

## Physicochemical Characterization and Origin of the 20 March 2002 Heavy Dust Storm in Beijing

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### Abstract

This study characterized the profiles of particles collected during a dust-storm (DS) period in Beijing on 19-21 March 2002, which was one of the heaviest episodes in the previous decade. Several determinations of particle measurements were observed, including total mass concentrations, particle size distributions, dry deposition flux, and chemical ions concentrations. The TSP concentrations reached an extremely high peak value of 12 mg/m<sup>3</sup> in DS period, and especially showed a characteristic increase in the size range of coarse particles (> 2.0 μm). The mass concentrations of coarse particles during DS period accounted for 91% of total particles, compared to 61% on non-DS days. The dry deposition mass flux of the dust storm reached 17.5 g/m<sup>2</sup>-d on 20 March in Beijing. Additionally, the transported pathway of the pollutants was investigated by using backward trajectory analysis. The result of analysis indicated that the high level of dust sand originated from the arid regions of southern Mongolia, passing through central Inner Mongolia, Shanxi Province, and then to Beijing. Concentrations of Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, and SO<sub>4</sub><sup>2-</sup> in TSP were about 10 times higher in DS period than non-DS, probably because of some atmospheric processes enhancing chemical accumulation in the transported aerosols.

**Keywords:** Dust storm; Size distribution; Number concentration; Backward trajectory analysis.

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## INTRODUCTION

In North and Northwest China, East Russia, and Mongolia there are a variety of environmental systems, such as hyper-arid, arid, and semi-arid areas where dust storms occur frequently. Dust storms, a kind of severe natural disaster in dust source regions (Fang *et al.*, 1997; Ye *et al.*, 2000), have a negative impact on air quality, human health, and industrial products and activities (Prospero, 1999; Chung *et al.*, 2003a; Wang *et al.*, 2005). Great economic losses result from dust storms every year. A great amount of dust is produced by wind storms and transported to the east and Pacific regions (Wang *et al.*, 2000; Zhang *et al.*, 2000). Dust particles, a main source of atmospheric aerosols, greatly influence ecosystems, environment, climate, and weather in the extended downstream areas (Iwasaka *et al.*, 1983, 2003; Tegen and Fung, 1994; Sokolik *et al.*, 2001; Zhang *et al.*, 2004). Dust storms are widely recognized as one of the issues in the intercontinental transport of pollutants (Zhang *et al.*, 1997; Chun *et al.*, 2001a; Gong *et al.*, 2003). In order to understand the effects of dust particles on the atmospheric environment and climate, it is important to investigate the concentrations and size distributions of dust particles when a dust storm occurs (Kanai *et al.*, 2002; Shen *et al.*, 2005).

During 2000-2002, sand and dust weather events occurred frequently in North China, which resulted in negative impacts on traffic, air quality, and people's daily life in local and downstream areas (Ye *et al.*, 2000; Zou and Zhang, 2003). During 19-21 March 2002, a heavy dust storm in North China struck Beijing on the 20th reducing visibility to less than 200 m. According to dust-storm classifications (Yoshino, 2000; Zhou, 2001), it can strictly be called a "heavy dust storm." This paper reports on the mass concentration, size-segregated concentration, number concentration, dry deposition flux, and ion concentration of this dust storm, based on ground-based observation. The storm's origin was determined by the backward trajectory analysis method. The objective of this paper is to provide reliable dust storm observation data for estimating the flux of Asian dust transportation from source areas to downstream areas, and to validate dust transport and prediction models.

## METHODOLOGY

The sampling site was located on the roof of a building in Beijing, 8 m above the ground. A high-volume air sampler (HV-1000F) manufactured by SIBATA Scientific Co., Ltd. was used to collect total suspended particles (TSP). PF040 polyflon filters (25 cm × 20 cm) manufactured by Advantec Co., Ltd were used. The volumetric air flow rate was 1 m<sup>3</sup>/min. A low-volume air sampler (Andersen, AN-200), manufactured by Shibata Scientific Co., Ltd., was also employed. The flow rate was maintained at 28.3 L/min to achieve ideal size separation. The Andersen sampler has eight stages and a backup filter. The particle size discrimination is as follows: > 11,

11-7.0, 7.0-4.7, 4.7-3.3, 3.3-2.1, 2.1-1.1, 1.1-0.65, 0.65-0.43, and < 0.43  $\mu\text{m}$  (backup filter), respectively. The filters used for the AN-200 were 80-mm diameter sized PF050 polyflon filters manufactured by Advantec Co., Ltd., for stage Nos. 0-6; and the 2500QAT-UP quartz filter manufactured by Tokyo Dylec Co., Ltd., for stage No. 7 and the backup filter. Dry deposition flux was measured by an open box with the PF040 polyflon filter (25 cm  $\times$  20 cm). The deposition area of the filter paper was 17.5 cm  $\times$  22.5 cm.

The filters before and after sampling were stored under a fixed temperature (25°C) and relative humidity (37%) condition for over 24 hours and then weighed with a LAC214 balance manufactured by Changsu Balance Factory, China, with a resolution of  $10^{-4}$  g. The BCJ-1 optical particle counter (OPC) made in Suzhou, China was used to measure the size distributions of the aerosols. This counter measured six channels of aerodynamic diameters as follows: 0.3-0.5, 0.5-0.7, 0.7-1.0, 1.0-2.0, 2.0-5.0, and > 5.0  $\mu\text{m}$ . The volumetric air flow rate was 2.83 L/min. The OPC instrument was calibrated before observation, and detailed descriptions were presented in Zhang *et al.* (2001).

Four major ionic species ( $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$  and  $\text{NH}_4^+$ ) of TSP samplers were measured by ion chromatography (Dionex, DX600). A CS12 column (150  $\times$  4 mm) was used for cation analysis and an AS14 column (150  $\times$  4 mm) was used for anion analysis. The concentrations of ionic species were all corrected by using field blanks. The detection limits of  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$  and  $\text{NH}_4^+$  were 0.5, 15, 20 and 15  $\mu\text{g/L}$ , respectively. The detection precision of  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$  and  $\text{NH}_4^+$  was 3.2%, 4.5%, 6.1%, and 2.8%, respectively. Before ion analysis, standard solution and blank tests were conducted and standard curves were plotted for real sample analysis.

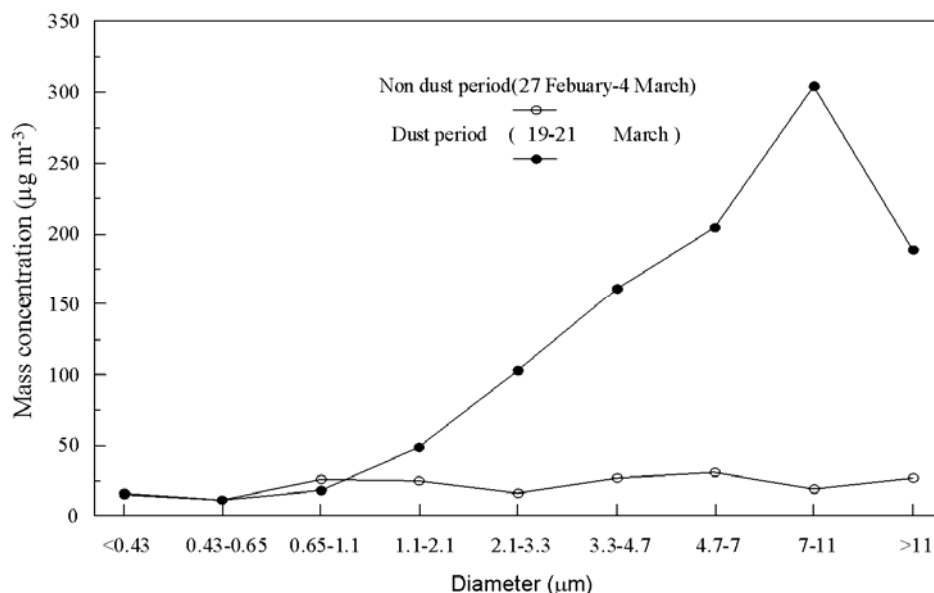
## RESULTS AND DISCUSSION

### *TSP variation during the dust storm*

The severe dust storm (DS) reached Beijing on 20 March 2002. At 0915 LST, the sky turned yellow and was permeated with a soil taste. By 1000 LST, visibility was less than 1000 m and about an hour later (1100 LST), visibility was down to 200 m and the sky became a red, soil-like color. After 1500 LST, the dust storm began to decay and visibility improved to 800 m. During the high peak period (1050 to 1530 LST), the results obtained from the high-volume sampler indicated that the mass concentration of TSP reached 12  $\text{mg/m}^3$  (Zhang *et al.*, 2005), which was approximately 40 times the daily average of TSP standards issued by the China Environment Protection Administration (China EPA). During a previous severe dust storm on 6 April 2000 in Beijing, the TSP mass concentration in the city reached only  $\sim 6 \text{ mg/m}^3$  (Zhuang *et al.*, 2001; Wang *et al.*, 2002). In comparing the two episodes, it is likely that the March 20<sup>th</sup> event was the strongest experienced in Beijing during the last decade. Also, in Chongwon, Korea on March 21<sup>st</sup>

this dust storm was observed with maximum values of  $3,006 \mu\text{g}/\text{m}^3$  for  $\text{PM}_{10}$  and  $331 \mu\text{g}/\text{m}^3$  for  $\text{PM}_{2.5}$  (Chung *et al.*, 2003b).

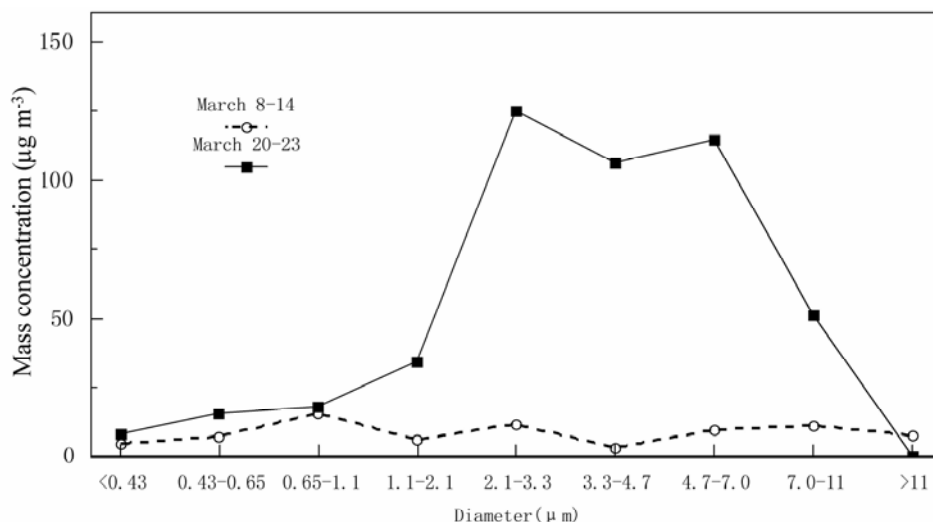
### *Size distribution of mass concentrations*



**Fig. 1.** Size distribution of mass concentration of aerosols in the non-dust period (1000 LST 27 February - 1000 LST 4 March 2002) and dust storm period (1000 LST 19 March - 1000 LST 21 March 2002) in Beijing.

Fig. 1 presents the size distribution of particles in both non-DS (27 February - 4 March) and DS periods (19-21 March) in spring 2002 in Beijing. The size distribution of mass concentration in non-DS differed slightly across eight stages ranging from  $11.8$  to  $31.4 \mu\text{g}/\text{m}^3$ . During the DS period, they differed greatly, ranging from  $11.0$  to  $304.3 \mu\text{g}/\text{m}^3$ . The mass concentrations increased most notably in the coarse stages and reached a peak of  $304.3 \mu\text{g}/\text{m}^3$  in the range of  $7$ – $11 \mu\text{m}$  during the DS period. The mass concentrations of coarse particles and fine particles in DS period were  $7.8$  and  $1.2$  times higher than those in non-DS days, respectively. Coarse particles ( $> 2.1 \mu\text{m}$ ) accounted for  $91\%$  of the total in DS period and  $61\%$  on non-DS days. It is apparent that the coarse particles ( $> 2.1 \mu\text{m}$ , even in the range of  $7$ – $11 \mu\text{m}$ ) dominate in mass concentration of particles during the dust period. The particle mass concentrations similarly showed a peak value in the range of  $2.1$ – $7 \mu\text{m}$  for the same event in Qingdao ( $36^{\circ}6'N$ ,  $120^{\circ}19'E$ ), located on China's eastern seashore, downstream of Beijing (Fig. 2). Kanai *et al.* (2002) reported that the mass concentration of particles in dust-storm season in Japan usually had peak values in the range of  $4$ – $5 \mu\text{m}$ . Because of gravity settling, not only will the concentration decrease, but also the

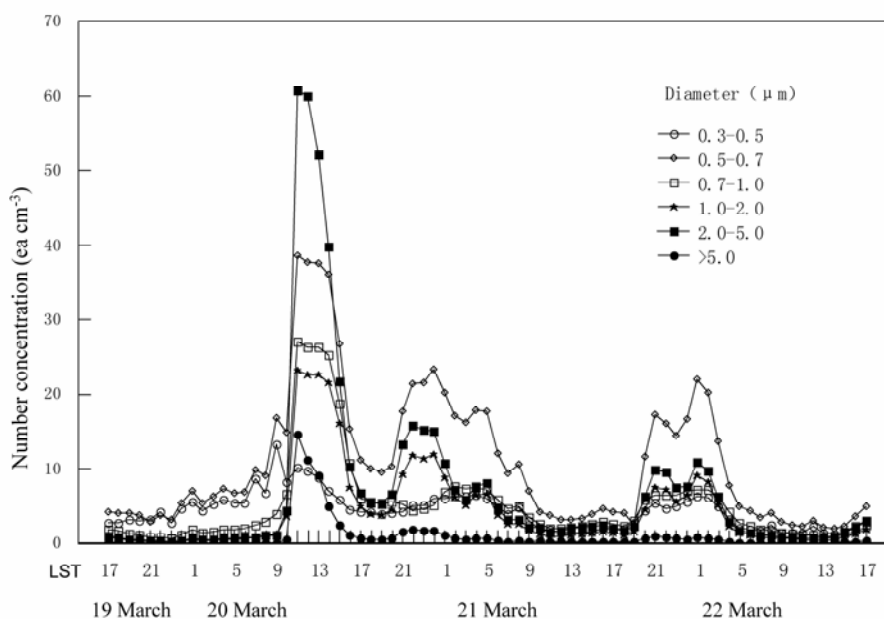
diameter range of peak values will become smaller in areas downwind of Beijing during DS periods.



**Fig. 2.** Size distribution of mass concentration of aerosols in the non-dust period (1130 LST 8 March - 1130 LST 14 March 2002) and dust-storm period (1045 LST 20 March - 1015 LST 23 March 2002) in Qingdao.

### *Size distribution of number concentrations*

Fig. 3 shows the size distribution of particle number concentration with a size range of 0.3-0.5, 0.5-0.7, 0.7-1.0, 1.0-2.0, 2.0-5.0, and  $> 5.0$   $\mu\text{m}$  during 19-22 March 2002, when the number concentrations of dust in six stages all increased obviously and reached a maximum value at 1100 LST, 20 March 2002. Here the number concentrations between 1700 LST 19 March 2002 (before the dust period) and 1100 LST 20 March 2002 are compared. The number concentrations of dust particles with diameters of 0.3-0.5, 0.5-0.7, 0.7-1.0, 1.0-2.0, 2.0-5.0, and  $> 5.0$   $\mu\text{m}$  in the dust period were 3.8, 9.1, 15.9, 57.3, 59.7, and 89.1 times as much as those before the dust period, respectively. The number concentrations of fine particles ( $d < 2$   $\mu\text{m}$ ), coarse particles ( $d > 2$   $\mu\text{m}$ ), and total number of particles were 26.4, 63.8, and 30.5 times as much as those before the dust period, respectively. The stages of particle number concentration in the dust period, listed from high to low, were as follows: 2.0-5.0, 1.0-2.0, 0.5-0.7, 0.7-1.0,  $> 5.0$ , and  $> 0.3-0.5$   $\mu\text{m}$ . This shows that the number concentrations of both fine and coarse particles increased considerably. Although the overall number concentrations of fine and coarse particles were higher than during the non-dust period, the coarse particle concentration was higher than fine particle concentration.

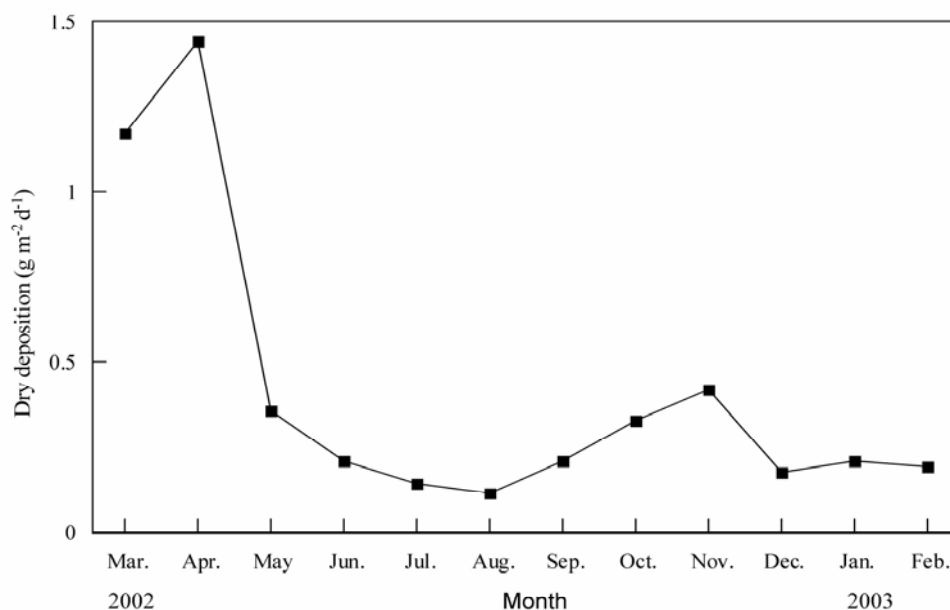


**Fig. 3.** Size distributions of particle number concentration during 19–22 March 2002 in Beijing.

Fig. 3 shows that the number concentrations reached a peak at 1100–1600 LST 20 March 2002 during the heavy dust period. The observation results obtained from the high-volume sampler were in good agreement with the number concentration from the optical particle counter. Observations from the optical particle counter indicated that the number concentrations of coarse particles ( $d > 2 \mu\text{m}$ ) were about 20 times as much as those after the dust storm, while the number concentrations of fine particles ( $d < 2 \mu\text{m}$ ) were only seven times as much as those after the dust storm (Zhang *et al.*, 2000). Thus, the 20 March 2002 dust storm event was much heavier than the 6 April 2000 dust event in Beijing.

### ***Dry deposition flux over Beijing***

Dry deposition fluxes of particles were also collected during the observation period from March 2002 to February 2002 in Beijing as shown in Fig. 4. The dry deposition flux reached a maximum in spring (1.14 and 1.44  $\text{g}/\text{m}^2\text{-d}$  in March and April, respectively) and a minimum of 0.12  $\text{g}/\text{m}^2\text{-d}$  in August. The dry deposition mass flux in dust-storm period reached 17.5  $\text{g}/\text{m}^2\text{-d}$  (0900-2100 LST 20 March) which was much higher than average. The monthly average dry deposition flux was 0.42  $\text{g}/\text{m}^2\text{-d}$  in Beijing, which was 3 times that of 0.137  $\text{g}/\text{m}^2\text{-d}$  in Seoul, Korea (Yi *et al.*, 2001). It was much higher in Beijing than in Korea due to weight deposition during transport of dust particles.



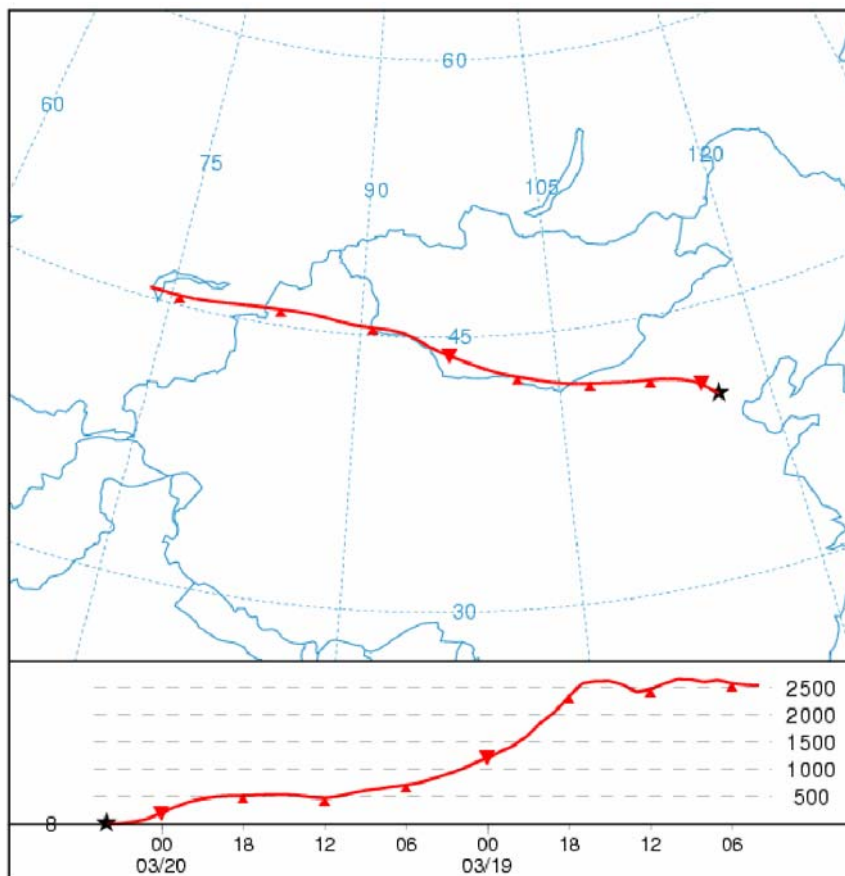
**Fig. 4.** Seasonal variation of dry deposition of atmospheric aerosols in Beijing.

#### ***Origin of dust storm on 20 March 2002***

A 48-hour calculation of three-dimensional backward trajectories was made using the NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model with FNL meteorological database from 0400 UTC, 20 March 2002 (1200 LST in Beijing). The FNL archive data is generated by the National Center for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS) wind field reanalysis. Further information on the FNL meteorological database can be found at <http://www.arl.noaa.gov/ss/transport/archives.html> as shown in Fig. 5. The backward trajectory analysis shows that the air mass which caused the heavy dust storm over Beijing came from Kazakhstan and Xingjiang Province, China, passing through southern Mongolia, central Inner Mongolia, Shanxi Province, and then to Beijing. This result is consistent with recent research results by Wang *et al.* (2004). This pathway was the most important one contributing to Beijing's high aerosol concentration in dust events in the spring.

Fig. 5 also shows that when the air mass passed over southern Mongolia and central Inner Mongolia, where considerable desert and semi-desert areas exist, its altitude turned out to be lower than 1.5 km, making it easier to inject particles from the ground level into the air. This implied that the dust storm over Beijing originated from southern Mongolia and central Inner Mongolia, which was further confirmed by the dust model simulation (Sugimoto *et al.*, 2003). When the air mass passed through Shanxi Province, an industrial area in China, its altitude turned out to be below 500 m. Dust particles could then be mixed with anthropogenic aerosols at the

ground level during their transport over Shanxi Province. Results from backward trajectory analysis strongly indicated that the origin of dust storms over Beijing came from long-range transport.

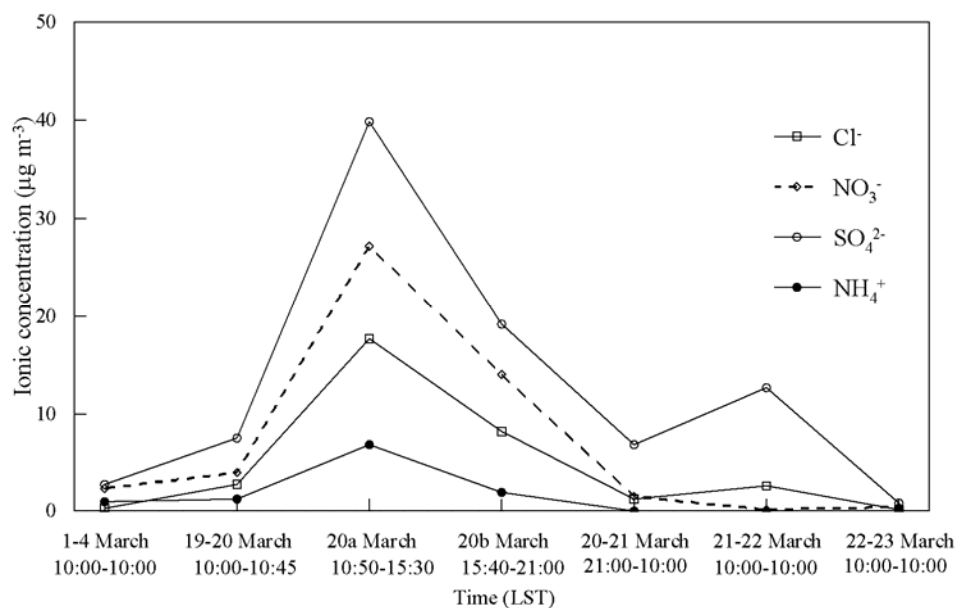


**Fig. 5.** A 48-hour backward trajectory calculation for 0400 UTC, 20 March 2002 for the observation site at Beijing. This shows the origin of the dust storm and its trajectory prior to reaching Beijing. The top and bottom panels display horizontal and vertical motion, respectively. Note that the time is in UTC, not LST.

### ***Water-soluble ions variations***

Fig. 6 presents the evolutions of the concentrations of  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{NH}_4^+$  in March 2002. Concentrations of  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{NH}_4^+$  had similar trends and the highest concentrations were observed on 20 March in the dust-storm period, which corresponds to the high concentration of TSP. Concentrations of  $\text{Cl}^-$ ,  $\text{NO}_3^-$ , and  $\text{SO}_4^{2-}$  in heavy dust period were about 10 times as much as those in the non-dust period, while  $\text{NH}_4^+$  concentration was about 6 times as those before the dust period. Higher concentrations of nitrate and sulfate in dust period may suggest aerosols were influenced by the anthropogenic sources during the transport process (Cao *et al.*, 2003). Back trajectory analyses in Fig. 5 indicates that the air containing dust particles

had passed over the northwest of Beijing-Shanxi Province where many large coal mines are located. Therefore, the mixing of materials emitted from the anthropogenic source, such as coal mines, with the desert dust might be a possible explanation for high concentration of  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{NH}_4^+$ . These results also concurred with previous study of a dust storm of 6 April 2000 in Beijing (Zhuang *et al.*, 2001). Moreover, significant increases of water-soluble ions for particles were observed in the spring in Taiwan District during the dust period of 2002 (Yuan *et al.*, 2004).



**Fig. 6.** Concentrations of  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{NH}_4^+$  in TSP in Beijing in March 2002.

## SUMMARY

The dust storm on 20 March 2002 in the northern part of China was one the heaviest in the last decade. In this paper, the physicochemical characteristics of Beijing dust-storm aerosols during March 2002 are well-depicted. Evidences for this strong dust storm are as follows: The TSP concentrations in Beijing reached peak values of  $12 \text{ mg/m}^3$  between 1050 and 1530 LST on 20 March. This is the highest value ever reported in Beijing, and one infrequently reported for dust source regions. During this dust storm, the size distribution of mass concentration and number showed a characteristic increase especially in the coarse particle size range. The mass concentration of coarse particles ( $> 2.1 \mu\text{m}$ ) accounted for 91% of the total in the dust period and 61% in the non-dust period. The number concentrations of fine particles ( $d < 2 \mu\text{m}$ ), coarse particles ( $d > 2 \mu\text{m}$ ), and total particles were 26.4, 63.8, and 30.5 times as much as those before the dust period, respectively. The dry deposition flux of particles reached a peak in spring ( $1.14$  and  $1.44 \text{ g/m}^2\text{-d}$  in March and April, respectively), and a minimum of  $0.12 \text{ g/m}^2\text{-d}$  in August with

a monthly average of 0.42 g/m<sup>2</sup>-d. The dry deposition mass flux in the dust-storm period was 17.5 g/m<sup>2</sup>-d (0900-2100 LST, 20 March). During the storm, the air mass was transported directly from Mongolia, central Inner Mongolia and Shanxi Province, then to Beijing, as demonstrated by backward trajectory analysis. Concentrations of Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, and SO<sub>4</sub><sup>2-</sup> in TSP in the heavy dust period were about 10 times as that in non-dust period, which implies that anthropogenic materials, together with dust particles, were transported to Beijing.

Located downwind from areas where Asian dust storms originate, Beijing is vulnerable to them. Consequently, it is necessary to strengthen future ground-based observations in Shanxi Province and Beijing in order to gain better understandings of origin, transportation and deposition of Asian dust storms.

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## REFERENCES

- Chun, Y.S., Boo, K.O., Kim, J., Park, S.U., and Lee, M. (2001a). Synopsis, Transport, and Physical Characteristics of Asian Dust in Korea. *J. Geophys. Res.* 106 (D16): 18461-18469.
- Chun, Y.S., Kim, J., Choi, J.C., Boo K.O., Oh, S.N., and Lee, M. (2001b). Characteristic Number Size Distribution of Aerosol During Asian Dust Period in Korea. *Atmos. Environ.* 35: 2715-2721.
- Chung, Y. S., Kim, H. S., Park, K. H., Jhun, J. G. and Chen, S. J. (2003a). Atmospheric Loadings, Concentrations and Visibility Associated with Sandstorms: Satellite and Meteorological Analysis. *Water, Air and Soil Poll.* 3(2): 21–40.
- Chung, Y.S., Kim, H.K., Dulam, J., and Harris, J. (2003b). On Heavy Dustfall Observed with Explosive Sandstorms in Chongwon-Chongju, Korea in 2002. *Atmos. Environ.* 37: 3425–3433.
- Cao, J.J., Lee, S.C., Zheng, X.D., Ho, K.F., Zhang, X.Y., Guo, H., Chow, J.C., and Wang, H.B. (2003). Characterization of Dust Storms to Hong Kong in April 1998. *Water, Air and Soil Poll.* 3(2): 213–229.
- Fan, K. and Wang, H.J. (2004). Antarctic Oscillation and the Dust Weather Frequency in North China. *Geophys. Res. Lett.* 31: L10201, doi:10.1029 (2004GL019465).
- Fang, Z.Y, Zhu, F.K., Jiang, J.X., and Qian, Z.A. (1997). Studies on Dust Storm in China, Beijing. *China Meteorological Press*: 158.

- Gong, S.L., Zhang, X.Y., Zhao, T.L., McKendry, I.G., Jaffe, D.A., and Lu, N.M. (2003). Characterization of Soil Dust Aerosol in China and its Transport and Distribution During 2001 ACE-Asia:2. Model Simulation and Validation. *J. Geophys. Res.* 108(D9): 4262, doi:10.1029 (2002JD2633).
- Iwasaka, Y., Minoura, H., and Nagaya, K. (1983). The Transport and Spatial Scale of Asian Dust-Storm Clouds: A Case Study of the Dust-Storm Event of April 1979. *Tellus* 35B: 189-196.
- Iwasaka, Y., Shibata, T., Nagatani, T., Shi, G.Y., Kim, Y. S., Matsuki, A., Trochkin, D., Zhang, D., Yamada, M., Nagatani, M., Nakata, H., Shen, Z., Li, G., Chen, B., and Kawahira, K. (2003). Large Depolarization Ratio of Free Tropospheric Aerosols Over The Taklamakan Desert Revealed by Lidar Measurements: Possible Diffusion and Transport of Dust Particles. *J. Geophys. Res.* 108(D23): 8652, doi:10.1029 (2002JD003267).
- Kanai, Y., Ohta, A., Kamioka, H., Terashima, S., Matsuhisa, Y., Shimizu, H., Takahashi, Y., Kai, K., Xu, B., Hayashi, M., and Zhang, R.J. (2002). Preliminary Study on The Grain-Size Distribution and Concentration of Aeolian Dust Collected in Japan. *J. of Arid Land Studies* 11(4): 307-314.
- Prospero, J.M. (1999). Long-Range Transport of Mineral Dust in the Global Atmosphere: Impact of African Dust on the Environment of the Southeastern United States. *Proc. Natl. Acad. Sci. U.S.A.* 96: 3396-3403.
- Shen, Z.X., Li. X.X., Cao, J.J., Caquineau, S., Wang Y.Q., and Zhang X.Y. (2005). Characteristics of Clay Minerals in Asian Dust and Their Environmental Significance. *China Particuology* 3(5): 260-264.
- Sokolik, I.N., Winker, D.M., Bergametti, G., Gillette, D. A., Carmichael, G., Kaufman, Y.J., Gomes, L., Schuetz, L., and Penner, J.E. (2001). Introduction to Special Section: Outstanding Problems in Quantifying the Radiative Impacts of Mineral Dust. *J. Geophys. Res.* 106 (D16): 18015-18027 (2000JD900498).
- Sugimoto, N., Uno, I., Nishikawa, M., Shimizu, A., Matsui, I., Dong, X.H., Chen, Y., and Quan, H. (2003). 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).
- Tegen, I., and Fung, I. (1994). Modeling of Mineral Dust in the Atmosphere: Sources, Transport, and Optical Thickness. *J. Geophys. Res.* 99: 22897-22914.
- Wang, C.S., Friedlander, S.K., and Madler L. (2005). Nanoparticle Aerosol Science and Technology: An Overview. *China Particuology* 3(5): 243-254.
- Wang, W., Yue, X., Liu, H.J., Pan, Z., Tang, D.G., Wang, Y., Du, R.G., Su, H.M., Qian, F., and Sakamoto, K. (2002). Study on Pollution Characteristics of Aerosols During Sand-Dust Storm Weather in Beijing. *Huanjing Kexue Xuebao* 22(4): 494-498.

- Wang, Y.Q., Zhang, X.Y., Arimoto, R., Cao, J.J., and Shen, Z.X. (2004). The Transport Pathways and Sources of PM<sub>10</sub> Pollution in Beijing During Spring 2001, 2002 and 2003. *Geophys. Res. Lett.* 31: L14110, doi:10.1029 (2004GL019732).
- Wang, Z.F., Ueda, H., and Huang, M.Y. (2000). A Deflation Module for Use in Modeling Long-Range Transport of Yellow Sand over East Asia. *J. Geophys. Res.* 105(D22): 26947-26959.
- Ye, D.Z., Chou, J.F., Liu, J.Y., Zhang, Z.X., Wang, Y.M., Zhou, Z.J., Ju, H.B., and Huang, H.Q. (2000). Causes of Sand-Stormy Weather in Northern China and Control Measures. *Dili Xuebao* 55(5): 513-521.
- Yi, S.M., Lee, E.Y., and Holsen, T.M. (2001). Dry Deposition Fluxes and Size Distributions of Heavy Metal in Seoul, Korea During Yellow-Sand Events. *Aerosol Sci. Tech.* 35: 569-576.
- Yoshino, M. (2000). Problems in Climatology of Dust Storm and its Relation to Human Activities in Northern China. *J. Arid Land Studies* 10: 171-181.
- Yuan C.S., Sau C.C., and Chen M.C. (2004). Influence of Asian Dusts On the Physiochemical Properties of Atmospheric Aerosols in Taiwan District Using the Penchu Islands as an Example. *China Particuology* 2(4): 144-152.
- Zhang, M.G. (2004). Modeling of Organic Carbon Aerosol Distributions over East Asia in the Springtime. *China Particuology* 2(5): 192-195.
- Zhang, M.G. (2005). A Numerical Simulation of Nitrate, Sulfate, and Ammonium Aerosol Distributions over East Asia with a Comprehensive Chemical Transport Model, *China Particuology* 3(5): 255-259.
- Zhang, R.J., Wang, M.X., Pu, Y.F., Liu, Q., Fu, J.Z., and Zhang, W. (2000). Chemical and Physical Properties of “2000.4.6” Super Dust Storm in Beijing (In Chinese). *Climate and Environmental Research*, 5(3): 259-266.
- Zhang, R.J., Wang, M.X., and Fu, J.Z. (2001). Preliminary Research on the Size Distribution of Aerosols in Beijing. *Adv. Atmos. Sci.* 18(2): 225-230.
- Zhang, R.J., Wang, M.X., Sheng, L.F., Kanai, Y., and Ohta, A. (2004). Seasonal Characterization of Dust Days, Mass Concentration and Dry Deposition of Atmospheric Aerosols over Qingdao, China. *China Particuology* 2(5): 196-199.
- Zhang, R.J., Arimoto, R., An, J.L., Yabuki, S., Sun, J.H. (2005). Ground Observation of a Strong Dust Storm in Beijing in March 2002, *J. Geophys. Res.* 110: D18S06, doi:10.1029 (2004JD004589).
- Zhang, X.Y., Arimoto R., and An, Z.S. (1997). Dust Emission from Chinese Deserts Linked to Variation in Atmospheric Circulation. *J. Geophys. Res.* 102: 28041-28047.
- Zhou, Z.J. (2001). Blowing-Sand and Sandstorm in China in Recent 45 years (in Chinese), *Quaternary Sciences*, 21(1): 9-17.

Zhuang, G.S., Guo, J.H., Yuan, H., and Zhao, C.Y. (2001). The Compositions, Sources, and Size Distribution of the Dust Storm from China in Spring of 2000 and its Impact on the Global Environment, *Kexue Tongbao* 46(3): 191-197.

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