OPTICAL PROPERTIES OF ASIAN DUST AEROSOL DERIVED FROM SEAWIFS AND LIDAR OBSERVATIONS: A CASE STUDY OF DUST OVER CLOUDS

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ABSTRACT

Asian dust aerosol layer of 4-6 km altitude accompanied by low clouds was observed by LIDAR and sky-radiometer in Tokyo urban area on April 10, 2001. To synthesize the top of atmosphere (TOA) reflectance, radiative transfer simulation conducted assuming aerosol/cloud vertical structure and aerosol size distribution that were modeled after the ground observations. The refractive index of Asian dust is derived from a laboratory measurement of sampled Chinese soil particles. The synthesized TOA reflectance is compared to the SeaWiFS-derived one sampled at the low cloud pixels whose airmass is the same as the one passed at the observation site. While the two TOA reflectances compare generally well with few percent difference in reflectance, possible sources of the discrepancy are discussed.

INTRODUCTION

The optical effect of Asian dust aerosol is very important in terms of radiation forcing which affects climate change. It also affects satellite ocean color remote sensing due to its strong absorption in the short wavelength region. Despite the intensive studies that have been conducted by many researchers, the optical properties of dust particles are not very well known. In spring 2001, extensive and comprehensive observations under ACE-Asia international program were conducted, including concurrent ground, ship and airplane observations as well as satellite overflight. The current study aims at enriching our knowledge on characterization of Asian dust aerosol by comparing satellite-observed reflectance with ground observation-based top of atmosphere (TOA) reflectance over a case where we have elevated Asian dust layer above a low and thin cloud layer. The vertical structure of aerosol and cloud is observed by LIDER while the aerosol size distribution is estimated via contemporaneous sky-radiometer observations. We also refer to a particle transport simulation which predicts the optical thickness for Asian dust layer and the vertical profile of the dust aerosol.

OBSERVATION OF A DUST LAYER IN TOKYO

LIDAR and sky-radiometer observations

On April 6, 2001, there occurred a large scale Asian dust event in Gobi desert area. Two days later, another dust storm occurred in Takramakan desert. These dust airmass reached to the Japan area in few days later, when many Japanese LIDAR sites who participate in the Asian Dust Network (AD-Net) observed uplifted dust layer of 3.5-6.5 km altitude (Murayama et al., 2002).

On April 10, LIDAR observation together with sky-radiometer observation was conducted at Tokyo University of Mercantile Marine (TUMM) which locates in urban Tokyo area. At around 12:40 JST when Orbview–II/SeaWiFS overpassed, the sky was cloud free and LIDAR profile of extinction coefficient and depolarization ratio (Figure 1(a)) depicts the elevated dust layer at 4-6 km altitude and non-dust aerosol layer near the surface. After around 13:00, low but thin cloud

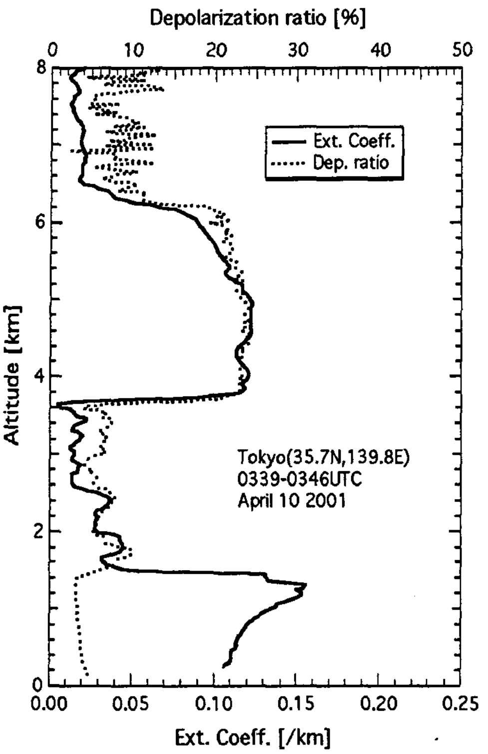

Figure 1. Vertical profiles of extinction coefficient and depolarization ratio based on the measurements made on (a) 12:46 JST under cloud-free condition and (b) 13:30 JST under cloud condition.

emerged just above the near-surface aerosol layer at 1.2-1.6 km altitude, which is mostly persistent over more than an hour.

At the cloud-free condition around 12:45, sky-radiometer observation was conducted with PREDE MK-II instrument. From the measured data, we derived volume size distribution using an inversion code (sky-rad pack) based on Nakajima *et al* (1996). The retrieved size distribution (Figure 3) shows coarse mode and fine particles mode. Since the LIDAR observation confirms that there were dust particles, the coarse mode is supposed to correspond to the Asian dust layer. The fine mode is considered to be of the low layered aerosol.

Satellite reflectance

Figure 3 shows SeaWiFS image of total reflectance ρ_A, where $\rho_A(865)$ is obtained by

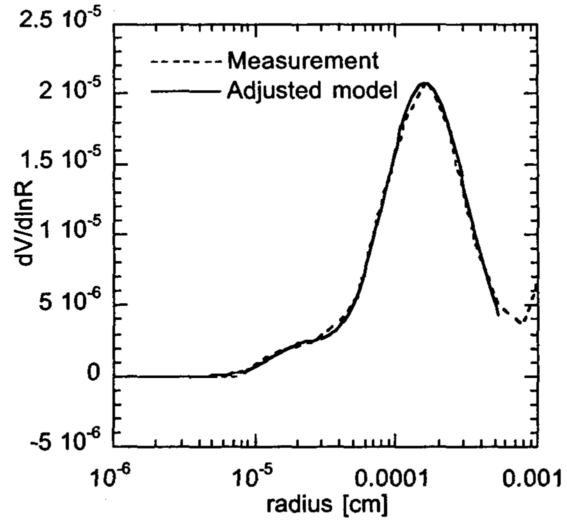

Figure 2. Derived aerosol size distribution based on the sky-radiometer observations at Tokyo University of Mercantile Marine. The data was averaged over three observations conducted in 12:07-12:52 JST. Solid line shows a modeled size distribution used for radiative transfer simulation.

$$\rho_A(865) = \frac{\pi L_T(865)}{F_0(865)\cos\theta_0}.$$

Here, L_T is the satellite-observed radiance, F_0 the extraterrestrial solar irradiance, θ_0 the solar zenith angle. While it is cloud-free at the location of the observation site (indicated as "TUMM") there are significantly many cloud pixels near Tokyo. Since the rawinsonde observation record at Tateno which locates about 60 km NNE of Tokyo indicates that the wind direction was 81 with the speed of 9 m/s at 1.5 km altitude, the clouds observed at TUMM is judged to be the ones shown in the east of Tokyo. As shown in figure 3, We define sample pixels whose airmass (with cloud) is estimated to be observed at the site during 14:00-15:00. Along the sample line we collected the reflectance for all the 8 SeaWiFS bands (412 ~ 865 nm bands). We only took the pixels with the reflectance higher than 0.25 to make it sure the pixels contain cloud which is in favor of diminishing the surface reflectance effect on the TOA reflectance. The average spectral TOA reflectance is shown in Figure 4 together with error bars.

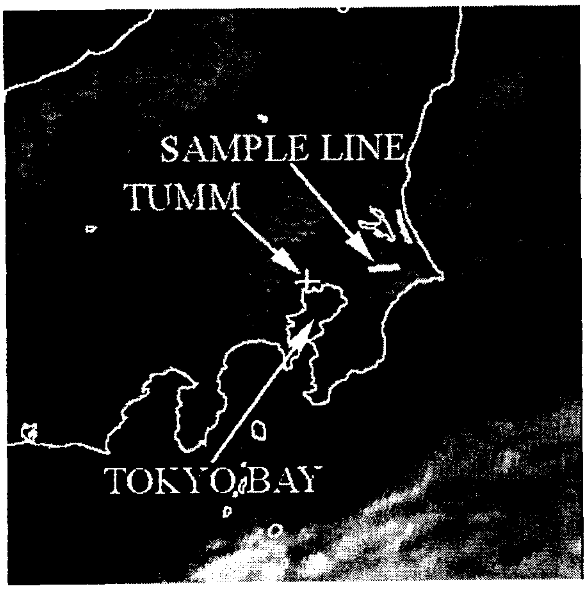

Figure 3. SeaWiFS image of TOA reflectance at 865 nm band, obtained on April 10, 2001.

As we need to define surface reflectance for radiative transfer simulations, we derived the estimated average surface reflectance nearby the sample line location. Since the sample pixels in the April 10 image are covered by clouds and contaminated by dust aerosol, we sampled pixels from the SeaWiFS data obtained on April 7 (three days prior to the dust observation when the sky was clear with less aerosol concentration). The surface reflectance ρ_{SURF} is estimated form the total reflectance ρ_T and the Rayleigh reflectance ρ_R under the "aerosol–free" condition based on the following equation,

$$\rho_T(\lambda) = \rho_R + \frac{t(\lambda)t_0(\lambda)\rho_{SURF}(\lambda)}{1-\overline{r}_R\rho_{SURF}}$$

where $\overline{r}_R$ is spherical albedo of an aerosol-free atmosphere, t the transmittance between the surface and the satellite, t_0 the transmittance between the sun and the surface. This equation is based on the one shown by Chandrasekhar (1960). We adopted the spherical albedo values from a NASA–provided software for SeaWiFS data processing (SeaDAS ver, 4.3). The estimated surface reflectance is also shown in Figure 4.

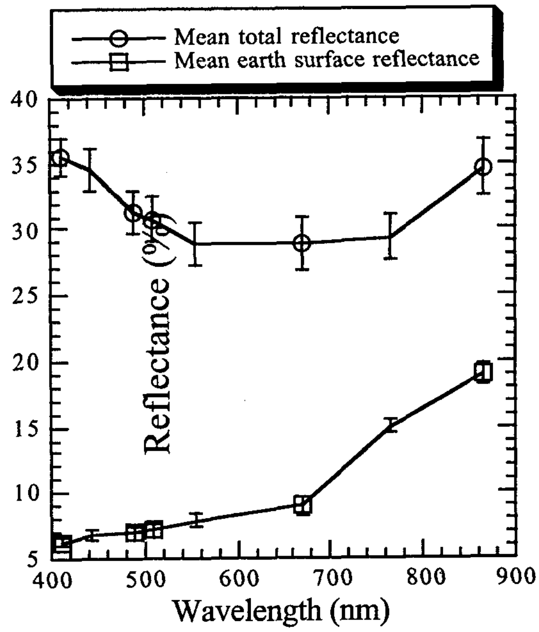

Figure 4. Satellite-observed TOA spectral reflectance averaged along the sampling line shown in Figure 3. Vertical lines indicate the standard deviation range. Lower curve indicates surface reflectance estimated from SeaWiFS data on April 7, three days prior to the dust event.

Particle transport simulation

Aerosol transportation during ACE–Asia was simulated with the real-time chemical weather forecast (CFORS) (Uno *et. al*, submitted). CFORS is based on a 3–dimensional on–line regional scale chemical transport model fully coupled with the Regional Modeling System (RAMS). Figure 5 shows the spatial distribution of Asian dust aerosol optical thickness at the time of the satellite and ground observations, demonstrating the wide-spread dust aerosol with the optical thickness of 0.2 – 0.6 all over Japan. The extracted vertical profiles of extinction for Asian dust and for all the aerosol species confirm our observation that we have elevated dust layer above the near-surface aerosol (Figure 6).

COMPARISON OF SATELLITE AND SYNTHESIZED TOA REFLECTANCES

Model atmosphere and aerosols

To assess the validity of our Asian dust aerosol

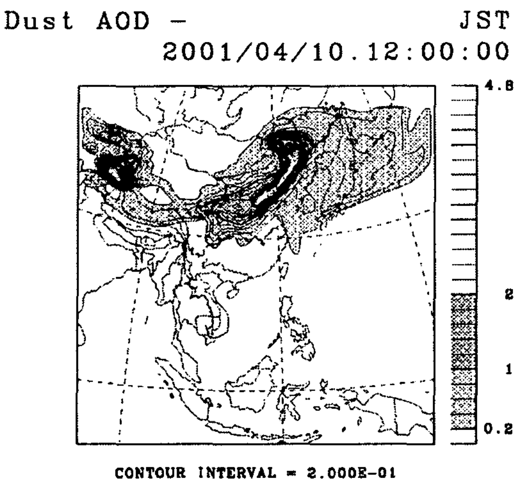

Figure 5. Spatial distribution of Asian dust predicted by CFORS particle transport simulation. Note that the optical thickness of Asian dust is predicted to be about 0.4 at Tokyo area.

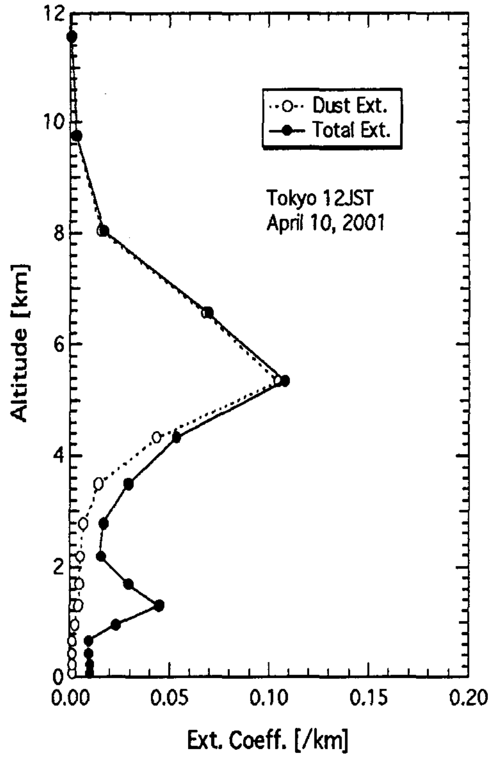

Figure 6. Predicted vertical profile of Asian dust aerosol derived from CFORS simulation.

model, radiative transfer simulations were conducted assuming several aerosol models. Since the observations strongly suggest that there are two aerosol layers, namely of elevated dust particles and of near-surface non-dust aerosol, we define the baseline vertical distribution of aerosol as low altitude "tropospheric" model and high altitude "Asian dust" model. We also assume a cloud layer on the top of the tropospheric aerosol. The reason for choosing the cloud-present case is to avoid the direct effect of the surface reflectance to the TOA reflectance since the surface reflectance tends to be high and inhomogeneous in the urban area. The parameters for the modeled aerosol profile is shown in Table 1. We assume log-normal volume size distribution (Shettle and Fenn, 1979) for each aerosol species including cloud. The size parameters for tropospheric and Asian dust were determined based on the sky-radiometer observation (Figure 2) while we adopted typical values for the size parameters for cloud (shown also in Table 1). The refractive indices for troposoheric and water cloud were the same as defined by Shettle and Fenn (1979) and shown in Table 2. The refractive index for Asian dust was determined by a laboratory measurement of Chinese soil particles sampled at the loess layer in Gansu Province (Table 2).

Table 1. Baseline vertical profile of aerosols assumed for the radiative transfer simulation together with the mode radius and the standard deviation of the volume size distribution for each aerosol model.

Model	Measurement [km]	Assumed model [km]	R_m[μm]	σ
Tropospheric	0-1.3	0-1	0.216	1.68
Cloud (water)	1.3-1.8	1-2	8.0	1.5
Asian dust	3.6-6.5	4-6	1.60	1.97

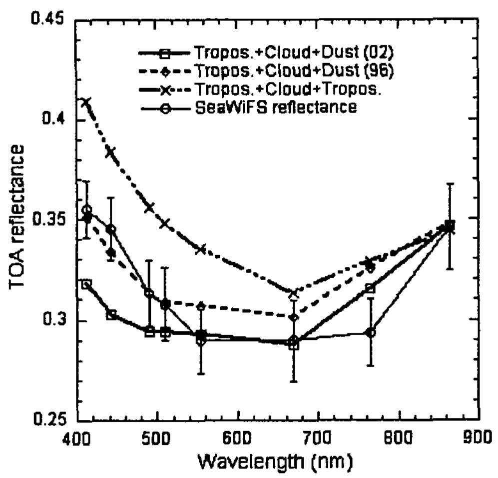

Figure 7. Simulated TOA spectral reflectances of the aerosol-cloud structure observed in Tokyo on April 10, 2001. SeaWiFS reflectance is also shown for comparison.

Radiantive transfer simulation

To obtain a synthesized TOA spectral reflectance, we preformed radiative transfer simulation using the Rstar 5b code developed by T. Nakajima (Nakajima and Tanaka, 1986; 1988). While the optical thickness for the tropospheric and the dust aerosol are determined from the LIDAR-observed extinction profile (Figure 1), the cloud optical thickness is adjusted so that the simulated TOA reflectance at 865 nm has the same value as the one retrieved by the SeaWiFS observation. The result are presented in Figure 7. we have tested two different sets of Asian dust refractive index, one obtained in 2002 (thick solid line) and the other in 1996 (thick dotted line). Both generally compares well with the SeaWiFS-derived reflectance (Thin line with error bars) although there remains ~3% discrepancies depending on the model and the wavelength. A case where the elevated dust layer is substituted by tropospheric aerosol is also shown in Figure 7 to demonstrate the sensitivity of TOA reflectance to aerosol species.

Possible sources of the discrepancies

The discrepancies between stallite-deriucd and the simulated reflectance may be explained by several different reasons. First possible explanation is that the refractive index of dust-dominated aerosol we had on the day of the observation might be significantly different from those of the samples measured at laboratory since dust particle change in its chemical and optical properties during the long range transportation. Another possible reason is that there may be other aerosol species like maritime, soot, or carbonaceous aerosols present in addition to the assumed two species. Another possibility of a different kind is the uncertainty in estimating the surface reflectance that is particularly difficult in spring time when atmosphere is mostly hazy.

Table 2. Imaginary part of refractive indices for each aerosol model.

Wavelength (nm)	412	443	490	510	555	670	765	865
Tropospheric	$5.08*10^{-3}$	$5.17*10^{-3}$	$4.99*10^{-3}$	$4.96*10^{-3}$	$6.05*10^{-3}$	$6.46*10^{-3}$	$8.98*10^{-3}$	$1.22*10^{-3}$
Cloud (water)	$1.53*10^{-9}$	$1.08*10^{-9}$	$9.53*10^{-10}$	$1.10*10^{-9}$	$2.20*10^{-9}$	$2.10*10^{-8}$	$1.53*10^{-7}$	$3.48*10^{-7}$
Asian dust (2002)	$1.05*10^{-2}$	$8.42*10^{-3}$	$5.27*10^{-3}$	$4.37*10^{-3}$	$3.31*10^{-3}$	$1.94*10^{-3}$	$1.29*10^{-3}$	$5.05*10^{-4}$
Asian dust (96)	$7.00*10^{-3}$	$6.01*10^{-3}$	$5.53*10^{-3}$	$5.30*10^{-3}$	$4.54*10^{-3}$	$3.70*10^{-3}$	$3.29*10^{-3}$	$2.94*10^{-3}$

CONCLUSION

We have tried to validate our dust aerosol model by comparing the satellite reflectance with the simulated reflectance whose model parameter values were derived form the contemporaneous measurements. The current dust aerosol models give spectral reflectance that agrees with the satellite-derived reflectance within a few percent error. It might have enough precision for certain applications but still necessitates further investigation.

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