Record heavy Asian dust in Beijing in 2002: Observations and model analysis of recent events

Nobuo Sugimoto,[1] Itsushi Uno,[2] Masataka Nishikawa,[1] Atsushi Shimizu,[1]
Ichiro Matsui,[1] Xuhui Dong,[3] Yan Chen,[3] and Hao Quan[3]

Received 27 September 2002; revised 6 February 2003; accepted 7 February 2003; published 26 June 2003.

[1] A record heavy Yellow Sand event was observed on 20 March in Beijing. This event was unusual because the wind speed was low and the dust concentration was extremely high at the dust front. Observations with a polarization lidar, an optical particle counter, and a high-volume sampler were performed throughout the event in Beijing. The visibility derived from the lidar data was 650 m, and the total suspended particle concentration was 11 mg/m3 at the peak. Chemical transport model analysis revealed that the main part of the dust originated in the Mongolian border area near Ejinaqi. This dust event severely affected Korea and northern Japan. Continuous lidar observations in Beijing, Nagasaki and Tsukuba revealed that the frequency of dust events in 2001 and 2002 was similar in Beijing but much higher in 2002 in Nagasaki and Tsukuba. The model showed dust was transported to the east more frequently in 2002 and the difference is probably related to the smaller perturbation of the westerly jet. This indicates that a slight change in climate can cause a large difference in dust phenomena in the northwestern Pacific region. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 3360 Meteorology and Atmospheric Dynamics: Remote sensing. **Citation:** Sugimoto, N., I. Uno, M. Nishikawa, A. Shimizu, I. Matsui, X. Dong, Y. Chen, and H. Quan, Record heavy Asian dust in Beijing in 2002: Observations and model analysis of recent events, *Geophys. Res. Lett.*, *30*(12), 1640, doi:10.1029/2002GL016349, 2003.

1. Introduction

[2] Asian dust (Yellow Sand) is a significant spring phenomena in East Asia. It is estimated that several tens of millions of tons of mineral dust are transported every year from desert areas in China and Mongolia to western Pacific regions, and some dust occasionally reaches North America [*Husar et al.*, 2001]. Mineral dust has various effects on the atmospheric environment, including chemical [*Iwasaka et al.*, 1988; *Nishikawa et al.*, 1991] and radiative effects [*Sokolik and Toon*, 1996], and also on the oceanic environment [*Uematsu et al.*, 1983]. Effects of heavy dust events on human health have also become a concern recently. Some statistics indicate that the number of dust events has been increasing in recent years. However, observations for quantitatively estimating the amount of dust generated and transported are lacking. To study dust phenomena quantitatively, we started observations in 2001 with a sampling network in northeastern China and continuously operated polarization lidars in Beijing and two locations in Japan (Nagasaki and Tsukuba). Polarization lidars are effective tools for monitoring Asian dust sensitively [*Murayama et al.*, 2001; *Sugimoto et al.*, 2002]. We also employ a chemical transport model (Chemical Weather Forecast System (CFORS)) to analyze dust phenomena [*Uno et al.*, 2001; *Uno et al.*, 2003]. Our goal is to achieve quantitative understanding by improving the model with observations.

[3] A heavy dust event, the largest in the last ten years, was observed in Beijing on 20 March. The event was singular because wind speed was very low when the dust front reached Beijing. We also observed a large dust event on 6 April. This case was rather typical with high wind speed when the dust front arrived. We will compare observations and model results for these two cases in the following discussion to understand why the dust concentration was extremely high in the 20 March case. In 2002, heavy dust events were transported to Korea and Japan more frequently than in 2001. We will discuss the difference between 2001 and 2002 using continuous lidar data in Beijing, Nagasaki and Tsukuba, and the model post analysis.

2. Observations and the Model

[4] The lidar observation in Beijing was performed at the Sino-Japan Friendship Center for Environmental Protection SJFCEP. The lidar employs a flashlamp-pumped, second-harmonic Nd:YAG laser and a receiver telescope with a diameter of 20 cm. The transmitted laser (532 nm) was linearly polarized, and two polarization components of the scattered light were detected with two photomultiplier tubes. Five-minute measurements were taken automatically every 15 min. The lidars in Nagasaki and Tsukuba have similar hardware systems [*Sugimoto*, 2002].

[5] In the analysis of the heavy dust cases in Beijing, we used the Klett's inversion method to derived the extinction coefficient [*Klett*, 1981], after applying a geometrical-form-factor correction. We used single-component Klett's method instead of two-component Fernald's method because the scattering of dust aerosols was much higher than molecular scattering. We set a boundary condition at the height where the attenuated signal intensity is 50 times of theoretical Rayleigh scattering signal intensity from the atmospheric molecules. We then increased the boundary value and confirmed the convergence of the inversion result.

[6] The aerosol depolarization ratio (ADR), defined as the ratio of the perpendicular polarization component to the

[1]National Institute for Environmental Studies, Onogawa, Tsukuba, Japan.
[2]Research Institute for Applied Mechanics, Kyushu University, Kasuga, Fukuoka, Japan.
[3]Sino-Japan Friendship Center for Environmental Protection, Beijing, China.

0094-8276/03/2002GL016349$05.00

Figure 1. View from SJFCEP in Beijing on a clear day and in the heavy dust event of March 20, 2002. Distances were 100 m to A, 400 m to B, 800 m to C, and 1100 m to D.

parallel component of aerosol scattering, indicates the nonsphericitiy of aerosol [*Browell et al.*, 1990; *Murayama et al.*, 1999]. We estimated the rate of contribution of dust in extinction coefficient *R* with the following equations assuming external mixing of dust and spherical aerosols [*Chen et al.* 2001; *Sugimoto* 2002]. $R = \{(\delta - \delta_2)(1 + \delta_1)/\{(1 + \delta)(\delta_1 - \delta_2)\}$, where δ_1 and δ_2 are ADRs of dust and air-pollution aerosols. δ is the observed ADR. Values of δ_1 and δ_2 were determined empirically. Observed ADR in Beijing was about 0.05 in the clear cases and 0.35 in heavy dust cases. We consequently used $\delta_1 = 0.35$ and $\delta_2 = 0.05$.

[7] The measurement with an optical particle counter (OPC) was performed every hour. The OPC was a hand-held model (Sibata GT-521) with two counter channels. It was controlled with a compact PC to perform one-minute measurements five times with different size settings (10 sizes). The total suspended particle density (TSP) were also measured with a high-volume sampler. Both the OPC and the sampler were set on the top of the SJFCEP building.

[8] The real-time Chemical Weather Forecast System (CFORS) was developed based on a 3D on-line regional-scale chemical transport model fully coupled with the Regional Atmospheric Modeling System (RAMS) [*Pielke et al.*, 1992]. The simulation domain adopted is centered at 25°N, 115°E. The horizontal grid consists of 100 by 90 grid points, with a resolution of 80 km. In the vertical dimension, the domain is divided into 23 layers. The present CFORS system includes the following chemical transport species: SO_2/Sulfate, DMS, volcano tracer, megacity urban plume, black carbon, organic carbon, sea salt, CO, hydrocarbons, and Radon and mineral dust (12 bins, ranging from 0.1 to 20 μm in radius). Mineral dust emissions are calculated on-line using a vertical dust deflatation scheme as a power law function of surface friction velocity u_* [*Gillette and Passi*, 1988]. Dust emission areas are defined as desert and semi-desert areas in the US Geological Survey vegetation database (based on NOAA/AVHRR data obtained in 1992/93). Snow cover data is used to mask emission areas.

3. Results and Discussion

[9] Figure 1 shows photographs taken at SJFCEP in Beijing on a clear day and during the Asian dust event on 20 March. The visibility was less than 1 km in this case as seen in the photograph. Figure 2 depicts a time-height cross

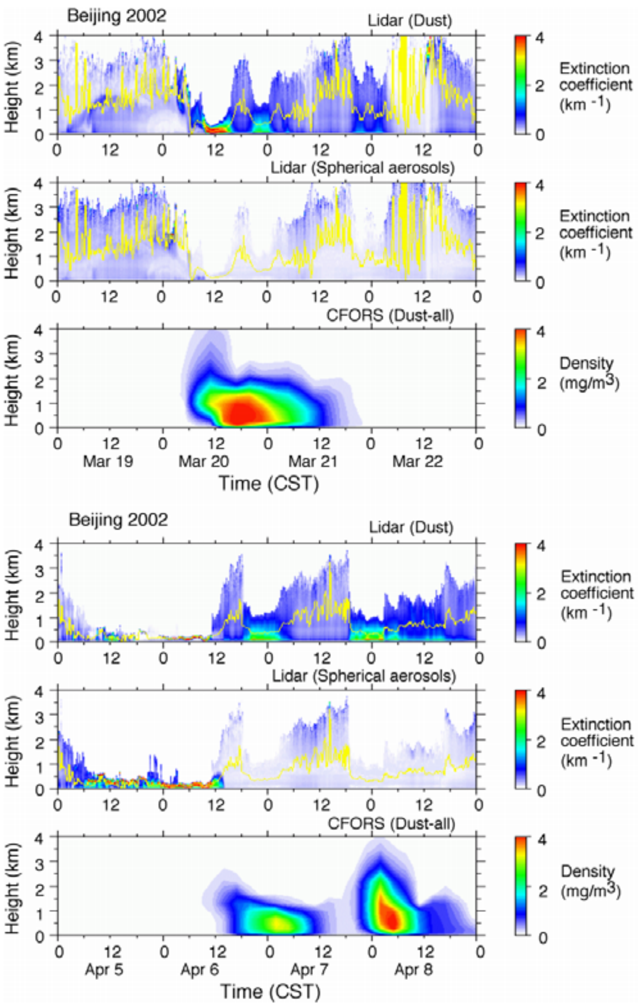

Figure 2. Extinction coefficients of dust and spherical aerosols derived from lidar observations for the dust events on March 20 and April 6. The Klett's inversion method was applied in the lidar data analysis. The yellow lines in the figure indicate the height range where the error is estimated to be less than 20%. The lidar did not penetrate to the top of the dust layer in dense dust events. Dust concentration calculated by CFORS is also indicated in the figure. The ECMWF reanalysis data were used as the boundary data for the CFORS.

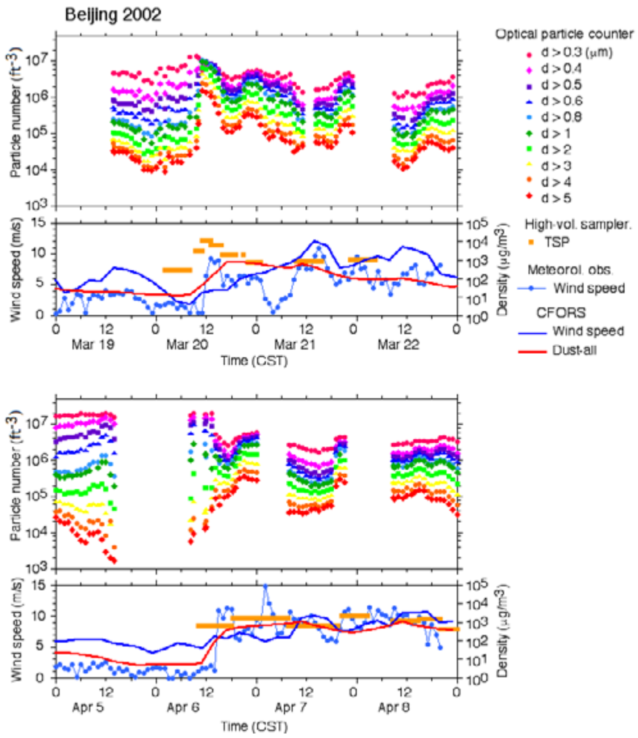

Figure 3. Number of particles measured with an OPC and concentration of total suspended particles measured with a high-volume sampler. Sampling time of the sampler is indicated with the length of the data point in the figure. Wind speed observed at the meteorological observatory of Chao Yang district in Beijing is indicated. Wind speed and dust concentration calculated by CFORS are also shown in the figure.

section of the extinction coefficient of dust and spherical aerosols observed with the lidar in the 20 March and 6 April cases. Dust density calculated for the two cases using CFORS is also shown in Figure 2. Dust and spherical aerosols were separated using the method described in the previous section. Though the lidar did not penetrate the thick dust layer at the dust-density peaks, the extinction coefficient derived with the Klett's method converged well in the lower altitude. Figure 2 indicates that CFORS generally describes both events fairly well. For example, the two density peaks on April 7 and 8 are reproduced well. However, the details of the structure in the 20 March case are not reproduced well. This shows the limitation of the current model with a grid size of 80 km. We cannot obtain the thickness of the dust layer at the peak density from the lidar because of the complete attenuation of the signals. We may, however, estimate the thickness of the dust layer from the low-density part of the profile to be about 3 km, which qualitatively agreed with the model. The lidar-obtained extinction coefficient at the density peak on March 20 was 6 km^{-1}. This corresponds to a visibility of 650 m and is consistent with the photograph in Figure 1. In the 6 April case, the extinction coefficient of spherical aerosol (mostly air pollution aerosols) was high before the dust arrived, and disappeared when the dust front arrived with strong northwesterly wind. This can be seen more clearly in the OPC data in Figure 3.

[10] Figure 3 indicates the number of particles observed with an OPC with 10 diameter discrimination levels, wind speed observed at the meteorological observatory in Beijing, and the TSP observed at SJCEP. Wind speed and dust density calculated by CFORS are also indicated. The OPC data revealed that the increase of large particles was steep in the 20 March case. It was more gradual in the 6 April case, and a drastic decrease of small particles is seen during the increase of large particles. The wind speed plot shows that in both case the wind increased to about 10 m/s when the dust front arrived. After the passage of the dust front, the wind subsided in the 20 March case and increased in the 6 April case. In the latter case, the density of small aerosols (air pollution aerosols) was extremely high before the dust event, and the particles were blown away by the wind with the dust storm. Similar situations are often observed in the beginning of dust events in Beijing. The TSP observed at SJFCEP reached 11 mg/m^3 at the peak on 20 March. This was extremely high and is consistent with the lidar-obtained extinction coefficient of 6 km^{-1} when we apply a mass/extinction conversion factor of 1.78 $(mg/m^3)/km^{-1}$, which

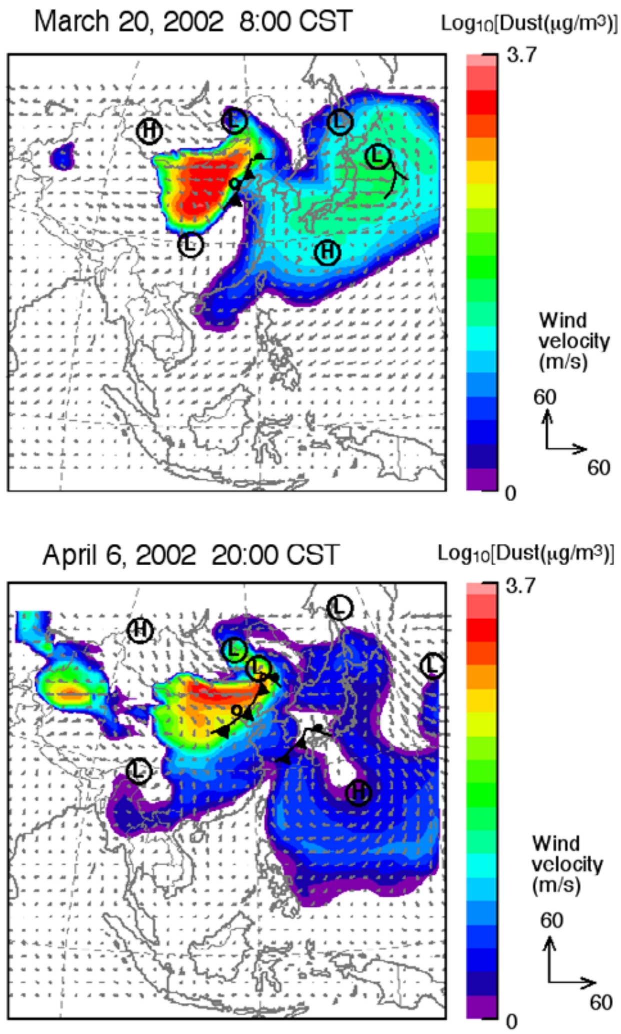

Figure 4. Dust concentration and wind vector calculated by CFORS. Locations of low pressure, high pressures and fronts are superimposed. The open circle denotes the location of Beijing.

we determined for dust in Beijing from the TSP and lidar data of 2001 [*Chen et al.*, 2001]. (It must be noted, however, that the mass/extinction conversion factor depends on particle size distribution. This value can be applied only to typical dust in Beijing. The conversion factor is generally smaller for smaller particles.) The CFORS results explained the features of the observed time variations of dust concentration and wind speed in both cases.

[11] We analyzed the source of dust and transport path using the CFORS and studied the meteorological conditions that caused low wind speed and a high concentration in Beijing in the 20 March case. Figure 4 shows a map of dust concentration calculated by CFORS for the two cases. Locations of low pressure, high pressure, and cold and warm fronts are also indicated in the figure. From the time sequence of the dust distribution, we can identify the origin of the dust. In the 20 March case, dust originated in Inner Mongolia near Ejinaqi, was transported above Arashan Plateau, and reached Beijing from the west. When dust front arrived in Beijing, the horizontal pressure gradient becomes very small because of a low pressure in southern China. This means that Beijing was in between the low pressures in the north and south. This situation caused exceptionally low wind speed in Beijing and resulted in a steep boundary of the dust front and an extremely high concentration of dust. In the 6 April case, the origin was also in Inner Mongolia. The source region then moved eastward to Gobi desert in Mongolia, and dust came to Beijing from the northwest. In this case, wind speed was high at the dust front and the dust boundary was blurred. Figure 4 also indicates that the main stream of dust went north in this event. On a macroscopic scale, however, the two events had similar structures. In fact, a large amount of dust was transported to Korea and northern Japan in both cases after passing Beijing.

[12] In the dust season of 2002, dust was transported to Japan more frequently than in 2001, and several severe dust phenomena were reported in Korea. The continuous lidar data show that, from March to May, a dust layer (depolarization ratio >10%) was observed at heights of 0 to 6 km for 63 (67) days in Beijing, for 27 (25) days in Nagasaki, and for 11 (24) days in Tsukuba in 2001 (2002). The result indicates that the number of days was similar in Beijing and Nagasaki for 2001 and 2002 but doubled in Tsukuba. This suggests that the emission of dust was similar but the transport pattern was different. CFORS also shows the difference in transport patterns (not shown). Major dust events observed in Beijing usually originate in Inner Mongolia and/or Mongolia and are transported rapidly to Beijing by strong westerlies with the storm. The main part of dust stream is usually transported north before reaching Korea. However, in 2002, heavy dust streams reached Korea several times. This was probably related to the fact that the perturbations in the westerly jet was smaller in 2002. In the current calculation with CFORS, the same surface conditions were used for both years. To understand these dust phenomena more quantitatively, we must further investigate surface conditions. The change of dust emission due to the change in surface conditions probably has significant effects in a longer time scale. The present study indicated that a change in transport pattern due to a slight change in climate can also cause a large difference in dust phenomena in the northwestern Pacific region.

References

Browell, E. V., C. F. Butler, S. Ismail, P. A. Robinette, A. F. Carter, N. S. Higdon, O. B. Toon, M. R. Schoeber, and A. F. Tuck, Airborne lidar observations in the wintertime Arctic stratosphere: Polar stratosphere clouds, *Geophys. Res. Lett.*, *17*, 385–388, 1990.

Chen, Y., H. Quan, X. Dong, N. Sugimoto, I. Matsui, and A. Shimizu, Continuous measurement of dust aerosols with a dual-polarization lidar in Beijing, *Proc. Nagasaki workshop on aerosol-cloud radiation interaction and Asian lidar network*, Nagasaki University, Dec. 2001.

Gillette, D., and R. Passi, Modeling Dust Emission Caused by Wind Erosion, *J. Geophys. Res.*, *93*, 14,233–14,242, 1988.

Husar, R. B., D. M. Tratt, B. A. Schichtel, S. R. Falke, F. Li, D. Jaffe, S. Gasso, T. Gill, N. S. Laulainen, F. Lu, M. C. Reheis, Y. Chun, D. Westphal, B. N. Holben, C. Gueymard, I. McKendry, N. Kuring, G. C. Feldman, C. McClain, R. J. Frouin, J. Merrill, D. DuBois, F. Vignola, T. Murayama, S. Nickovic, W. E. Wilson, K. Sassen, N. Sugimoto, and W. C. Malm, Asian Dust Events of April 1998, *J. Geophys. Res.*, *106*, 18,317–18,330, 2001.

Iwasaka, Y., M. Yamato, R. Imasu, and A. Ono, Transport of Asian Dust (KOSA) Particles; Importance of Weak KOSA Events on the Geochemical Cycle of Soil Particles, *Tellus, Ser. B*, *40*, 494–503, 1988.

Klett, J. D., Stable analytical inversion solution for processing lidar returns, *Appl. Opt.*, *20*, 211–220, 1981.

Murayama, T., H. Okamoto, N. Kaneyasu, H. Kamataki, and K. Miura, Application of lidar depolarization measurement in the atmospheric boundary layer: Effects of dust and sea-salt particles, *J. Geophys. Res.*, *104*, 31,781–31,792, 1999.

Murayama, T., N. Sugimoto, I. Uno, K. Kinoshita, K. Aoki, N. Hagiwara, Z. Liu, I. Matsui, T. Sakai, T. Shibata, K. Arao, B-J. Shon, J-G. Won, S-C. Yoon, T. Li, J. Zhou, H. Hu, M. Abo, K. Iokibe, R. Koga, and Y. Iwasaka, Ground-Based Network Observation of Asian Dust Events of April 1998 in East Asia, *J. Geophys. Res.*, *106*, 18,345–18,359, 2001.

Nishikawa, M., S. Kanamori, N. Kanamori, and T. Mizoguchi, Kosa aerosol as eolian carrier of anthropogenic material, *Sci. Total Environ.*, *107*, 13–27, 1991.

Pielke, R. A., W. R. Cotton, R. L. Walko, C. J. Tremback, W. A. Lyons, L. D. Grasso, M. E. Nicholls, M. D. Moran, D. A. Wesley, T. J. Lee, and J. H. Copeland, A comprehensive meteorological modeling system—RAMS, *Meteorol. Atmos. Phys.*, *49*, 69–91, 1992.

Sokolik, I. N., and O. B. Toon, Direct radiative forcing by anthropogenic airborne mineral aerosols, *Nature*, *381*, 681–683, 1996.

Sugimoto, N., Network observations of Asian dust and anthropogenic aerosols with dual-polarization Mie-scattering lidars, *Proc. Int. Laser Radar Conf.*, 269–271, 2002.

Sugimoto, N., I. Matsui, A. Shimizu, I. Uno, K. Asai, T. Endoh, and T. Nakajima, Observation of dust and anthropogenic aerosol plumes in the Northwest Pacific with a two-wavelength polarization lidar on board the research vessel Mirai, *Geophys. Res. Lett.*, doi:10.1029/2002GL015112, 2002.

Uematsu, M., R. A. Duce, J. M. Prospero, L. Chen, J. T. Merrill, and R. L. McDonald, Transport of mineral aerosol from Asia over the North Pacific Ocean, *J. Geophys. Res.*, *88*, 5343–5352, 1983.

Uno, I., H. Amano, S. Emori, K. Kinoshita, I. Matsui, and N. Sugimoto, Trans-Pacific yellow sand transport observed on April 1998: A numerical simulation, *J. Geophys. Res.*, *106*, 18,331–18,344, 2001.

Uno, I., G. R. Carmichael, D. G. Streets, Y. Tang, J. J. Yienger, S. Satake, Z. Wang, J.-H. Woo, S. Guttikunda, M. Uematsu, K. Matsumoto, H. Tanimoto, K. Yoshioka, and T. Iida, Regional chemical weather forecasting using CFORS: Analysis of surface observations at Japan island stations during the ACE-Asia experiment, *J. Geophys. Res.*, in press, 2003.

N. Sugimoto, M. Nishikawa, A. Shimizu, and I. Matsui, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba 305-8506, Japan. (nsugimot@nies.go.jp; mnishi@nies.go.jp; shimizua@nies.go.jp; i-matsui@nies.go.jp)

I. Uno, Research Institute for Applied Mechanics, Kyushu University, Kasuga Park 6-1, Kasuga, Fukuoka 816-8580, Japan.

X. Dong, Y. Chen, and H. Quan, Sino-Japan Friendship Center for Environmental Protection, 1 South Yuhui Road, Chaoyang District, Beijing 100029, China.