Ground observations of a strong dust storm in Beijing in March 2002

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[1] On 20 March 2002, one of the most intense dust storms of the last decade struck Beijing: the total suspended particle (TSP) mass concentrations during the event reached 12 mg/m^3 and the visibility was reduced to less than 200 m. Variations in meteorological conditions in the boundary layer were monitored during the event, and changes in the physical properties and chemical composition of the aerosol also were studied. The dust storm was accompanied by a sharp and distinct increase in wind speed, a decrease in relative humidity, and increased mixing in the boundary layer due to turbulence. Back trajectory analysis and meteorological analysis showed that the main sources of dust particles that affected Beijing were most likely in southern Mongolia and the western part of Inner Mongolia, China. The amounts of Mg, Al, K, Ca, Ti, V, Cr, Mn, and Fe relative to one another were similar for the dust storm and nondust storm samples, and these elements occurred in near-crustal proportions. In contrast, both the concentrations and enrichments relative to the crustal reference material for other elements, such as Se, Ni, Pb, Br, and Cu, were much higher during the dust storm than before or afterward. These elements, which are often associated with pollution emissions, apparently originated from distant sources upstream as well as from local sources in Beijing. Even though their enrichments were lower during the dust event, the concentrations of S, Zn, and Cl during the dust storm were higher than in the nondust periods; these results are further evidence that dusty air often contains higher levels of pollutants than nondusty air.

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1. Introduction

[2] Asian dust storms have been studied for many years [*Duce et al.*, 1980; *Iwasaka et al.*, 1983; *Husar et al.*, 2001], and dust particles are a major component of the atmospheric aerosol in Asia [*Zhang et al.*, 1996; *R. J. Zhang et al.*, 2003]. Each spring, dust particles from arid and semiarid areas in Asia are transported over eastern Asia to the North Pacific and even to North America [*Perry et al.*, 1996; *Chun et al.*, 2001; *R. J. Zhang et al.*, 2003; *Gong et al.*, 2003]. The long-range transport and deposition of fine dust particles affects biogeochemical cycles in the oceans [*Gao et al.*, 1997], and high concentration of dust also have implications for human health [*Prospero*, 1999]. Although scientists have begun to recognize that dust particles are important in the context of the radiative forcing of climate [*Tegen and Fung*, 1994; *Sokolik et al.*, 2001], there still exists great uncertainty about the magnitude of the radiative forcing caused by mineral dust.

[3] The effects of mineral dust on the Earth's radiation budget are complex and important relative to other types of aerosols because of the widespread distribution of dust and heavy loadings of mineral aerosol that periodically occur [*Sokolik and Toon*, 1996]. The particle size distributions, radiative properties and chemical composition of particles are key characteristics that determine the effects of dust on climate [*Sokolik et al.*, 1998; *Tegen et al.*, 1996]. The atmospheric dust concentrations diminish during transport because of dispersion, rainout, and gravitational settling, and furthermore, the chemical composition of the dust can be altered by interactions with trace gases and other aerosols [*Falkovich et al.*, 2001]. Consequently, it is important to consider the chemical composition and physical properties of the dust together with meteorological information to better understand the origins, transport and effects of the ambient aerosol.

[4] Dust storms can be serious natural disasters in China [*Yang et al.*, 1997], and observations of dust in suspension, blowing dust, dust storms, and severe dust storms are recorded in routine Chinese meteorological reports [*Qian et al.*, 1997; *Yoshino*, 2000]. Dust particles lofted by strong surface winds are linked to soil erosion, and vegetation can be damaged or destroyed under certain circumstances [*Zhou et al.*, 1981]. From 2000 to 2002, sand-dust storms occurred frequently in northern China, and these disrupted impacts on air traffic, commerce, air quality, and daily life over

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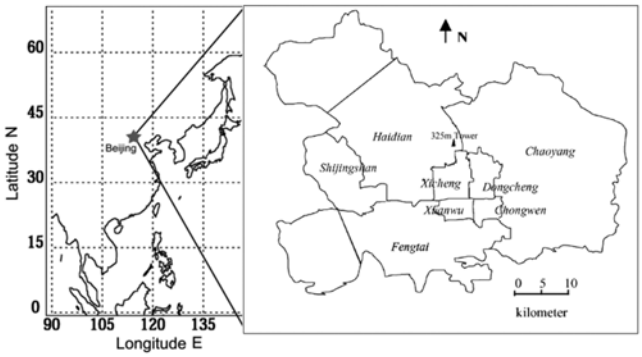

Figure 1. Map showing eight regions of Beijing and the location of the 325-m meteorological tower where the observations were made.

broad areas of the country [*Ye et al.*, 2000; *Zhou and Zhang*, 2003; *Wang et al.*, 2000; *Zhou et al.*, 2002].

[5] The dust storm on 20 March 2002 was one of the most severe to occur in the last decade: During this event, visibility was reduced to less than 200 m in Beijing. The dust storm passed through several provinces, including Ganshu, Inner Mongolia, Shaanxi, Shanxi, Hebei, Beijing, and Tianjing, and it covered 1.4×10^6 km^2, affecting some 130 million people. We present here data on the meteorological conditions and the physical and chemical properties of the atmospheric aerosol during the passage of this major dust storm. Possible origins for dust were investigated by using air mass trajectory analysis.

2. Observational Methods

[6] The aerosol samples were collected from the top of a two-story building 8 m above ground; this building is ~50 m west of the 325-m-tall meteorological tower (39°58′N, 116°22′E) at the Institute of Atmospheric Physics, Chinese Academy of Sciences. The tower site lies between the North Third Ring Road and the North Fourth Ring Road in Beijing. The 325-m-high meteorological tower (Figure 1) was used to collect data of wind speed, relative humidity and temperature at altitudes of 8, 15, 32, 47, 63, 80, 102, 120, 140, 180, 200, 240, 280, and 320 m.

[7] A high-volume air sampler HV-1000F manufactured by SIBATA Scientific Co., Ltd.,Japan, was used to collect total suspended particle (TSP) samples. The collection substrates were PF040 polyflon filters (25 cm × 20 cm) manufactured by Advantec Co., Ltd., Japan. The flow rate for the sampler was 1000 L/min. The sample filters were weighed before and after sampling using a LAC214 microbalance; this balance has an accuracy of 10^{-4} g and is manufactured by Changsu Balance Factory, Changsu, China.

[8] Additional aerosol samples were collected using eight-stage cascade impactors (PIXE International Corporation) for chemical composition studies, with 8 size cuts as follows: <0.25, 0.25–0.5, 0.5–1, 1–2, 2–4, 4–8, 8–16, and >16 μm. Millipore filters (0.4 μm porosity, Millipore Corp., Bedford, Massachusetts) were used as the backup filters, and Mylar films (3.5 μm thick and coated with paraffin on stage 1 and Vaseline on stages 2–7) were used as the impaction surfaces. The flow rate at the beginning and the end of each sampling intervals was recorded, and the arithmetic mean of the two flow rates was used to calculate the average flow rate for each sample and from that the volume of air sampled. A typical flow rate was 1.1 L/min. Table 1 summarizes the times during which samples were collected from 19 to 21 March 2002.

[9] The aerosol samples were analyzed by a Particle Induced X-Ray Emission (PIXE) technique at the Institute of Low Energy Nuclear Physics, Beijing Normal University. The PIXE analyses were carried out using 2.5 MeV proton bombardments with a beam of 30 to 40 nA. This PIXE method has been widely used to study inorganic chemical components of aerosols in China in recent years [*Zhu and Wang*, 1998; *Zhang et al.*, 1996; *R. J. Zhang et al.*, 2003; *X. Y. Zhang et al.*, 2003]. The concentrations of 20 elements were determined for each sample; these elements were Al, As, Br, Ca, Cl, Cr, Cu, Fe, K, Mg, Mn, Ni, P, Pb, S, Se, Si, Ti, V, and Zn.

3. Results and Discussion

3.1. Meteorological Conditions in the Boundary Layer

[10] When dust storms occur, changes in boundary layer structure are often dramatic [*Zhou et al.*, 1981]. The 20 March 2002 dust storm arrived in Beijing at approximately 1000 LT (UTC plus 8 hours), and this was accompanied by remarkable variations in meteorological parameters and greatly increased turbulence in the boundary layer. Figure 2 shows the variations in wind, temperature and relative humidity measured at the 8 m level of the meteorological tower from March 19 to 20. From 0000 to 0900 LT on 20 March, winds were light and variable; at 1000 LT the wind speed increased abruptly, rising from 0.2 m/s before 1000 LT to 9.3 m/s at 1200 LT. The winds also became northwesterly during this time. Strong winds (>5 m/s) persisted until 1800 LT.

[11] Figure 3 shows variations in the wind speed profile before and during dust storm period. The wind speed increased with height when the dust storm arrived, causing strong wind sheer in the surface layer. The relative humility also decreased as the dust storm approached, falling rapidly from 54% at 0900 LT to 14% at 1100 LT, with a further decrease to 7% later in the day. The normal daytime increase in air temperature was apparently suppressed by dust storm; that is, the daily temperature variation of 4.5°C

Table 1. Aerosol Particle Collections

Sample	Sampling Period, LT	Weather Conditions
Mar19a	19 March 1000 to 19 March 1800	before dust period (clear)
Mar19b	19 March 1800 to 20 March 0800	before dust period (light rain)
Mar20a	20 March 0830 to 20 March 1230	dust storm
Mar20b	20 March 1230 to 20 March 1800	dust storm
Mar20c	20 March 1830 to 21 March 0800	dust period (mostly clear)
Mar21	21 March 0800 to 21 March 1800	after dust period (clear)

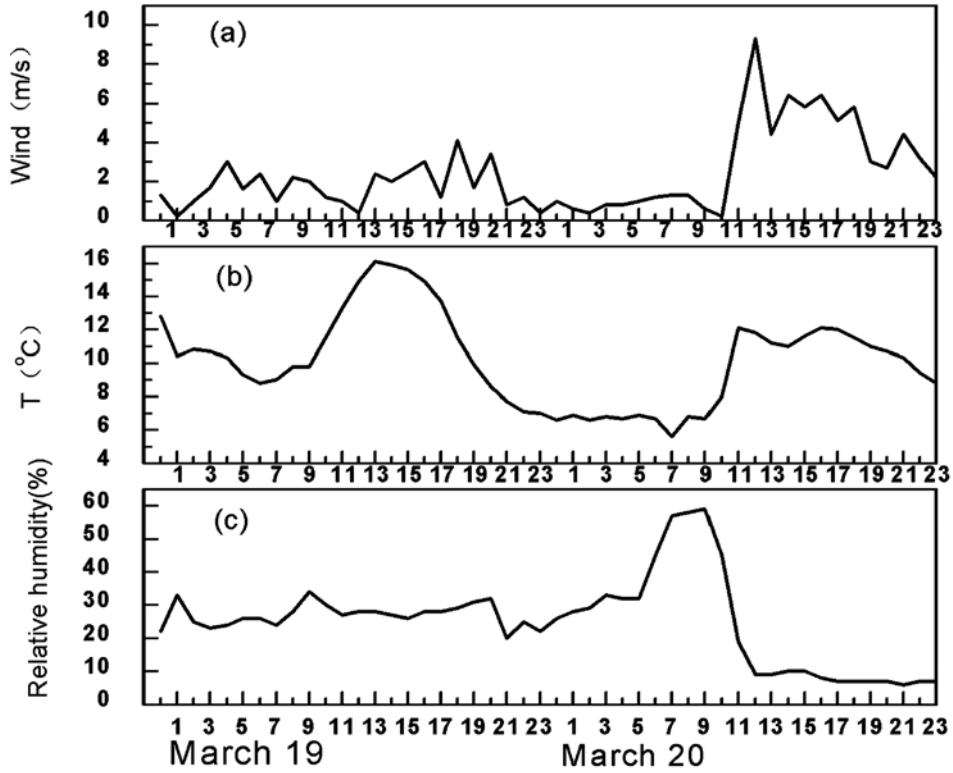

Figure 2. Ground (a) wind speed, (b) temperature, and (c) relative humidity on 19 to 20 March 2002.

on 20 March was much less than that during the preceding day when the temperature varied by 9.1°C.

[12] The relationship between dust concentrations and turbulence in the atmosphere was investigated by calculating and evaluating changes in the Richardson number (Ri) over time (Figure 4). These nondimensional numerical indicators of atmospheric stability were determined from measurements made on the meteorological tower at a height of ~140 m on 20 March. The Ri is defined as

$$Ri = \frac{\frac{g}{\theta_v}\frac{\partial \overline{\theta_v}}{\partial z}}{\left[\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2\right]} \quad (1)$$

According to the potential temperature formula, the following equation applies:

$$\frac{1}{\theta_v}\frac{\partial \overline{\theta_v}}{\partial z} = \frac{1}{T}(\Gamma_d - \Gamma) \quad (2)$$

where θ_v is potential temperature, V is wind speed, z is height, g is gravity velocity. Γ_d and Γ denote the dry adiabatic lapse rate and the temperature lapse rate, respectively,

$$\Gamma_d = \frac{g}{C_p} = 0.0098 \text{ K/m}, \ \Gamma = -\frac{\partial T}{\partial z} \quad (3)$$

Ri ranged from 0.3 to 1.3 before 0800 LT on March 20 (Figure 4), reflecting the stability of atmosphere prior to the arrival of the dust. After 0800 LT, however, the Ri began to decrease at the onset of mixing, and at 1000 LT, when the dust storm arrived in force, Ri quickly decreased to below 0.1 and remained there until the end of the day. The rapid changes in Ri were associated with increasing turbulence produced by wind shear combined with strong winds. The lower R_i indicates that there was a more efficient exchange of material and energy between ground and boundary layer during the dust storm. Momentum in the upper layer was thus easily transferred downward, consistent with high dust concentrations near the ground.

3.2. Source of Dust Storm

[13] Back trajectory analyses techniques are useful for studying the potential source regions of airborne

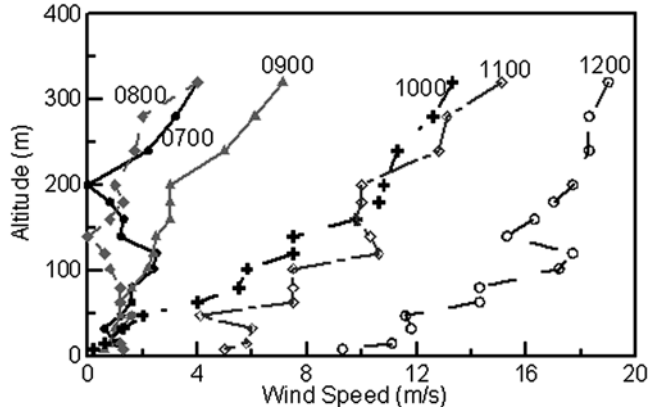

Figure 3. Wind profile on 20 March 2002. Times shown are from 0700 LT (UTC plus 8 hours) to 1200 LT 20 March 2002.

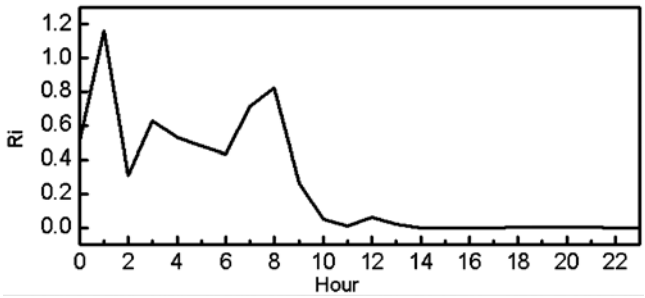

Figure 4. Richardson number (Ri) at 140 m on 20 March 2002. Times shown are LT time.

pollutants [*Draxler*, 1996]. A 48-hour calculation of three-dimensional back trajectories was calculated on line with the HYSPLIT model of NOAA Air Resources Laboratory (http://www.arl.noaa.gov/ready/hysplit4.html) using the National Centers for Environmental Prediction (NCEP) Final Analyses (FNL) meteorological database for 14 LT on 20 March 2002. The back trajectory in Figure 5 shows that 48 hours prior to reaching Beijing, the air mass was located to the north of Lake Balkhash in Kazakhstan. From there it passed over Xinjiang Province, Mongolia, northern Shanxi Province, and Inner Mongolia before finally reaching Beijing.

[14] However, the back trajectory of air mass cannot reveal the dust sources distinctly, and the surface observations are analyzed here for that purpose. In weather observations made by the China Meteorological Administration (CMA), dust events are classified into four categories: dust in suspension, blowing dust, a dust storm, or a severe dust storm. These categories are defined on the basis of horizontal visibility, that is, the horizontal visibilities for dust in suspension, blowing dust, dust storm and severe dust storm are less than 10 km, 1 to 10 km, 500 to 1000 m and less than 500 m, respectively. Here, 6-hour routine surface observations are used to delineate the progression of the dust storm.

[15] A cyclone formed over central Mongolia at 0800 LT on 19 March (not shown). Strong northwesterly winds, with a maximum exceeding 20 m/s, behind surface cold front resulted in blowing dust and dust storms over southern Mongolia (Figure 6). As the cyclone propagated, dust storms and severe dust storms were observed over Inner Mongolia at 1400 LT. Severe and widespread dust storms occurred on 20 March. From 21 to 22 March, the cyclone passed over eastern Inner Mongolia and northeastern China, and it was accompanied by weak dust storms over northeastern China and the Korean Peninsula. Meteorological observations showed that the dust storm arrived in Beijing at 0800 LT on 20 March and its influence continued for 24 hours. The observations also showed that dust storms first occurred in southern Mongolia on 19 March, and then moved eastward with the propagation of the Mongolian cyclone; therefore the main sources of dust particles sampled in Beijing apparently were in southern Mongolia and western part of Inner Mongolia, China.

3.3. TSP Concentrations in Beijing

[16] At 0915 LT in the morning of 20 March, the sky in Beijing turned yellow, and the air became permeated with dust. By 1000 LT, visibility was less than 1000 m. At 1100 LT, the visibility was only 200 m, and the sky was reddish in color. After 1500 LT, the dust storm started to abate, and the visibility increased to 800 m. Results obtained with a high-volume sampler showed that the TSP mass concentration during the peak of the dust storm, that is from 1050 to 1530 LT, reached 12 mg/m^3 (Figure 7). This dust concentration is 40 times the value for daily average TSP Grade 2 Standard promulgated by the China Environment Protection Administration in 1996. *Sugimoto et al.* [2003] evidently sampled the same event in Beijing and measured 11 mg/m^3 of dust. In comparison, during a strong previous dust storm on 6 April 2000, the TSP mass concentration in Beijing reached about 6 mg/m^3 [*Zhuang et al.*, 2001; *Wang et al.*, 2002].

3.4. Chemical Composition of the Dust

3.4.1. Soil Mass Concentrations

[17] According to *Malm et al.* [1994] the soil mass concentration of aerosols can be estimated by summing the concentrations of several elements predominantly associated with soil, plus oxygen assuming the compounds involved are the most common oxides. The formula recommended for the calculation of soil mass concentrations by elemental concentrations is as follows:

$$C_{Soil} = 2.2C_{Al} + 2.49C_{Si} + 1.63C_{Ca} + 2.42C_{Fe} + 1.94C_{Ti} \quad (4)$$

where C represents concentration and the names of the crustal elements are shown as subscripts. The calculated soil mass concentrations in Beijing in March 2002 are shown as a function of particle size in Figure 8. The concentration of coarse soil particles (aerodynamic diameter $r > 2$ μm) during the dust period was about six times that immediately before the event. The concentration of fine soil particles (aerodynamic diameter $r < 2$ μm) during the dust period is similarly about eight times that before the event. Soil particles accounted for 96.6 to 96.9% of the coarse mass during the dust storm period and 94.6 to 94.9% of the mass before and after dust storm.

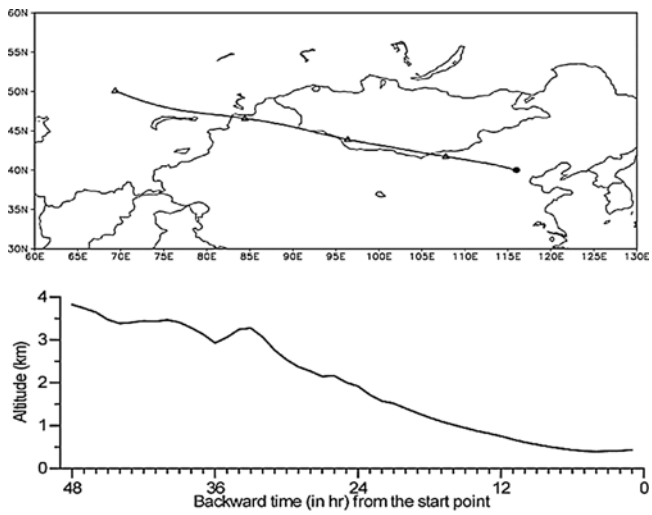

Figure 5. A 48-hour back trajectory calculation for 1400 LT on 20 March 2002 in Beijing.

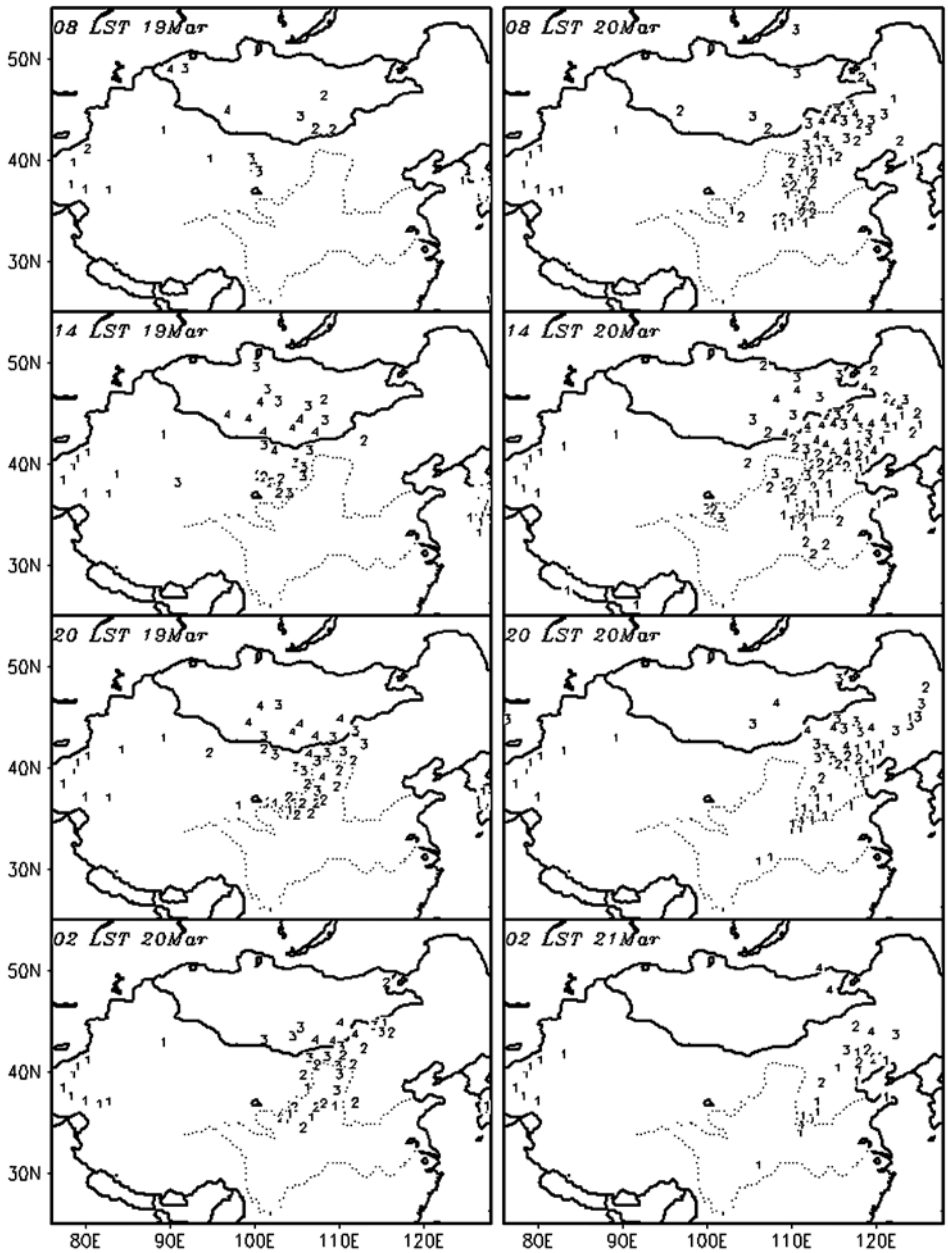

Figure 6. Observed surface weather phenomena from 0800 LT 19 March to 0200 LT 21 March 2002 (1, 2, 3, 4 represent dust in suspension, blowing dust, dust storm, and severe dust storm respectively).

3.4.2. Enrichment Factor Analysis

[18] Enrichment factors (EFs) were calculated to compare the composition of trace elements in the aerosol samples relative to the composition of a reference material, in this case, the Earth's upper crust. Enrichment factors are related to the delta notation used in studies of oxygen and carbon isotopes, and they are calculated as follows

$$EF = (C_x/C_r)_a/(C_x/C_r)_c \quad (5)$$

where C_x is the concentration of any element interest x, C_r is that of a reference elements, the subscript "a" refers to that in aerosol particle sample, while c refers to that in the crustal reference material. Typically, Al, Si, Fe are chosen as indicator elements in the EF calculations, and here Si is used for that purpose [*Winchester et al.*, 1981]. The EF results are shown in Table 2.

[19] The EFs for Mg, Al, K, Ca, Ti, V, Cr, Mn, and Fe, were in the range of 1 to 4, and the EFs for these elements showed negligibly small variations between the dust storm samples and the nondust storm samples. Thus the major source for these nine elements was undoubtedly crustal material even during nondust storm conditions. On the basis of the trajectory analyses, one would expect that deserts in the western and northwestern of China, and possibly deserts in Mongolia and the Inner Mongolia were the main sources of these crustal elements. The enrichment factors for Ca before the dust storm were higher than those in the high-

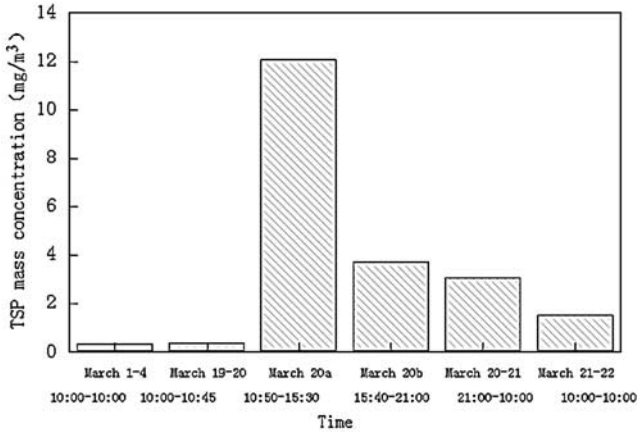

Figure 7. Mass concentrations of dust in Beijing in spring 2002.

dust period, suggesting that Ca has local sources, most likely local construction activities.

[20] The enrichment factors calculated for the major pollution element Se were the highest of all elements considered. Before the dust storm, the EF for Se was 2600. The Se enrichment factors for the two samples collected during the dust storm increased to 6400 and 13,000 (see Figure 9). Thus both the Se concentrations and the Se EFs during the dust event were much higher than those before or afterward, indicating a stronger impact from noncrustal sources on Se during the high-dust event. It is possible that fractionation of the mineral aerosol precursor or differences in sources for the dust contributed to the Se enrichments. However, Se is a major impurity in coal, and coal is used extensively for heating and industrial purposes in China, and therefore emissions from coal combustion are a more compelling explanation for the high Se concentrations and EFs. What was unexpected was that the data suggest disproportionately higher amounts of Se-rich aerosols relative to the dust were present during the dust event.

[21] Back trajectory analyses indicate that the air containing the dust had passed over the northern part of Shanxi Province where many large coal mines, such as the famous Datong Mine, are located. Therefore the mixing of material emitted from the coal mines with the desert dust is a possible explanation for why Se showed such high EFs during the dust event. It then follows that the pollution sources for Se in both the dust storm and nondust storm samples is probably a combination of emissions from local sources in Beijing and sources a considerable distance upwind. The EFs for Ni, Pb, Br, and Cu in during the high-dust event also were higher than those in the nondust period (Figure 10), suggesting that pollution sources for these elements also were stronger during the dust storm.

[22] The concentration of sulfur during the dust storm was $\sim$4 $\mu g/m^3$; this is approximately two times higher than before or after the dust storm (Figure 11). The enrichment factor for S was as high as 69 in nondust storm samples and $\leq$17 during the dust storm. These results further support the argument that dusty air can contain higher levels of pollutants than nondusty air. In the case of sulfur, the high-dust samples had more S than the low-dust samples, but the relative amount of this pollutant compared with dust was lower. S in the dust particles can result from the sorption of

Table 2. Enrichment Factors for Elements in Aerosol Particles

	Before Dust Storm		During Dust Storm			After Dust Storm
Element	Mar19a	Mar19b	Mar20a	Mar20b	Mar20c	Mar21
Mg	1.4	1.1	0.9	1.0	1.0	1.2
Al	0.9	0.9	0.9	0.9	0.9	0.9
P	9.8	9.1	3.3	3.3	2.4	4.1
S	55.9	69.2	17.3	14.5	10.8	22.3
Cl	117.4	141.7	23.9	13.7	10.9	18.2
K	1.2	1.2	1.3	1.4	1.4	1.1
Ca	3.4	4.1	1.8	1.8	1.5	1.8
Ti	1.8	1.8	1.9	2.2	2.2	1.7
V	1.6	1.6	2.6	3.9	3.1	3.1
Cr	3.7	2.5	1.7	1.9	0.7	2.3
Mn	1.9	1.7	1.6	1.9	1.9	1.6
Fe	1.5	1.6	1.7	2.1	2.0	1.5
Ni	8.3	7.5	11.1	14.9	8.5	7.6
Cu	13.8	15.6	20.4	27.8	17.0	13.3
Zn	15.4	27.9	2.7	4.0	1.2	5.0
As	136.0	335.7	95.9	134.6	42.6	100.2
Se	2623.7	2524.3	6393.5	13321.9	2039.2	905.2
Br	56.1	37.7	85.2	298.7	65.7	24.3
Pb	76.7	35.5	120.2	187.5	102.0	37.9

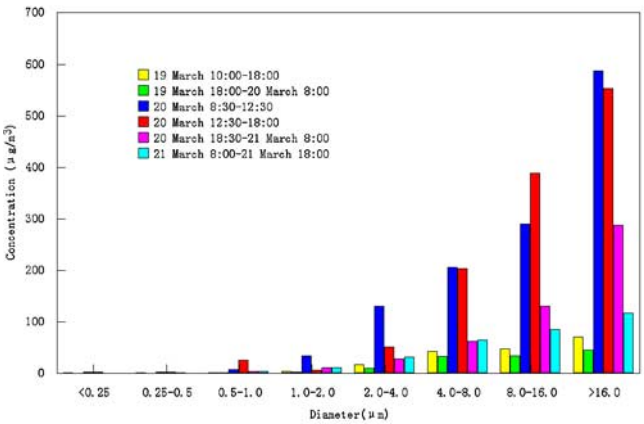

Figure 8. Soil mass concentrations on 19–21 March 2002.

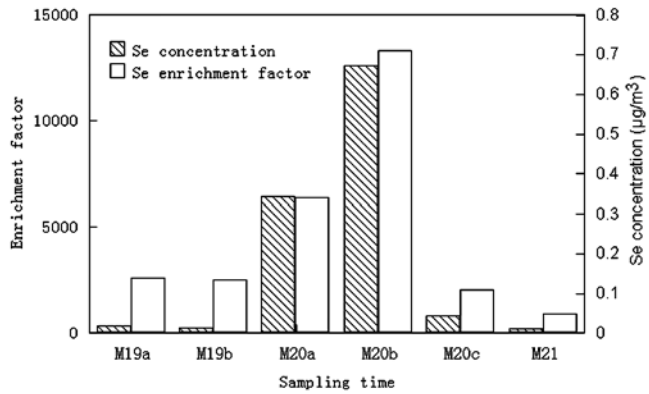

Figure 9. Enrichment factors and concentration for Se.

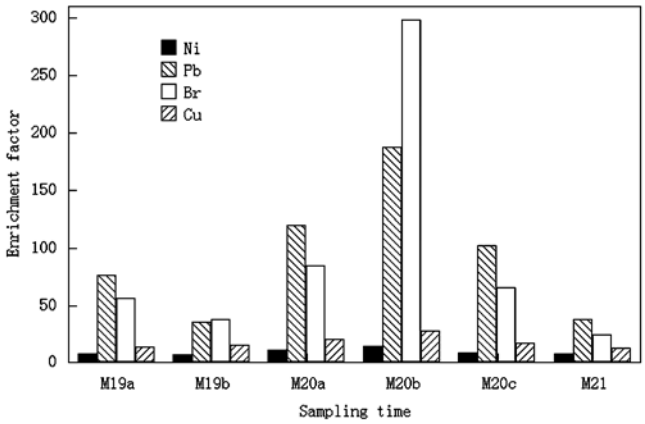

Figure 10. Enrichment factors for Ni, Pb, Br, and Cu.

gaseous SO_2, and the consequent transformation to sulfate aerosol or the high S in the dust storm samples could be due to the mixing of sulfate aerosol with the dust [*Arimoto et al.*, 2004]. The S in the aerosols, especially in fine particles can be transported thousands of kilometers and deposited into the Pacific [*Zhuang et al.*, 2001].

[23] The Zn and Cl concentrations in the high-dust samples were greater than those in less dusty ones, and similar to S, but in contrast to Se, the EFs for Zn and Cl were lower during the dust storm than before or afterward (Figure 12). The amount of noncrustal Zn, which was calculated from the observed Al concentration and the Zn/Al ratio in the Earth's crust [*X. Y. Zhang et al.*, 2003], did not vary greatly among the different types of samples, suggesting a relatively persistent background for this trace metal (Figure 13). Comparable calculations for Cl showed negative noncrustal Cl for the dust storm samples, which indicates that the Cl/Al reference ratio in Chinese loess [*Alfaro et al.*, 2003] was possibly too high. Even so, this comparison of high-dust versus low-dust samples indicates that the pollutants transported along with the dust are not a dominant source for either Zn or Cl at Beijing.

4. Conclusions

[24] In this study, ground observations were conducted when a major dust storm struck Beijing. Meteorological

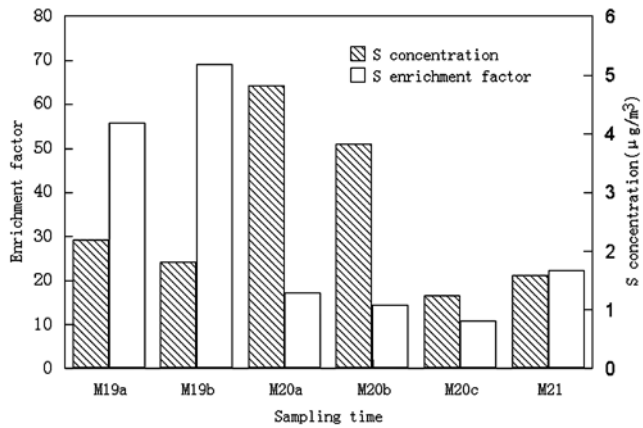

Figure 11. Enrichment factors and concentration of S.

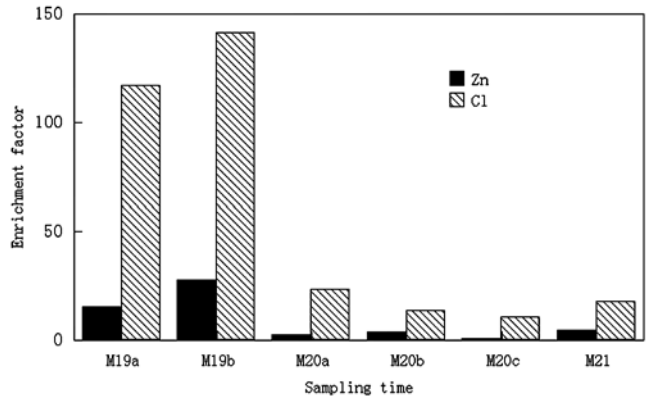

Figure 12. Enrichment factors of Zn and Cl.

data showed a sharp and distinct increase in wind speed, a decrease in relative humidity, and the development of turbulence and mixing in boundary layer during the event. The TSP concentrations during the dust storm reached 12 mg/m^3, disrupting daily life and triggering concerns over health effects. The main sources of the dust that affected Beijing were most likely in southern Mongolia and western part Mongolia, China.

[25] The enrichment factors for Mg, Al, K, Ca, Ti, V, Cr, Mn, and Fe relative to the Earth's upper crust showed small variations in both the dust storm and the nondust storm samples, indicating that these nine elements were mainly from crustal sources under all conditions. In contrast, both the concentrations and EFs for pollution elements, such as Se, Ni, Pb, Br, and Cu were much higher in high-dust period than before or afterward. The sources of these pollution-derived elements were evidently a combination of emissions from distant upwind areas and from the local sources in Beijing. In the case of sulfur, the high-dust samples had more S than the low-dust samples, but the relative amount of this pollutant compared with dust was lower. On the other hand, neither Zn nor Cl appears to be strongly affected by pollutants transported along with the dust. On the basis of these results, we conclude that detailed information on the evolution of the aerosol, not just in terms of mass loadings

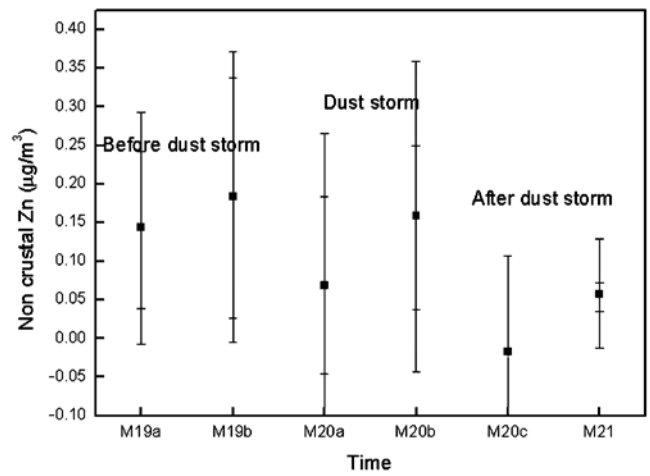

Figure 13. Noncrustal Zn calculated from observed Zn and Al in this paper and Zn/Al ration in the Earth's crust by *X. Y. Zhang et al.* [2003].

and size distribution, but also composition, is essential for evaluating the integrated aerosols' effects on human health, chemistry and climate.

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