Source, long-range transport, and characteristics of a heavy dust pollution event in Shanghai

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[1] Daily particulate matter with particles less than 2.5 μm in aerodynamic diameter ($PM_{2.5}$) and total suspended particulates (TSP) were analyzed for chemical composition and daily PM_{10}, SO_2, and NO_2 were monitored by automatic monitoring systems on the seven sites over China along the pathway of the long-range transport of the dust from 20 March to 19 April 2007. The highest recorded dust and daily Air Pollution Index topped 500 for the first time since 2002, when the routine continuous monitoring of PM_{10} was initiated in Shanghai. The daily 24 h average PM_{10} concentration of 648 μg m^{-3} was observed on 2 April 2007. The ratios of SO_2/PM_{10}, NO_2/PM_{10}, and $PM_{2.5}/PM_{10}$ were 0.066, 0.077, and 15.5% on 2 April 2007, which were significantly different from the nondust day and could be used as the index to judge the occurrence of dust in Shanghai. On the peak dusty day, the ratios of crustal matter rose to 70% and 64% of the total mass of $PM_{2.5}$ and TSP, respectively, while the ratios were 13% and 37% on nondust days. The ratio of Ca/Al in the dust aerosol in Shanghai was much closer to that in Duolun and Yulin near Mongolia Gobi rather than that in Tazhong of Taklimakan desert, indicating that the dust was transported from Mongolia Gobi instead of Taklimakan desert in Xinjiang province. The compositions of sea salt aerosol in $PM_{2.5}$ and TSP, combined with back trajectories, indicated that the dust passed through the East China Seas before reaching Shanghai, which is one of the typical dust pathways that lead to heavily polluted days in Shanghai due to dust transport. The anthropogenic sources along the pathway also partially contributed to the PM pollution in Shanghai during this dust event.

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1. Introduction

[2] Asian dust aerosol is the major mineral aerosol transported from central Asia to the Pacific, even to the western coast of America [*Duce et al.*, 1991; *Arimoto et al.*, 1997]. Based on the study on the sources and transport routes of 42 dust storms in Asia, *Zhang and Gao* [2007] found that 70% of Asian dust were transported from China eastern coast to the upper level of northeastern Pacific, and the rest through the Korea Channel and the Japan Sea. China's eastern coast is the major transport pathway of dust from Asia to the Pacific and also the origin of mineral aerosol deposit from inland areas to the ocean.

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[3] Asian dust not only carries mineral-rich particles to the North Pacific but also the anthropogenic pollutants from the eastern industrialized cities in Asia. A strong correlation (0.91) was found between the concentration of particulate matter (PM) in the west coast of North America and in the dust from the source area of Asian dust storms [*Zhao et al.*, 2008]. A correlation between dust and PM in North America does not necessarily mean dust can carry Asian pollution to North America. However, Asian dust storms may have an important impact on local air quality due to mixing with anthropogenic pollution in its transport pathway.

[4] Most studies compared the different physical and chemical features of aerosols during dust and nondust days at a certain site, such as Beijing [*Zhuang et al.*, 2001; *Wang et al.*, 2006], Qingdao [*Guo et al.*, 2004a, 2004b], Taiwan [*Lee et al.*, 2006; *Chuang et al.*, 2008], and Hong Kong [*Cao et al.*, 2003] in China, Incheon, Ulsan, and Gosan in Korea [*Lee et al.*, 2004; *Park et al.*, 2003], and Kyoto in Japan [*Zhou et al.*, 1996; *Ma et al.*, 2001]. These studies indicated the impact of dust storm on the local environment; however, few studies have been done to demonstrate the impact on the Yangtze River delta, which is one of the most important commercial and industrial centers of China. The

Table 1. Ratio of Gaseous Pollutants and PM_{10} on Six Heavily Polluted Days Impacted by Dust in Shanghai During 2002–2010[a]

	API	SO_2 ($\mu g\ m^{-3}$)	NO_2 ($\mu g\ m^{-3}$)	PM_{10} ($\mu g\ m^{-3}$)	SO_2/PM_{10}	NO_2/PM_{10}	Aerosol Type
21 March 2010	500	45	52	672	0.067	0.077	dust
02 April 2007	500	41	48	623	0.066	0.077	dust
08 April 2002	434	34	47	534	0.064	0.088	dust
19 January 2007	412	193	123	513	0.38	0.24	pollution
22 March 2002	401	26	47	501	0.052	0.094	dust
13 November 2002	355	37	76	464	0.080	0.16	pollution
8 year annual average (Daily concentrations from 2002 to 2009)		48	57	92	0.53	0.63	

[a]Data source: Shanghai Environmental Monitoring Center, http://www.semc.gov.cn; the period is from 1 January 2002 to 31 May 2010.

most polluted PM_{10} day due to dust in Shanghai since the establishment of total suspended particulates (TSP) automatic monitoring system in 1980s and PM_{10} in 2002 occurred on 2 April 2007. This provided a precious opportunity to study the impact of dust events on the air quality and demonstrate the mixing characteristics of dust aerosol with anthropogenic pollution along the transport pathway from the deserts to the northern cities in China.

2. Background

[5] To protect public health and the environment, the Ministry of Environmental Protection in China has established the ambient air quality standards for criteria pollutants, as annual, daily, and hourly averages, for SO_2, NO_2, PM_{10}, CO, and O_3, codified in 1996. Furthermore, China's standards are classified into three grades according to the types of land use (Grade I for natural reserves, Grade II for residential areas, and Grade III for industrial parks). Taking the daily average PM_{10} standard as an example, the standards are 50 $\mu g\ m^{-3}$ (Grade I), 150 $\mu g\ m^{-3}$ (Grade II), and 250 $\mu g\ m^{-3}$ (Grade III) (China State Environmental Protection Administration (SEPA), 1996 [*Hao and Wang*, 2005]). The daily average standards are also applied to develop the daily API (Air Pollution Index) for public notification in 84 major cities in China, which is quite similar to the AQI (Air Quality Index) in U.S. Environmental Protection Agency (USEPA). The categories of API are defined according to the daily standards, and a day is called a Polluted Day once the daily concentration of SO_2, NO_2, and PM_{10} exceed the Grade II standard. More severely, the day is considered as a Heavily Polluted Day when the API is larger than 300, which is equivalent to daily average of SO_2, NO_2, or PM_{10} over 1600, 565 and 420 $\mu g\ m^{-3}$, respectively. PM_{10} API is calculated based on the daily hourly average of PM_{10} concentration according to the following formula:

$$I = I_{low} + \left(I_{high} - I_{low}\right) \times (C - C_{low}) / \left(C_{high} - C_{low}\right),$$

where I is the API value of PM_{10} and C is the concentration of PM_{10}. I_{high} and I_{low}, the two values most approaching to value I in the API grading limited value table, stand for the value larger and lower than I, respectively; C_{high} and C_{low} represent the PM_{10} concentration corresponding to I_{high} and I_{low}, respectively.

[6] Since 2002, there have been six heavily polluted days (concentration of daily average of PM_{10} is higher than 420 $\mu g\ m^{-3}$, namely API is higher than 300), with 3 days in 2002, 2 days in 2007 and 1 day in 2010 (Table 1). Based on the meteorological analysis, 4 days of heavy pollution were clearly affected by the transport of dust from northwestern China, which usually occurs in the spring [*Fu et al.*, 2008]. These dust days were 2 March 2002, 8 April 2002, 2 April 2007 and 21 March 2010. Among the four heavily polluted days in Shanghai, the daily API ranked the upper level of 500 on 2 April 2007 for the first time with a daily PM_{10} concentration of 648 $\mu g\ m^{-3}$. Such a serious dust pollution episode happened again 3 years later in 2010; as a result, it is meaningful to study this case so as to understand the source, transport, mixing with the anthropogenic emission of dust and its impact on air pollution in the Yangtze River Delta around Shanghai.

3. Experiments

3.1. Automatic Sampling

[7] The daily averaged ambient pollutant concentration for Shanghai is an average of 24 h concentrations from eight automatic air quality monitoring stations approved by China Environmental Protection Bureau, producing the API reported to the public every day.

[8] The air quality monitoring network was established in the 1980s and has been in routine operation for almost 30 years, comprising a routine maintenance team, QA/QC laboratory, data collecting and checking information system. The data checking and reporting system has being upgraded to meet the U.S. guideline, supported by the Airnow-I demonstration project sponsored by Shanghai Environmental Bureau and USEPA since 2005. These stations are operated and maintained by the professional team in Shanghai Environmental Monitoring Center (SEMC) following the systematic technical specification of QA/QC (Automated methods for ambient air quality monitoring (HJ/T193–2005)). Instruments of SO_2, NO_2, and PM_{10} are installed at the eight stations with five-factor meteorological meters (wind speed, wind direction, temperature, relative humidity and pressure). Additionally, one instrument measuring hourly $PM_{2.5}$ concentrations is installed at the Putuo station, which represents a residential and educational area and has monitored hourly $PM_{2.5}$ concentrations since 2005. Daily average concentrations for 8 years and the heavily polluted days from 2002 to

Table 2. Information of Seven PM Filter Sampling Sites in China[a]

Site	Site Code	Location coordinates	Area (km^2)	Population (×10,000)	Note
Tazhong	TZ	39.00°N, 83.67°E	337,000		Deserted area
Urumqi	U	43.78°N, 87.61°E	10,902	202	Inland urban site: residential and traffic regions
Duolun	DL	42.3°N, 116.5°E	3773	10.05	Inland suburban site: residential regions, sand land, close to desert source
Yulin	YL	38.2°N, 109.8°E	43,578	352	Inland suburban site: residential and traffic regions, sand land, close to desert source
Beijing	BJ	39.9°N, 116.4°E	16,800	1581	Inland urban site: residential and traffic regions
Taishan	TS	36.3°N, 117.1°E			Tourist site of Taishan Mount
Shanghai	SH	31.2°N, 121.5°E	6341	1815	Coastal urban site: residential and traffic regions

[a]Data for Urumqi, BJ, and SH are from China Statistical Yearbook 2007 (http://www.stats.gov.cn); data for DL are from Inner Mongolia Statistical Yearbook 2007; and data for YL are from http://baike.baidu.com/view/148354.htm#4. All the data are the annual mean values in 2006.

2009 in Shanghai are summarized in Table 1. The hourly monitoring instruments API 200 (Advanced Pollution Instrumentation, Inc., U.S.) or TE 43C (Thermo Electron Corporation Environmental Instruments Division, U.S.), API 300 or TE 42C, and TOEM 1400A (Rupprecht & Patashnick Co., Inc., U.S.) were applied for the measurements of SO_2, NO_2, and PM_{10} ($PM_{2.5}$), respectively. The routine QA/QC includes the daily zero/standard calibration, span and range check, station environmental control, staff certification, etc., according to the Technical Guideline of Automatic Stations of Ambient Air Quality in Shanghai based on the national specification HJ/T193–2005, which was developed following the technical guidance established by the *U.S. Environmental Protection Agency* (*U.S. EPA*) [1998].

3.2. Manual Sampling

[9] Shown in Table 2, $PM_{2.5}$ and TSP filters were sampled for 1 month at five sites including the two desert sources in four provinces (Xinjiang, Shannxi, Inner Mongol and Shandong) and two cities (Beijing and Shanghai) in the spring of 2007 (20 March to approximately 19 April). These sites were set up along the transport pathway of Asian dust storm to study the characteristics and long-range transport of Asian dust and its mixing with pollution aerosol on the pathway of its transport (Figure 1). A total of 430 daily samples of $PM_{2.5}$ and TSP were collected at all sites, and four extra samples were added on the high-pollution day of 2 April in Shanghai. The samples were collected on the roof (20 m high) of a building at Fudan University, a mixed residential and traffic site in Shanghai. $PM_{2.5}$ samples were collected on Whatman 41 filters (Whatman Inc., Maidstone, UK) by a medium-volume sampler (model: (TSP/PM_{10}/$PM_{2.5}$)-2, flow rate: 77.59 L min^{-1}). The sampling time was from 0900 Beijing time (BJT) on one day to 0900 BJT on the next day. The samples were put in polyethylene plastic bags right after sampling and preserved in a refrigerator. All those filters

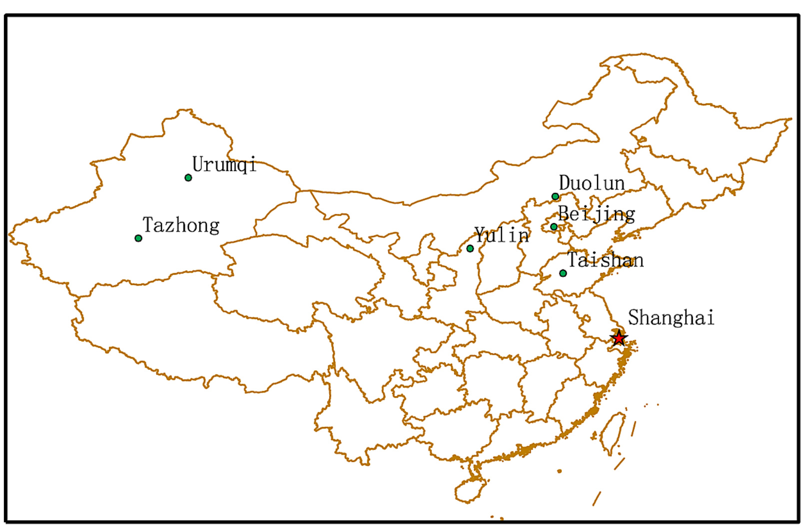

Figure 1. The locations of seven sampling sites in China.

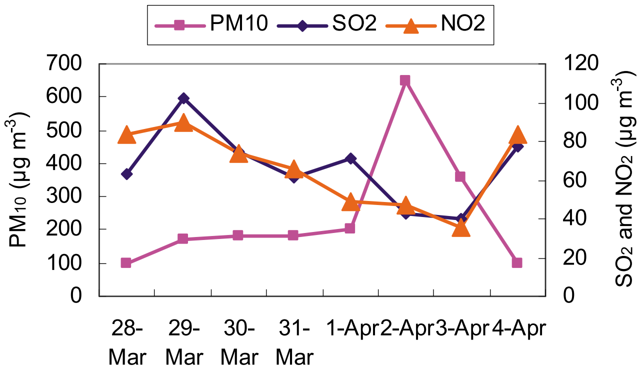

Figure 2. Daily concentrations of PM_{10}, SO_2, and NO_2 from 28 March to 4 April 2007 in Shanghai.

were weighed before and after sample collection with an analytical balance (Sartorius 2004MP, reading precision 10 μg) after stabilizing under constant temperature (20° ± °C) and humidity (40 ± 1%) for over 24 h. All the procedures were strictly quality-controlled to avoid any possible contamination of the samples.

3.3. Chemical Analysis

3.3.1. Ion Analysis

[10] One fourth of each sample and blank filter was extracted ultrasonically by 10 mL water, which was deionized to resistivity of 18 Ω cm^{-1}. After passing through microporous membranes (pore size, 0.45 mm; diameter, 25 mm; made by the affiliated plant of Beijing chemical school). Each filtrate was stored at 4°C in a clean tube for analysis. Five inorganic ions (SO_4^{2-}, NO_3^-, Cl^-, NH_4^+, Na^+) were analyzed by Ion Chromatography (IC, Dionex ICS 3000, USA), which consists of a separation column (Dionex Ionpac AS11 for anion and CS12A for cation), a guard column (Dionex Ionpac AG 11 for anion and AG12A for cation), a self-regenerating suppressed conductivity detector (Dionex Ionpac ED50), and a gradient pump (Dionex Ionpac GP50). The gradient weak base eluent (76.2 mM $NaOH^+H_2O$) was used for anion detection, while the weak acid eluent (20 mM MSA) was used for cation detection. The recovery of each ion was in the range of 80–120%. The relative standard deviation of each ion was less than 5% for a reproducibility test. The limits of detection (S/N = 3) were less than 0.04 mg L^{-1} for anions and 0.006 mg L^{-1} for cations. The quality assurance was routinely carried out using Standard Reference Materials (GBW 08606) produced by the National Research Center for Certified Reference Materials, China. Blank values were subtracted from sample determinations.

3.3.2. Element Analysis

[11] The sample filters were digested at 170°C for 4 h in a high-pressure Teflon digestion vessel with 3 mL concentrated HNO_3, 1 mL concentrated HCl, and 1 mL concentrated HF. After cooling, the solutions were dried, treated with 0.1 mL concentrated HNO_3, and diluted to 10 mL with deionized water (resistivity of 18 Ω cm^{-1}). Elements of Al and Ca were determined by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES, model, ULTIMA, made by JOBIN-YVON Company, France). The detailed analytical procedures were given elsewhere [*Zhuang et al.*, 2001; *Sun et al.*, 2004]. Al was used as the reference element of crustal source in this study.

4. Results and Discussion

4.1. Impact of Dust on Ambient Air Quality and Visibility in Shanghai

[12] Figure 2 showed the change of three major pollutants during this severe dust episode in Shanghai around 2 April 2007. The daily average concentration of PM_{10} increased from 169 μg m^{-3} on 28 March, which exceeded the criteria of daily concentration of PM_{10} in China of 150 μg m^{-3} to the peak of 648 μg m^{-3} on 2 April and subsequently dropped to 98 μg m^{-3} on 4 April 2007. However, the concentrations of SO_2 and NO_2 changed in the opposite direction from PM_{10}, which decreased from 102 μg m^{-3} and 90 μg m^{-3} to 40 μg m^{-3} and 36 μg m^{-3} on 3 April and increased back to 77 and 84 on 4 April 2007, which represented the beginning of a typical anthropogenic pollution day. The contrary change curves of particulate matter and gaseous pollutants are quite different from that on the heavily polluted days caused by the adverse weather condition and anthropogenic emission, for example, the regional haze episode in the Yangtze River delta [*Fu et al.*, 2008].

[13] The dust transported from the northern areas contributed to the poor air quality from 30 March to 1 April and reached the highest hourly PM_{10} concentrations of 1000 μg m^{-3} (the upper lime of detection) from 0600 BJT to 1600 BJT on 2 April 2007 in Shanghai, shown in Figure 3. The visibility decreased from 7~9 km at 2000 BJT on 1 April to less than 2 km at 1400 BJT on 2 April, then back to 9~11 km at 2000 BJT on 2 April. As shown in Figure 4, the spatial distribution of visibility around the whole Shanghai was lower in the southeastern area along the coast and higher in the northern side on 2 April 2007. The average visibility covering the whole Shanghai was less than 2.3 km with the lowest visibility of 1.7 km at 1400 BJT on 2 April 2007. The dust passed through Shanghai. A quickly fresh air mass ushered in cleaner air and, consequently, the visibility over the Shanghai exceeded 14 km on 3 April 2007. The distribution of visibility could also reflect that the pathway of dust was from the coast area to the inland, giving the possible influence by both sea salt and mineral aerosol, which will be discussed in sections 4.2.2 and 4.3.3.

4.2. Source Identification and the Long-Range Transport

4.2.1. Metrological Conditions of This Pollution Process

[14] The weak cold front passed over the Yangtze River Delta at night on 29 March 2007. Subsequently, the Yangtze River Delta was affected by the weak low pressure from the southwest before the next strong cold front on 30 March based on the ground weather chart. At 700 hPa, the Yangtze River Delta area was located at the bottom of the East Asia trough with the strong wind of 10–12 m s^{-1} from northwest, which brought the sand from desert of Gobi to the north Asia (Figure 5). However, the northeast ground wind sent the upper sand from north Asia back to the East Asia.

[15] Due to the influence from the low pressure system, the high pressure associated with cold air did not arrive in

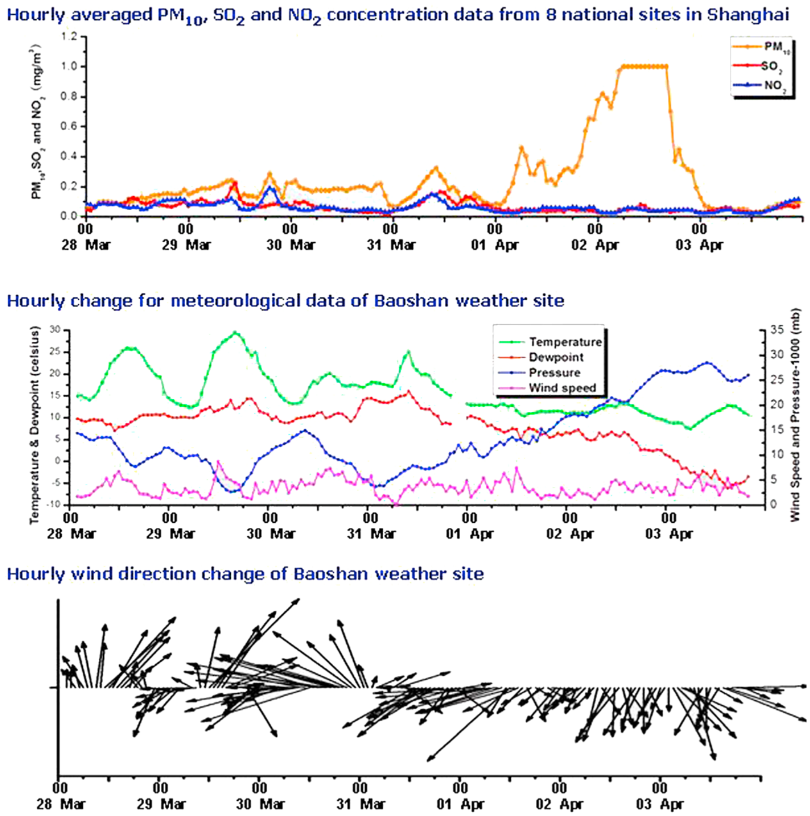

Figure 3. Surface meteorological variables from 0000 BJT on 28 March to 2300 BJT on 3 April 2007 in Shanghai.

Shanghai until the morning on 2 April after the frontal passage arrived at noon on 31 March. The concentration of PM_{10} increased contrarily from 87 $\mu g\ m^{-3}$ at 0000 BJT to 458 $\mu g\ m^{-3}$ on 1 April, when the upper-level trough was leading the approach of cold air from north to south.

[16] The tail of the cold front passed over Shanghai at noon on 31 March 2007. As shown in Figure 3, the temperature and dew point began to decrease, and the pressure and wind speed increased. The pressure increased from 1003.7 hPa on 31 March to 1028.5 hPa on 3 April continuously. The wind direction changed from southwest to northeast. It should be noted that the wind became relatively light (2–3 m s^{-1}) from the afternoon on 1 April and did not strengthen until 1200 BJT on 2 April. It was shown that the concentration of PM_{10} increased sharply from 0000 BJT on 1 April, while the concentrations of SO_2 and NO_2 remained low.

4.2.2. Back Trajectories Analysis

[17] Dust storms in northern China typically show regional characteristics. Using a rotated empirical orthogonal function and the annual days of dust storms from 1954 to 1998, *Qian et al.* [2004] observed five different regions associated with dust storms. They were Xinjiang region, the eastern part of Inner Mongolia, Tsaidam Basin, Tibetan Plateau, and Gobi Desert near Yellow River. Based on the dust storm weather report from China Meteorological Administration, this dust storm event occurred in the northwest area of China, including Xinjiang, Gansu, Inner Mongolia, Ningxia, and the north part of Shanxi province during 27 March to 2 April 2007. Based on the satellite images in Figure 6, the dust storm was transported to the north China, including Hebei, Henan and Shangdong province on 1 April. On 3 April the dust exited the main land and this area returned back to be clear and clean as evident on the satellite image.

[18] As shown in Figure 7, the 36 h back trajectories for the four highest heavy dust days in Shanghai can be classified into two major pathways. One was the inland pathway with northwest air mass from the Gobi Desert, the other was the ocean pathway originating from the eastern part of inner Mongolia with circuitous northeastern trajectories back to the land. On this dust episode, the dust was transported from the desert area in Inner Mongolia, passed through the upper space of Hebei and Shandong province, East China Sea, and returned to the land by reaching Shanghai. The transport pathway of dust on this episode was different from the typical routes of dust, in which the dust was originated from Gobi desert in Mongolia and China to the North Pacific Ocean [*Sun et al.*, 2001].

4.2.3. Transport Pathway of Dust

[19] Based on the national daily reporting of the ambient air quality in the major cities of China, the dust was transported from Hohehot, then through Zhaozhuang, Qingdao, and Lianyungang, ending in Shanghai (Figure 8). The daily concentrations of PM_{10} in Hohehot and Lianyungang exceeded 600 $\mu g\ m^{-3}$ on 31 March and 1 April separately (the maximum API is 500, which equals 600 $\mu g\ m^{-3}$ based on the national API reporting data, http://www.cnemc.cn).

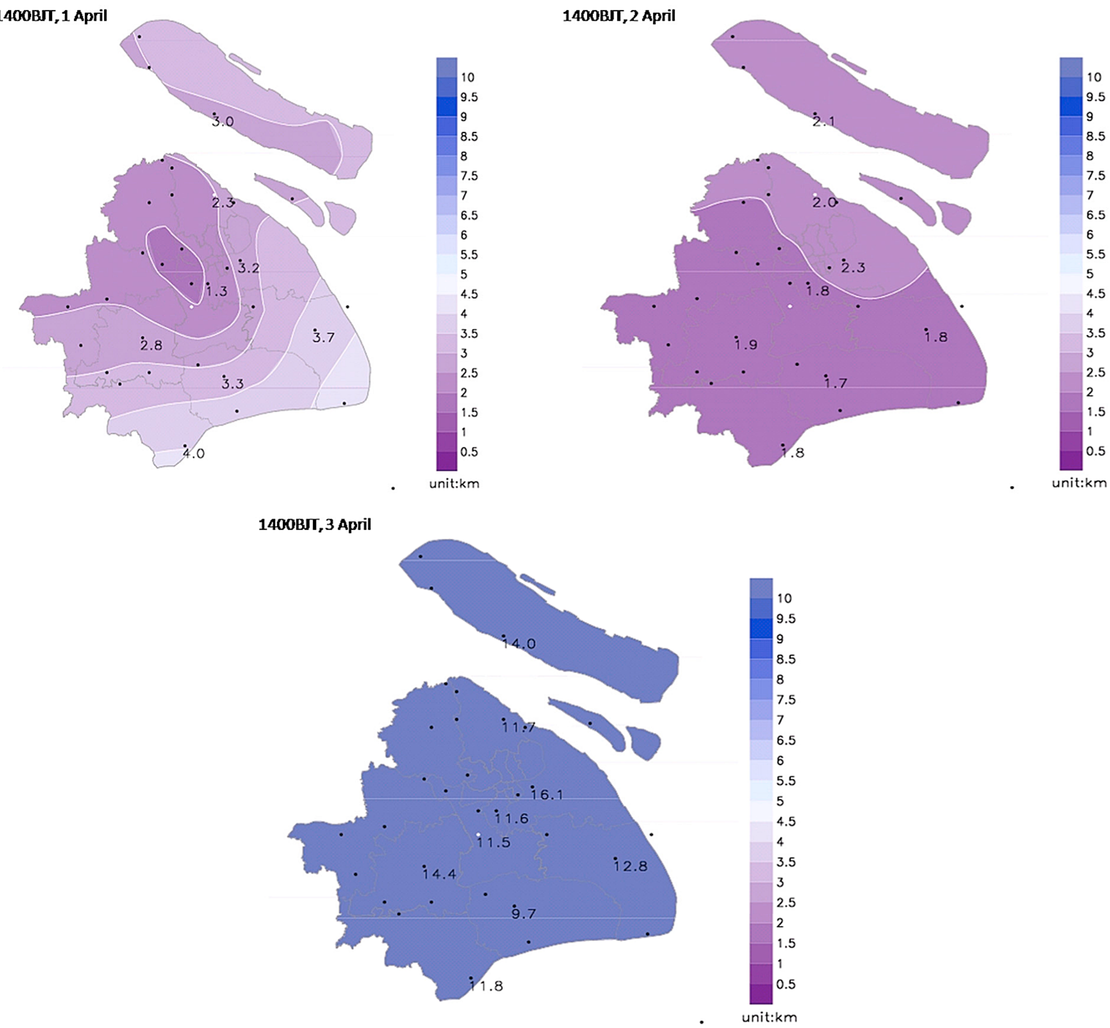

Figure 4. Change of visibility distribution during this high-pollution episode of dust from 1 to 3 April 2007 in Shanghai (data source from Shanghai Meteorological Bureau).

The variation of API further indicated the possible transport pathway of the dust shown by the satellite image in Figure 6.

[20] As compared to those dust storms occurred in 2001 [*Zhuang et al.*, 2001], 2002 [*Sun et al.*, 2004], 2004 [*Sun et al.*, 2010], and 2006 [*Zhang et al.*, 2010], their transport pathways were quite different from this dust event. Neither of the dust storms listed in these studies passed through Shanghai and impacted the air quality in Shanghai, indicating the pathways of the dust episodes arriving in the Yangtze River delta were basically different from those dust storms occurred in the northern China.

4.2.4. Sources of the Dust Storm

[21] Although there is neither an ideal tracer nor a specific element that is unique to a specific source region, it is still possible to find a pair of elements whose ratio could distinguish the sources. By analyzing surface soil samples collected from cities on the pathway of float dust, from many dust source areas, *Sun et al.* [2004] found that the ratio of Mg/Al in the aerosols could be the best tracer that met the two basic requirements (the distinct signature and the stability during transport) to distinguish the sources of inside a city from outside the city. The latest study by *Sun et al.* [2010] and *Huang et al.* [2010] suggested the ratio of Ca/Al could be used as the tracer to identify the sources of dust storms. In this study, we further approved this finding that the ratio of Ca/Al in $PM_{2.5}$ between dust day and nondust days was obviously different and helpful in identifying the possible sources and pathway of dust storms occurring in China. Seven monitoring sites as a network, including one desert source (Tazhong (TZ)), two sites near to the desert source (Doulun and Yulin (DL and YL)) and three cities on the pathway (Urumqi, Beijing and Taishan (U, BJ and TS)) as well as Shanghai, were set up along the transport pathway of Asian dust storm. The ratios of Ca/Al in the aerosols collected in these sites each day from 28 March to 2 April 2007 were shown in Figure 9. It was noted that the ratio of Ca/Al in Shanghai was 0.75 on 2 April, the day with the peak of mineral dust, while the average ratio of Ca/Al on nondust days was 1.67. The ratio of 0.75 is much closer to those ratios of the dust aerosols in DL (0.90), located in Inner Mongolia, YL (0.94), located in south of Mongolia Gobi

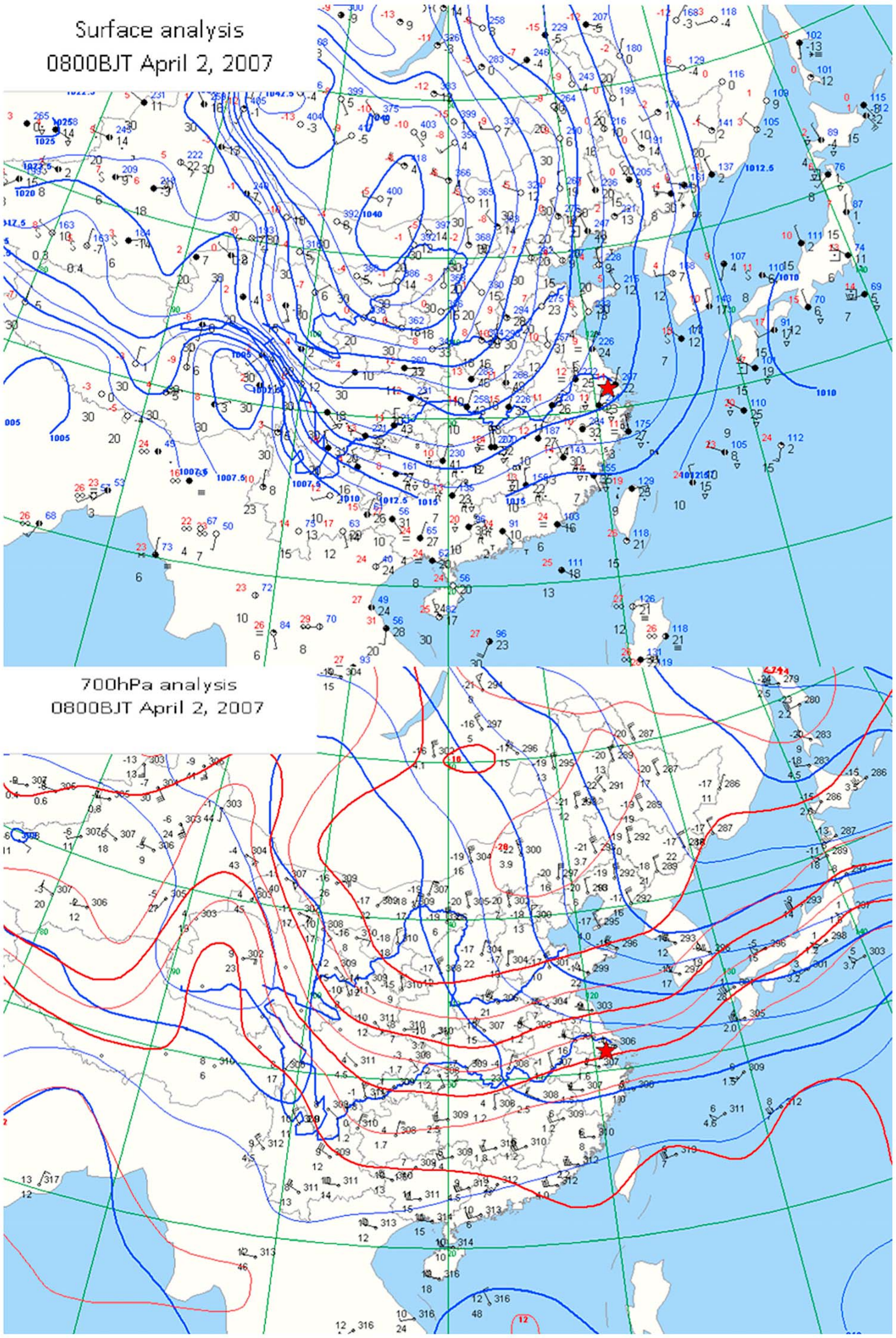

Figure 5. Surface and 700 hPa weather chart in China at 0800 BJT on 2 April 2007 (http://218.94.36.199:5050/dmsg/map.htm) (star is the location of Shanghai).

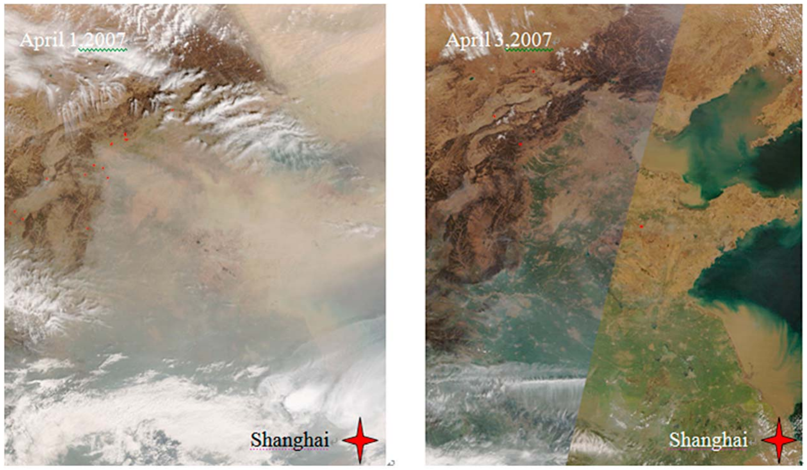

Figure 6. True color satellite image on 1 and 3 April 2007: Terra (the image was covered by cloud on 2 April 2007) (http://rapidfire.sci.gsfc.nasa.gov/subsets/?subset=FAS_China4.2007090).

and north of Loess Plateau, BJ (0.69), located near Hebei Province, and TS (0.78), located in Shangdong province, 1 or 2 days before 2 April when the peak of dust appeared in Shanghai. The ratios of Ca/Al in TZ (3.2) and U (2.2) on the days before 2 April were much higher than that (0.75) of the dust in Shanghai. The ratio of Ca/Al in $PM_{2.5}$ can provide useful information on sources of the dust in Shanghai through the long-range transport. As compared the ratio of Ca/Al among different sampling sites, it could be seen that the dust in Shanghai during this episode was not traceable from Taklimakan Desert; instead, it was more likely from the Mongolia Gobi, through Inner Mongolia, Hebei and Shangdong province, finally reaching Shanghai, as the back trajectory analysis showed.

4.3. Characteristics of the Dust Pollution in Shanghai

4.3.1. Regional Pollution Impacted by the Dust

[22] As shown in Table 3 from 28 March to 5 April 2007, several polluted days (>150 μg m^{-3}) occurred in those cities located in the Yangtze River delta with the peak on 2 April during this dust episode. The daily PM_{10} concentrations in the coastal cities, for example, Shanghai and Ningbo with PM_{10} of 648 μg m^{-3} and 474 μg m^{-3} respectively, were higher than the other inland cities on 2 April. After the episode, the concentrations of the aerosols in all cities decreased to the level of moderate on 4 April. The trend and the distribution of PM_{10} in this city cluster during this period revealed that the regional aerosol pollution happened in the Yangtze River delta.

4.3.2. Ratios of SO_2/PM_{10}, NO_2/PM_{10}, and $PM_{2.5}/PM_{10}$

[23] As shown in Figure 10 and Table 1, the ratios of gaseous pollutants and particulate matters varied a lot during the sampling period covering the days of dust pollution. The ratio of SO_2/PM_{10} jumped to as low as 0.066 on 2 April while the 8 year daily average was 0.53 from 2002 to 2009; the ratio of NO_2/PM_{10} was only about 0.077 on 2 April while the average was 0.63. In addition, the ratio of $PM_{2.5}/PM_{10}$ decreased to 19% on the dust days comparing with the average of 58% during 2006 to 2009. These values could be applied as the key index to judge the occurrence of dust and illustrate how the dust storm from the long-range transport impacted on the local ambient air quality in Shanghai.

4.3.3. Chemical Characteristics of PM

[24] The concentrations of TSP and $PM_{2.5}$ reached the highest values with 1340 μg m^{-3} and 383 μg m^{-3}, respectively, on 2 April, which ranked the highest records in Shanghai since 2002. Mineral matter (MM), sea salt aerosol (SSA), and inorganic secondary pollutants (IS) in dust aerosols were calculated based on the following formats: [MM] = [Al]/0.08; [SSA] = ([Na^+] + [Cl^-]) × 1.176 [*Chan et al.*, 1997]; [IS] = [NH_4^+] + 0.922 [SO_4^{2-}] + [NO_3^-] [*Turpin and Lim*, 2001], as shown in Table 4. The ratios of MM to the mass of $PM_{2.5}$, increased from 13% on 28 March to 70% on 2 April, and back to 16% after the peak day, while 37%, 64% and 15% of TSP. The concentrations of MM in $PM_{2.5}$ and TSP increased by 25.1 and 15.6 multiples, respectively, on the dust peak day. It must be noted that the changes in ratio of SSA and MM in $PM_{2.5}$ and TSP were different, showing that the dust was transported from the ocean and had a stronger impact on the concentrations of $PM_{2.5}$ compared to TSP. The ratio of SSA in $PM_{2.5}$ was 1% on 31 March 2007 before the dust arrived in Shanghai, which was obviously different from the value of 2–3% on the day of 2 April. However, the ratio of SSA in TSP was 1% on 2 April 2007, which was almost the same as the value of 1~2% before and after the dust day. Furthermore, the concentration of SSA in $PM_{2.5}$ rose to 10.9 μg m^{-3} on 2 April, which was 7.3 times of that on 31 March. The concentration of SSA in TSP rose to 19.9 μg m^{-3} on 2 April, which was 9.0 times of that on 31 March. The results indicated that the dust carried the mineral matter together with sea salt aerosol to Shanghai both in $PM_{2.5}$ and TSP during this high dust aerosol pollution episode. In addition, the concentrations of IS in $PM_{2.5}$ was increased from 7.5 μg m^{-3} on 28 March to 20.1 μg m^{-3} on 2 April, which was 11.6 μg m^{-3} to 60.0 μg m^{-3} in TSP. Although the concentrations of IS in $PM_{2.5}$ and TSP increased together on the dust peak day with the quick increment of the total mass of PM, both ratios of IS to the mass of $PM_{2.5}$

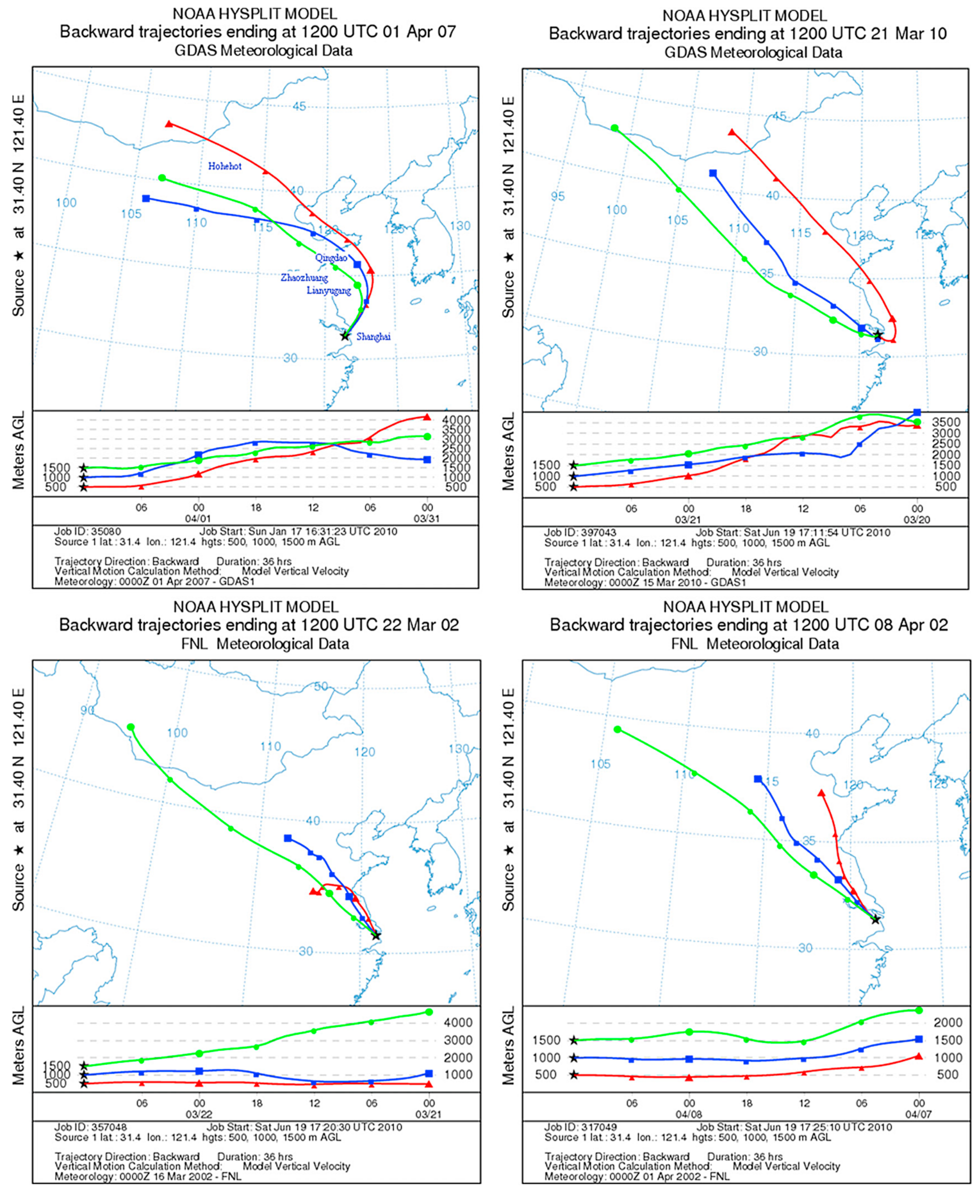

Figure 7. The 30 h back trajectories in Shanghai on four heavy dust days (http://ready.arl.noaa.gov/).

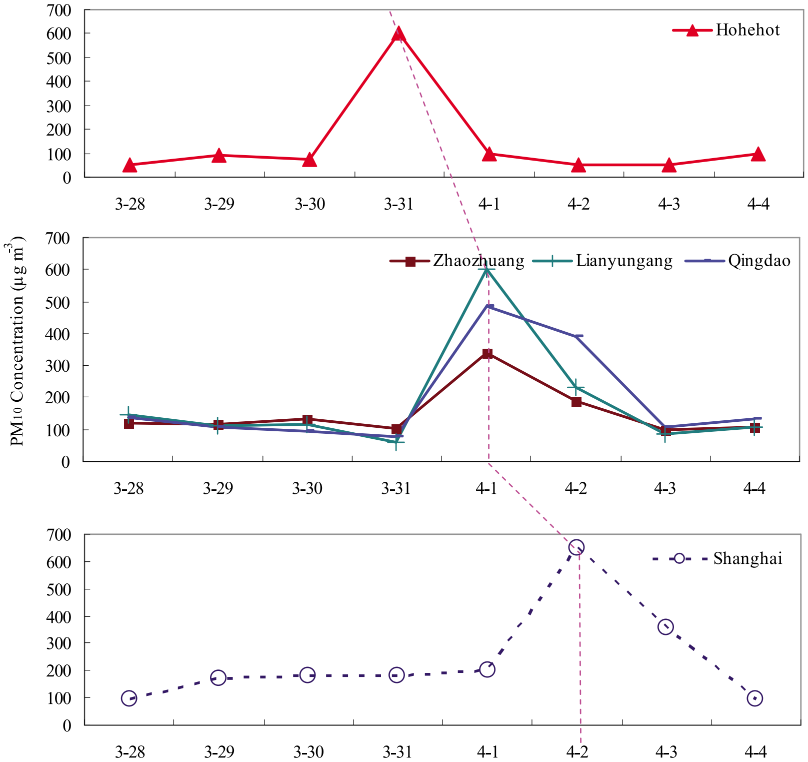

Figure 8. Transport of dust along the cities based on the PM_{10} concentration (data from China Environmental Monitoring Station, http://www.cnemc.cn).

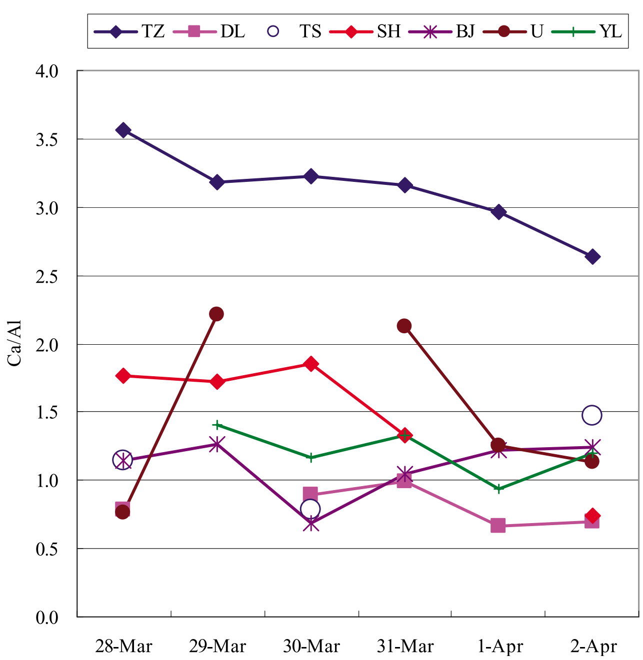

Figure 9. Ratios of Ca/Al in $PM_{2.5}$ at seven sites each day from 28 March to 2 April 2007. (No samples were taken on 1 April in Shanghai due to the rainy day. Only three samples were taken on the site of TS.)

and TSP were decreased, showing that the impact of anthropogenic sources played weak roles in this dust episode.

5. Conclusions

[25] The worst dust pollution episode in Shanghai was observed with daily PM_{10} concentration of 648 $\mu g\ m^{-3}$ and API of 500 since the routine monitoring of PM_{10} began in 2002. The lowest visibility was less than 2.0 km with the lowest ratios of $PM_{2.5}/PM_{10}$ (15.5%), SO_2/PM_{10} (0.066) and NO_2/PM_{10} (0.077), which could be used as important indices to distinguish dust days from nondust days in Shanghai. A drop-down flow from Inner Mongolia and

Table 3. Regional Pollution of PM_{10} on This Dust Episode in the Yangtze River Delta ($\mu g\ m^{-3}$)[a]

Date	Shanghai	Hangzhou	Shaoxing	Ningbo	Suzhou	Nanjing
28 Mar 2007	98	96	80	82	130	126
29 Mar 2007	170	124	84	112	182	186
30 Mar 2007	184	140	106	146	150	170
31 Mar 2007	182	244	142	138	182	218
1 Apr 2007	202	162	122	144	134	176
2 Apr 2007	648	316	284	474	222	222
3 Apr 2007	358	298	324	448	272	146
4 Apr 2007	100	86	76	82	102	86
5 Apr 2007	112	112	72	102	106	128

[a]Data are from China Environmental Monitoring Station, http://www.cnemc.cn.

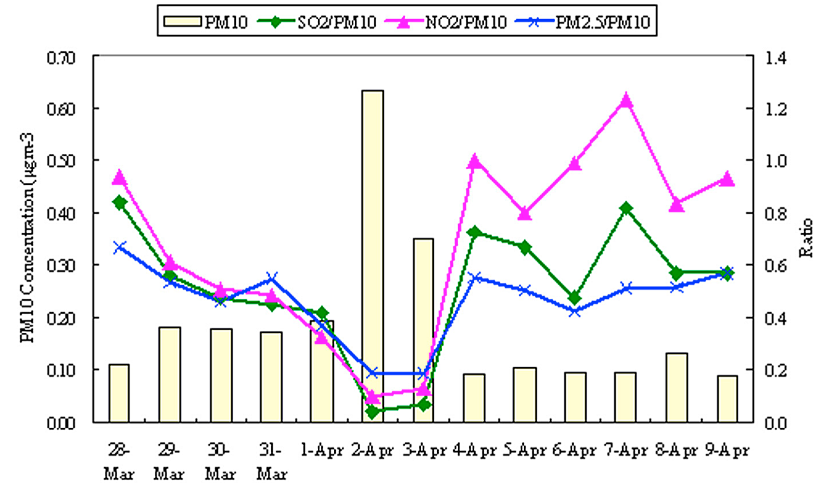

Figure 10. Ratios of gaseous pollutants and particulate matters during 28 March to 9 April 2007 in Shanghai.

Mongolia brought the dust to Shanghai through Hohehot, DL, Lianyungang, TS and East China Sea shown by the back trajectories. The ratio of Ca/Al and concentrations of PM_{10} at various sampling sites along the transport pathway of the dust were shown to be a useful tracer of the source region of dust that affects the Yangtze River Delta. Ca/Al ratio in SH, DL and TZ indicated the transport of crustal elements from DL to Shanghai, instead of the sources in TZ. In this specific dust event, concentrations of SSA in Shanghai were significantly increased both in $PM_{2.5}$ and TSP due to recirculated dust brought with sea salt aerosol from the ocean into Shanghai. The different variations of the SSA and MM ratios in $PM_{2.5}$ and TSP indicated the transport of dust from the ocean and a stronger impact on the $PM_{2.5}$ concentrations.

Table 4. Concentrations and Ratios of Three Major Parts in $PM_{2.5}$ and TSP in This Dust Episode in Shanghai[a]

Date	Concentration (μg m^{-3}) MM	SSA	IS	Ratio (%) MM	SSA	IS
		$PM_{2.5}$				
28 Mar 2007	10.7	1.5	7.5	13	2	9
29 Mar 2007	12.5	1.8	4.3	14	2	5
30 Mar 2007	10.8	1.6	8.5	12	2	9
31 Mar 2007	3.8	1.5	4.6	2	1	3
2 Apr 2007	269.0	10.9	20.1	70	3	5
3 Apr 2007	14.2	1.5	3.5	16	2	4
4 Apr 2007	14.9	1.3	4.3	18	2	5
5 Apr 2007	4.2	1.5	5.0	7	3	9
		TSP				
28 Mar 2007	55.0	2.2	11.6	37	2	8
29 Mar 2007	41.5	0.9	12.9	41	1	13
30 Mar 2007	28.8	2.3	11.9	27	2	11
31 Mar 2007	13.6	1.5	11.1	7	1	5
2 Apr 2007	858.1	19.9	69.0	64	1	5
3 Apr 2007	16.0	2.3	6.1	15	2	6
4 Apr 2007	21.3	2.2	9.2	23	2	10
5 Apr 2007	31.1	2.2	10.1	26	2	8

[a]The day 28 March 2007 was selected to be the representative nondust day before dust days. No sample was taken on 1 April in Shanghai due to the rainy day.

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