ. 66, 1-16 (1998).

[3] Dubovik, O., Holben, B.N., Eck, T.F., Smirnov, A., Kaufman, Y.J., King, M.D., Tanré, D. and Slutsker, I., “Variability of absorption and optical properties of key aerosol types observed in worldwide locations, “ J. Atmos. Sci. 59, 590-608 (2002).

[4] Shimizu, A., Sugimoto, N., Matsui, I., Arao, K., Uno, I., Murayama, T., Kagawa, N., Aoki, K., Uchiyama, A. and Yamazaki, A., “Continuous observations of Asian dust and ither aerosols by polarization lidars in China and Japan during ACE-Asia,” J. Geophys. Res. 109, 1-14 (2004) [doi:10.1029/2002JD003253].

[5] Smirnov, A., Holben, B. N., Savoie, D., Prospero, J.M., Kaufmann, Y. J., Tanré, D., Eck, T.F. and Slutsker, I. , “Relationship between column aerosol optical thickness and in situ ground based dust concentrations over Barbados,” Geophys. Res. Letters 27, 1643-1646 (2000) [doi:10.1029/1999GL011336].

[6] Wang, J. and Christopher, S.A. “Intercomparison between satellite-derived aerosol optical thickness and $PM_{2.5}$ mass: Implications for air quality studies,” Geophys. Res. Letters 30, 2095 (2003) [doi:10.1029/2003GL018174].

[7] Mukai, S., Nishina, M., Sano, I. Mukai(Nakata), M., Iguchi, N.

and Mizobuchi, S., "Suspended Particulate Matter sampling at an urban AERONET site in Japan Part 1: Clustering analysis of aerosols," J. Applied Remote Sensing 1, 013518 (2007).
[8] Sano, I., Mukai(Nakata), M., Iguchi, N., and Mukai, S., "Suspended Particulate Matter sampling at an urban AERONET site in Japan 2. Relationship between column aerosol optical thickness and $PM_{2.5}$ mass concentration," J. Applied Remote Sensing 4, 403-504 (2010).
[9] Dubovik, O., Smirnov, A., Holben, B. N., King, M. D., Kaufman, Y. J., Eck, T. F. and Slutsker, I., "Accuracy assessments of aerosol optical properties retrieved from AERONET sun and sky-radiaometric measurements," J. Geophys. Res. 105, 9791-9806 (2000) [doi:10.1029/2000JD900040].
[10] Dubovik, O. and King, M. D., "A flexible inversion algorithm for retrieval of aerosols optical properties from sun and sky radiance measurements," J. Geophys. Res. 105, 20673-20696 (2000) [doi:10.1029/2000JD900282].
[11] Smirnov, A., Holben, B. N., Eck, T. F., Dubovik, O. and Slutsker, I. "Cloud screening and quality control algorithms for the AERONET database," Remote Sens. Environ. 73, 337-349 (2000) [doi:10.1016/S0034-4257(00)00109-7].
[12] Eck, T. F., Holben, B. N., Reid, J. S., Dubovik, O., Smirnov, A., O'Neill, N. T., Slutsker, I. and Kinne, S., "Wavelength dependence of the optical depth of biomass burning, urban, and desert dust aerosols," J. Geophys. Res. 104, 31333-31349 (1999) [doi:10.1029/1999JD900923].
[13] Mukai (Nakata), M., Nakajima, T. and Takemura, T. "A study of long-term trends in mineral dust aerosol distributions in Asia using a general circulation model," J. Geophys. Res. 109, D19, D19204 (2004) [doi:10.1029/2003JD004270].
[14] Kacenelenbogen, M., Léon, J.-F., Chiapello, I. and Tanré, D. "Characterization of aerosol pollution events in France using ground-based and POLDER-2 satellite data," Atmos. Chem. Phys. 6, 4843–4849 (2006).
[15] Takemura, T., Nozawa, T., Emori, S., Nakajima, T. Y. and Nakajima, T., "Simulation of climate response to aerosol direct and indirect effects with aerosol transport-radiation model," J. Geophys. Res., 110, D02202 (2005) [doi:10.1029/2004JD005029].
[16] K-1 Model Developers, [K-1 coupled GCM (MIROC) description], edited by Hasumi, H. and Emori, S., K-1 Tech. Rep. 1, Cent. For Clim. Syst. Res., Univ. of Tokyo, Tokyo (2004).