Modeling study of long-range transport of Asian dust and anthropogenic aerosols from East Asia

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[1] A three-dimensional aerosol transport-radiation model, SPRINTARS, successfully simulates the long-range transport of the large-scale Asian dust storms from East Asia to North America which crossed the North Pacific Ocean during the springtime of 2001 and 2002. It is found from the calculated dust optical thickness that 10 to 20% of the Asian dust around Japan reached North America. The simulation also reveals the importance of the contribution of anthropogenic aerosols, which are carbonaceous and sulfate aerosols emitted from the industrialized areas in East Asia, to air turbidity during the dust storms. The contribution of the anthropogenic aerosol to the total optical thickness is simulated to be of a comparable order to that of the Asian dust, which is consistent with the observed values of the particle size index from the satellite and ground-based sun/sky photometry. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 0368 Atmospheric Composition and Structure: Troposphere—constituent transport and chemistry; 3359 Meteorology and Atmospheric Dynamics: Radiative processes. **Citation:** Takemura, T., I. Uno, T. Nakajima, A. Higurashi, and I. Sano, Modeling study of long-range transport of Asian dust and anthropogenic aerosols from East Asia, *Geophys. Res. Lett.*, *29*(24), 2158, doi:10.1029/2002GL016251, 2002.

1. Introduction

[2] Soil dust aerosols have a large impact on the earth's radiation budget through their scattering and absorbing of solar and thermal radiation, especially over the Saharan, Arabian, and Asian desert regions [e.g., *Miller and Tegen*, 1998], though the confidence level of the estimation of the dust radiative forcing is very low as suggested by past studies [*IPCC*, 2001]. They also have a harmful influence on human health, especially in East Asia, where dust sources are close to urban areas. The Asian dust is emitted from the Chinese and Mongolian arid regions by cyclone activities and transported to the Chinese coastal regions, Korea, and Japan mainly in the spring season. The scale and frequency of the Asian dust storm have rapidly increased since 2000 as observed by weather stations of the Japan Meteorological Agency. At Nagasaki, the west edge of Japan (129.8°E, 32.7°N), the number of days in which the arrival of Asian dust was observed is 6.1 days per year on an average of 1990's, on the other hand, 16 and 15 days in 2000 and 2001, respectively. A huge dust storm reaching the urban areas in East Asia was reported on 20 to 22 March 2002 with a visibility of less than 50 m in Beijing, China, although more investigations are still needed to confirm the detailed mechanism of this increase in the frequency and scale of Asian dust events. The large-scale Asian dust storms were shown in a modeling study [*Uno et al.*, 2001], ground-based observations [*Thulasiraman et al.*, 2002], and satellite remote sensing by the Total Ozone Mapping Spectrometer (TOMS) (http://toms.gsfc.nasa.gov/aerosols/aerosols.html) and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (http://eob.gsfc.nasa.gov/NaturalHazards/).

[3] In this study, we simulated the large Asian dust storm events in 2001 and 2002 by an aerosol transport-radiation model, and the simulated results are compared with several observations from the ground and satellite for the aerosol mass concentration and optical properties. It is significant to precisely simulate the Asian dust phenomena for understanding their effects on the atmospheric environment and climate over the Asian-Pacific region. Our concern in this paper is to study the effects of the mixture of dust and anthropogenic aerosols transported with the Asian dust storms on the atmospheric turbidity in the Asian-Pacific region.

2. Model Description

[4] The three-dimensional aerosol climate model used in this study is called SPRINTARS (Spectral Radiation-Transport Model for Aerosol Species) and has been developed at the Center for Climate System Research (CCSR), the University of Tokyo [*Takemura et al.*, 2000, 2002]. The model simultaneously treats the main tropospheric aerosols, that is, carbonaceous (organic and black carbons), sulfate, soil dust, and sea salt. The aerosol transport processes include emission, advection, diffusion, sulfur chemistry,

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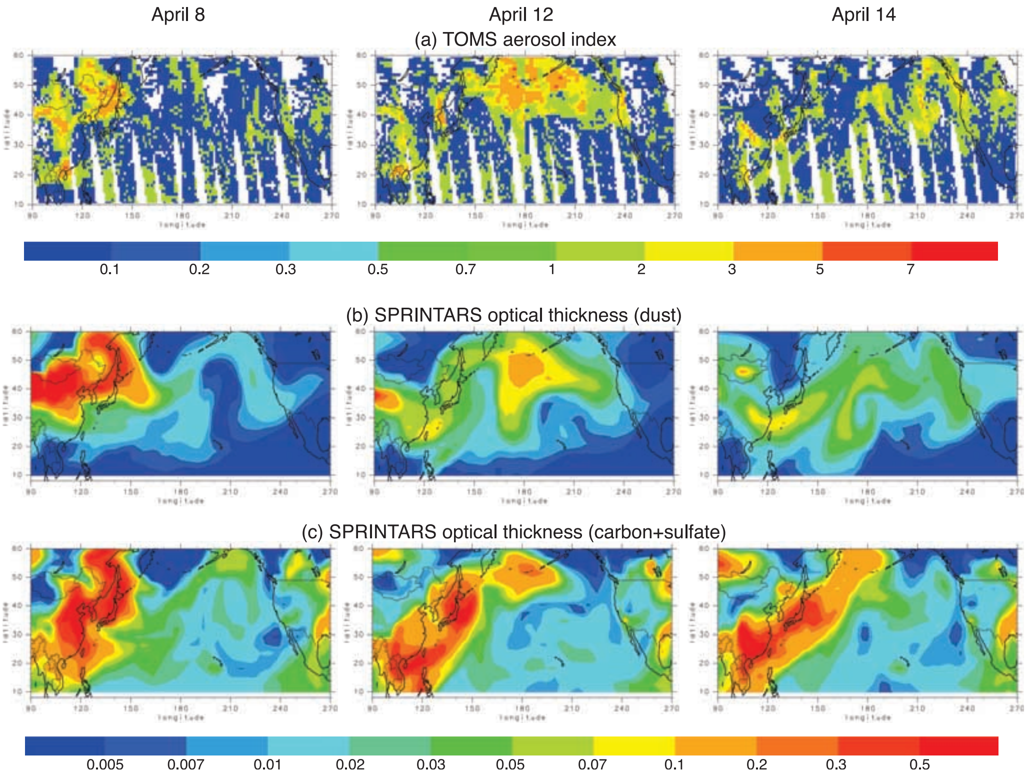

Figure 1. Daily mean distributions of the (a) TOMS aerosol index and simulated optical thickness for (b) soil dust aerosols and (c) carbonaceous plus sulfate aerosols on 8, 12, and 14 April 2001.

wet deposition, dry deposition, and gravitational settling. It is driven by the atmospheric general circulation model (AGCM) of CCSR and the National Institute for Environmental Studies (NIES), Japan [*Numaguti et al.*, 1995], and is combined with the radiation scheme in the AGCM [*Nakajima et al.*, 2000] for aerosol scattering and absorbing processes. The horizontal resolution of the triangular truncation is set at T42 (approximately 2.8° by 2.8° in latitude and longitude) and the vertical resolution at 11 layers (sigma level based on the surface pressure at 0.995, 0.980, 0.950, 0.900, 0.815, 0.679, 0.513, 0.348, 0.203, 0.092, and 0.021). The model time step is 20 minutes. The 6-hourly reanalysis data from the National Centers for Environmental Prediction/National Center for Atmospheric Research are used for nudging the wind, temperature, and specific humidity in order to provide a precise simulation during the specific period.

[5] The dust particle size is divided into 10 size bins from 0.1 to 10 μm radii, and the amount and location of the dust emission depend on the vegetation, wind speed near surface, soil moisture, and snow amount in the model [*Takemura et al.*, 2000]. The carbonaceous aerosol emission flux is based on the Special Report on Emissions Scenarios (SRES) data [*IPCC*, 2000] for forest fires, fossil fuel, and biofuel sources, and the original data [*Takemura et al.*, 2000] for the combustion of agricultural wastes and terpene conversion. The sulfur dioxide (SO_2) emission flux, which is the precursor gas of sulfate aerosols, is based on SRES for fossil fuel consumption and the Global Emissions Inventory Activities dataset for volcanic activities. The simulation also includes the SO_2 emission with the temporal variation from the large-scale continuous eruption of Miyakejima Island (139.5°E, 34.1°N), which is important for calculating the appropriate aerosol distribution in East Asia, 2001 and 2002. The refractive index for the aerosol radiative process calculation is based on the World Meteorological Organization recommendation [*WCP-55*, 1983].

[6] The simulated aerosol optical thickness, the Ångström exponent, which is a size index calculated by the log-slope exponent of the optical thickness between 0.55 and 1.0 μm, and the single scattering albedo by SPRINTARS were compared with observations by the sun/sky photometry from the Aerosol Robotic Network (AERONET) on a global scale [*Takemura et al.*, 2002] and of the Japanese sites [*Takemura et al.*, 2001]. These comparisons showed quantitatively reasonable agreements between the simulation and observations. The reproduction of aerosol distributions by SPRINTARS was shown to be realistic in the inter-comparisons among several global aerosol transport models and satellite retrievals [*Kinne et al.*, 2002].

3. Results and Discussion

[7] The simulated dust optical thickness of the severe Asian dust storm in April 2001 is presented in Figure 1 with the TOMS aerosol index which can detect UV-absorbing aerosols, such as soil dust [*Herman et al.*, 1997]. TOMS observed a large amount of dust intermittently emitted in the atmosphere from and around the Gobi Desert between 6 and 9 April by a developing cyclone and then transported eastward with the post-frontal outflow passing the northern Chinese coastal region, Korea, and Japan (Figure 1a). It also observed that the large-scale Asian dust reached North America about one week later from the emission crossing

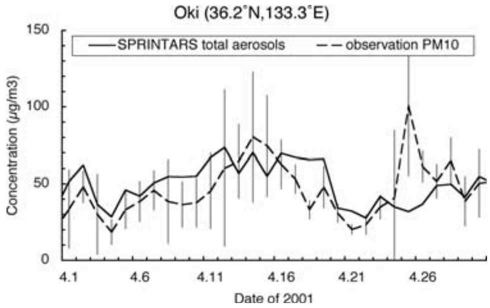

Figure 2. Comparison of the simulated total aerosol surface concentration (solid line) with the observed PM10 concentration (dashed line) at Oki (36.2°N, 133.3°E) in μg m^{-3} in April 2001. The vertical lines indicate the standard deviations of the observed PM10 concentrations.

over the North Pacific Ocean. These spatial and temporal patterns of the dust air mass are similarly simulated by SPRINTARS (Figure 1b). The simulation shows that the optical thickness of the dust air mass over the west coast of North America is ten to twenty percent of that over Japan. Moreover, the simulation suggests that anthropogenic aerosols from urban regions in East Asia, that is, carbonaceous and sulfate aerosols, were transported with the Asian dust (Figure 1c). In spring, these anthropogenic aerosols, which have constant emission sources mainly along the coast of the East Asian continent, strongly blow toward the cold front when the developed cyclone migrates around the northern Japan, and then they are transported by the westerlies concentrating on the cyclone and mixing with Asian dust. The optical thickness value of the carbonaceous plus sulfate aerosols in the air mass is calculated to be comparable to that of soil dust aerosols from East Asia to the mid-North Pacific, although it becomes low when the Asian dust reached North America because of the wet deposition and diffusion.

[8] There is a large volume of observational data regarding the aerosol characteristics in the spring of 2001 acquired by the intensive observation campaigns of the Asian Pacific Regional Aerosol Characterization Experiment (ACE-Asia) and the Asian Atmospheric Particulate Environmental Change Studies (APEX) carried out over the East Asian region. Figure 2 shows a good agreement between the simulated total aerosol concentration and the particle matter concentration below the 10 μm diameter (PM10) observed by the Acid Deposition and Oxidant Research Center (ADORC) in the west part of the Japan Sea in April 2001, though the simulation cannot represent the peak of the measured value on April 25. Soil dust and sea salt aerosols are the main contributors to the PM10 concentration at this location, so that the simulated and observed high concentrations suggest arrival of the Asian dust because the sea salt concentration is fairly constant during this season. The simulated aerosol optical thickness and Ångström exponent in April 2001 are compared with the SeaWiFS retrieval [*Higurashi and Nakajima*, 2002] in Figures 3a and 3b and AERONET [*Holben et al.*, 2001] in Figure 3c around Japan. Since the SeaWiFS data can be retrieved only under clear-sky conditions and it is difficult to pick up the pixel data only under clear-sky conditions from the simulated results, the regional mean values of the SeaWiFS aerosol optical thickness tend to be greater than the simulated values. The agreement between the simulated and observed Ångström exponent during this period suggests that the ratio of the optical thickness of anthropogenic aerosols, which have small radii, to that of soil dust aerosols is simulated well by SPRINTARS. Therefore, the results suggest that about half of the total optical thickness in this area is due to anthropogenic aerosols even when the strong Asian dust events occur, as also shown in Figure 1. *Takemura et al.* [2001] pointed out that 50 to 80% of the sulfate

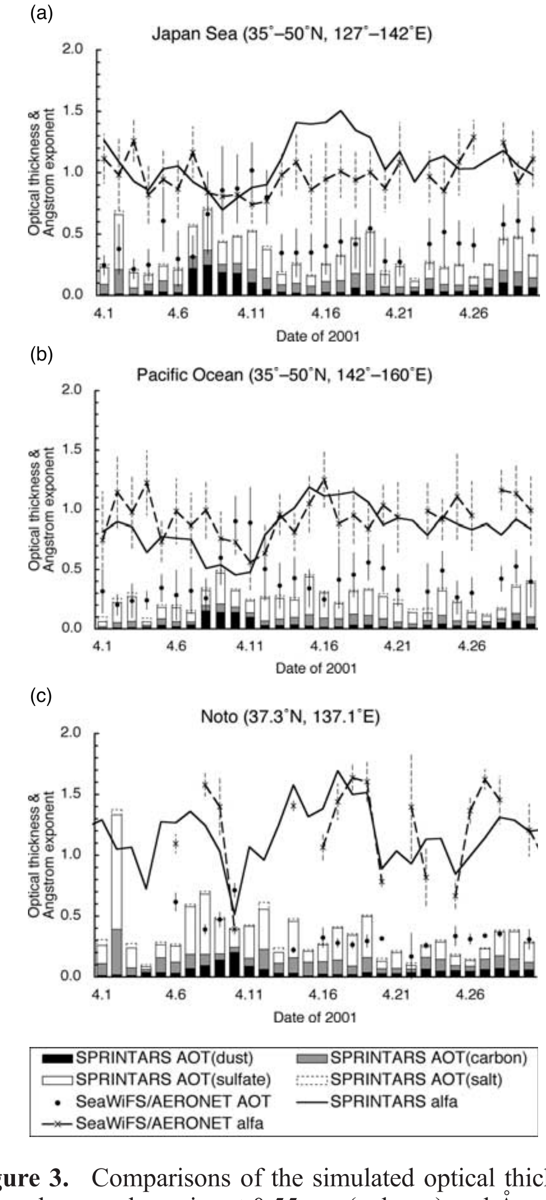

Figure 3. Comparisons of the simulated optical thickness for each aerosol species at 0.55 μm (column) and Ångström exponent (solid line) with the observed optical thickness (dot) and Ångström exponent (dashed line) over the (a) Japan Sea (35 to 50°N, 127 to 142°E) and (b) northwestern Pacific Ocean (35 to 50°N, 142 to 160°E) by the SeaWiFS retrieval and (c) at Noto (37.3°N, 137.1°E) by AERONET in April 2001. The vertical solid and dashed lines indicate the standard deviations of the observed optical thickness and Ångström exponent, respectively.

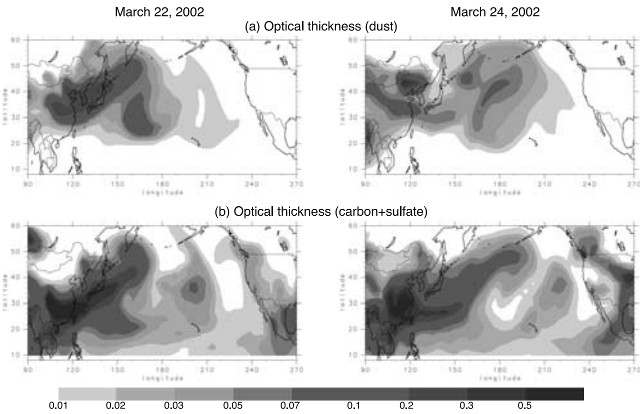

Figure 4. Daily mean distributions of the simulated optical thickness for (a) soil dust aerosols and (b) carbonaceous plus sulfate aerosols on 22 and 24 March 2002.

aerosols and 30 to 50% of the black carbon around Japan are imported from the East Asian continent to Japan.

[9] Figure 4 presents the simulated aerosol optical thickness during another large-scale Asian dust storm in March 2002. On March 22, the simulated high dust loading extended to Japan, especially the northern part of Japan, along the post-frontal outflow. The Asian dust event was scarcely observed in Hokkaido, the northeastern island of Japan (around 142°E, 43°N). The simulated spatial pattern of the dust transport is consistent with the near true-color images of SeaWiFS, although there are not much observed data for this dust storm. The simulation shows the transportation of a large amount of anthropogenic aerosols from East Asia to the North Pacific with Asian dust also in this event.

4. Conclusions

[10] The air-mass characteristics of the Asian dust events that occurred in 2001 and 2002 when the large-scale dust storms were transported from the East Asian continent over the North Pacific Ocean and North America have been studied by SPRINTARS. The simulation indicated that a significant amount of anthropogenic carbonaceous and sulfate aerosols were transported from the East Asian continent to the North Pacific with the Asian dust storms in 2001 and 2002. The emissions of sulfuric, nitric, and carbonaceous pollutants from the East Asian continent are predicted to continue increasing for the next several decades [*IPCC*, 2000], so that the trans-boundary air pollution associated with dust storms is expected to increase in the future.

[11] It is not clear why Asian dust storms have expanded in scale and frequency since 2000. Actually, *Qian et al.* [2002] indicates that meteorological station data in eastern China showed a steady decrease in the frequency of dust storms and dust weather till 1998 because warming in Mongolia and cooling in northern China reduced the meridian temperature gradient, resulting in the reduced cyclone frequency. A detailed analysis of the expanded dust events is an urgent task for us to study.

[12] **Acknowledgments.** We thank the contributors to the development of the CCSR/NIES AGCM, the NASA TOMS Science Team, and the ADORC for the measured PM10 data. This study is partly supported by the APEX project of the Core Research for Evaluational Science and Technology of the Japan Science and Technology Corporation.

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