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Characterization of dustfall in rural and urban sites during three dust storms in northern China, 2010

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ABSTRACT

Dust transport and deposition processes are important for understanding the environmental risk of dust storms. This study investigated characteristics of dustfall at two rural sites and four urban sites from dust sources to downwind regions during three dust storms (DS1: March 19–22, DS2: April 24–26, DS3: May 7–10, 2010). Analysis of near-surface instantaneous maximum wind speed and prevailing wind direction revealed the dust storms bursted out from northwestern arid and semiarid regions to eastern China. Microaggregates, angular, subangular, columnar, subrounded, and spherical particles were identified by scanning electron microscope. Dust deposition flux (DDF) during the dust storms was significantly high at sites near sand deserts and sandy land. During DS2, DDF was 25.1, 9.9, 2.3, and 1.5 g m^{-2} in Jingbian, Shapotou, Lanzhou, and Beijing, respectively. The three dust storms contributed 7.3% of Beijing's annual dustfall in 2010, which suggests anthropogenic dust might contribute the majority of annual dustfall in urban areas. The mass medium diameter of dustfall during DS2 in Shapotou, Jingbian, Lanzhou, and Beijing was 26.1, 9.0, 16.4, and 15.5 μm, respectively. Urban dustfall contained more heavy metals, sulfur and arsenic than rural dustfall. Cadmium contamination was identified in all urban dust particles. Anthropogenic pollutants in combination with mineral dust might lead to complex environmental risk on local, regional, and global scales. China's environmental pollution control should integrate reductions in land desertification and multisource anthropogenic emissions within the context of climate change mitigation.

1. Introduction

Aeolian processes (the entrainment, transport, and deposition of sediment by wind) affect almost all aspects of the biosphere and have important consequences for landform evolution, biogeochemical cycles, human health, climate, and desertification (Tang et al., 2004; Arimoto et al., 2006; Goudie and Middleton, 2006; Field et al., 2010; Ravi et al., 2011). Dust emission, transportation and deposition are chain processes in dust storm events. The main sources of aeolian dust are sand deserts and cultivated land in arid or dry regions (Lim and Chun, 2006). In East Asia, dust storms generally break out from inland arid and semiarid regions, and then sweep southeastward across eastern populated areas of China. Annually, over 800 Tg of Asian mineral dust is relocated from desert sources (Zhang et al., 1997). The two dominant source regions of aeolian dust that influence the atmospheric environment over China are the Gobi Desert in Mongolia and northern China, and the Taklimakan Desert in western China (Sun et al., 2001). During 2000–2002, 70% of Asian dust storms that influenced China originated over the deserts in Mongolia and northern China and strengthened along the dust transportation route from northwest to southeast (Zhang and Gao, 2007). Asian mineral dust particles can be transported across China, Korea, Japan, the Pacific Ocean, Canada, and the United States by cold waves and westerlies before finally deposit in Arctic regions (Zhang et al., 1997). In the

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western Loess Plateau of northern China, observations revealed that dustfall in spring, summer, autumn, and winter accounts for 42%, 18%, 15%, and 25% of the annual dust flux, respectively (Zhang et al., 1996; Derbyshire et al., 1998). The dustfall peak in spring is consistent with the high frequency of dust storms and strong winds in the arid regions of China.

Dust deposition is related to suspended particles, and it is an indicator of the intensity of dust storms and air pollution. During dust storms, the concentrations of total suspended particles around the source regions are much higher than in downwind regions (Zhang et al., 2003). The dust deposition rate during dust storms is 10–25 times higher than the annual average in China's western Loess Plateau (Liu et al., 2004). The deposition of dustfall during an intense dust storm that occurred in Beijing on April 16–17, 2006 was 12.5–15.0 g m^{-2}, which accounted for 10% of Beijing's annual dustfall (Lue et al., 2010). It has been estimated that the total amount of deposition to the Yellow Sea from Asian dust storms was 17.9 Tg yr^{-1} from 2000 to 2002 (Zhang and Gao, 2007). The mass medium diameter (MMD) of dustfall in Dunhuang (near the dust sources) during a dust storm on May 30, 1996 was 25.4 μm (Zhang et al., 1998). The MMD of dustfall during a severe dust storm in Beijing in 2006 was 12.0 μm (Lue et al., 2010). The mean diameter of deposited dust particles collected near the east coast of China (1600 km downwind from the dust sources) during a dust storm on March 19–22, 2010 (DS1) was 1.5 μm (Niu et al., 2016). Dust particles larger than 10.0 μm deposited near the dust sources, while finer particles (<10 μm) can suspend for longer periods of time and thus, travel longer distances (Liu et al., 2004; McTainsh et al., 2005). Dust particles in Asian dust storms are generally sharp-edged, subangular, and subrounded in shape and contain mostly crustal elements such as Si, Fe, Ca, Mg, K, and Al (Ma et al., 2001; Lue et al., 2010). The concentrations of the major crustal elements in dust storm particles can be 30–58 times higher than particles during non-dust-storm days (Sun et al., 2004). Atmospheric particles constitute material from the soil surface as well as aerosol pollutants released by various anthropogenic activities. Seinfeld et al. (2004) found that mineral dust could be mixed with significant amounts of pollutants from biomass burning, and from fossil and biofuel combustion, even in dust source regions. It has been established that As and heavy metals (e.g., Cu, Cd, Pb, Zn, and Cr) are enriched in dust storm particles (Sun et al., 2004; Khuzestani and Souri, 2013). Furthermore, compared with coarse particles, fine particles contain relatively higher amounts of toxic pollutants (Tsai et al., 2012).

During spring 2010, the emission of dust in China was approximately 35% higher than during spring 2006 and twice that of the 44-year average of 1960–2003 (Tan et al., 2017). DS1 was a severe dust storm that affected a wide region of China (16 provinces), Japan, Korea, and North America. The dust source, aerosol optical depth, air pollution index, and spatial and temporal distributions of PM_{10} concentrations associated with DS1 have been studied (Li et al., 2011, 2012; Wang et al., 2011; Han et al., 2012; Cao et al., 2014). A dust storm that occurred on April 24–26, 2010 (DS2) had multiple large layers of Asian dust with horizontal scales of 2000–3000 km that reached North America and occupied the entire troposphere (Uno et al., 2011). This study considered DS1, DS2, and a third dust storm that occurred on May 7–10, 2010 (DS3). The near-surface instantaneous maximum wind speed and prevailing wind direction, dust micromorphology, dust deposition flux, particle size distribution, and elemental composition of dust particles were analyzed at two rural sites near sand deserts (i.e., the assumed sources of mineral dust) and at four urban sites with heavy smog pollution in northern China. The objectives were to investigate the magnitude of deposition along the dust trajectory, understand the mixing of mineral particles and anthropogenic pollutants, and provide implications for the complex environmental pollution problem in China.

2. Methods

Dust storms are aerodynamically caused by strong winds. To discuss the formation and development of DS1, DS2, and DS3, daily instantaneous maximum wind speeds (IMWS, one-second interval) and wind directions at 376 stations in northern China were collected from the Chinese Meteorological Administration to analyze the near-surface wind fields. The regional distribution of IMWS was mapped using ArcGIS. The IMWS was classified into five levels of wind speed: <7.2, 7.2–12.2, 12.2–17.2, 17.2–22.2, and 22.2–27.2 m s^{-1}, respectively. In China, an IMWS of $\geq$17.2 m s^{-1} is categorized meteorologically as a strong wind. The prevailing wind direction of a strong wind is that with the highest frequency. The nearest meteorological stations to each dustfall sampling site were within 3–30 km.

The locations of the sampling sites are shown in Fig. 1. The sampling sites in Shapotou and Jingbian are rural sites located on the edge of desert and sandy land. The Shapotou site is on the southeastern edge of the Tengger Desert in a semifixed sand dune field. The Jingbian site is in a fixed dune field on the southern edge of the Mu Us sandy land to the north of the Loess Plateau. The urban sites in Lanzhou, Beijing, and Shijiazhuang are on the tops of residential buildings in downtown areas. Dust samples on car roofs in a residential area of Jinan city were collected using a hairbrush.

Table 1 shows the method adopted for the collection of dust particles. Circular plastic vessels with flat bottoms were used to trap deposited dust. For the convenience of investigations of the micromorphology, particle size, dust deposition flux (DDF), and elemental composition, the dust was primarily collected in a dry state using fine hairbrushes. Dust samples were stored in polyethylene bags for later laboratory analyses. Prior to any analysis, the dust samples were dried at 105 °C in an oven for 24 h. The DDF (g m^{-2}), i.e., the weight of dustfall (W_D) in unit collecting area (S), was calculated using the following formula:

$$DDF = W_D/S \quad (1)$$

In Beijing, the daily dustfall both before and after the dust storms was collected to analyze the variations of DDF, and the monthly dustfall was collected to determine the annual DDF. Because of the long distances between the sampling sites, the dust traps were purchased locally; thus, they were not identical sizes. For consistency, the DDF data in Shapotou and Lanzhou was calibrated to a trap with 56-cm diameter and 25-cm depth. Observation in Beijing revealed that for traps with approximately the same depth, the DDFs observed by traps with diameters of 33 and 46 cm were 40% and 20% higher, respectively, than that of a

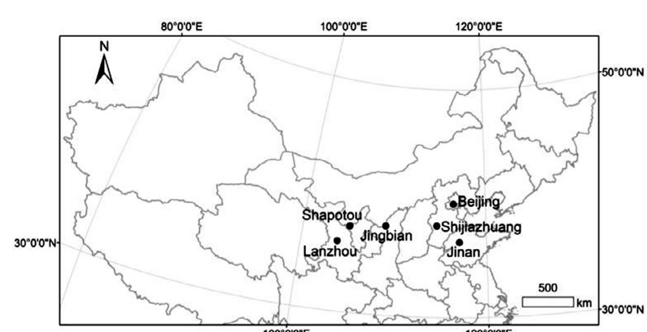

Fig. 1. The locations of the sampling sites.