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A multidisciplinary approach to trace Asian dust storms from source to sink

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HIGHLIGHTS

- A multidisciplinary approach can efficiently trace the source of Asian dust storms.
- Spring dust storms can be attributed to natural and anthropogenic origins.
- The northern Chinese deserts are the main sources for the natural dust storms.

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ABSTRACT

Tracing the source of dust storm (DS) in mega-cities of northern China currently suffers ambiguities from different approaches including source-sink proxy comparison, air mass back trajectory modeling, and satellite image monitoring. By integrating advantages of all three methods, we present a multidisciplinary approach to trace the provenance of dust fall in Xi'an during the spring season (March to May) of 2012. We collected daily dust fall to calculate dust flux variation, and detected eight DS events with remarkable high flux values based on meteorological comparison and extreme detection algorithm. By combining MODIS images and accompanying real-time air mass back trajectories, we attribute four of them as natural DS events and the other four as anthropogenic DS events, suggesting the importance of natural and anthropogenic processes in supplying long-range transported dust. The primary sources of these DS events were constrained to three possible areas, including the northern Chinese deserts, Taklimakan desert, and Gurbantunggut desert. Proxy comparisons based upon the quartz crystallinity index and oxygen isotope further confirmed the source-to-sink linkage between the natural DS events in Xi'an and the dust emissions from the northern Chinese deserts. The integration of geochemical and meteorological tracing approaches favors the dominant contribution of short-distance transportation of modern dust fall on the Chinese Loess Plateau. Our study shows that the multidisciplinary approach could permit a better source identification of modern dust and should be applied properly for tracing the provenance fluctuations of geological dust deposits.

1. Introduction

Dust storm (DS) is a disastrous natural phenomenon, which could bring serious damage to downwind human habitats, including causing soil degradation, breaking down industrial machineries, disrupting traffics, harming vegetation and crops, deteriorating air quality, and inducing acute respiratory diseases (Zhang et al., 2003a; Chen et al., 2004; Kan et al., 2007; Baddock et al., 2013). High dust loading in the air due to the DS events could also impact the solar radiation balance, cloud formation, secondary pollutant generation, and marine primary productivity, which have far more complex influence on the ecosystem (Zhuang et al., 1992; Zhang et al., 1994; Miller and Tegen, 1998; Jickells et al., 2005; Uno et al., 2009). Dust provenance studies in downwind mega-cities thus could provide critical information for government policy-making in DS damage control, and identify the parental material of the entrained dust for further assessment of its climatic, environmental and societal impacts. DS is also the primary dust

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transport mechanism in loess formation, which formed the Chinese Loess Plateau (CLP), the most valuable continental archive of past monsoonal climate (Liu, 1985; Zhang et al., 1997; An, 2000; Prins et al., 2007). Provenance studies of deposited "modern loess" (i.e., dust fall) are therefore critical to provide modern analogies on interpreting loess provenance.

Modern observation and modeling results had identified the Badain Juran and Tengger deserts (referred to as the northern Chinese deserts hereafter), Taklimakan desert, and Mongolian Gobi desert as the prime sources of modern dust in East Asia (Sun et al., 2001; Zhang et al., 2003b). Other areas including the Qaidam basin, Gurbantunggut desert, Mu Us desert, Hobq desert, and Horqin and Onqin Daga sandy lands were disputably considered as minor dust sources (Sun et al., 2001; Prospero et al., 2002; Zhang et al., 2003a,b; Shao et al., 2003; Qian et al., 2004; Laurent et al., 2006). To determine the sources of the dust deposits on the land and in the ocean, previous studies mainly followed the methodology of source-sink proxy comparison, including elemental ratios (Zhang et al., 1996; Lee et al., 2010b), rare earth elements (Lee et al., 2010a), mineralogy (Li et al., 2007), Nd–Sr isotopes (Chen et al., 2007; Lee et al., 2010a), U–Pb age spectrum (Stevens et al., 2010; Pullen et al., 2011; Xiao et al., 2012), Electronic Spin Resonance (ESR) signal intensity of the E_1' center and crystallinity index (CI) of quartz (Sun et al., 2007, 2013), and quartz oxygen isotope ($\delta^{18}O$) (Yan et al., 2014). These studies provided reasonable constraints on the dominant sources of aeolian deposits on the Chinese Loess Plateau, consistent with the meteorological and modeling evidence.

Proxy comparison, however, is often insufficient to make unambiguous identification of dust sources, since the potential sources may share similar geological and geochemical characteristics to a certain extent. For example, differentiating the dust of the Qaidam Basin from that of the northern Chinese deserts remains difficult by applying Nd–Sr isotopes (Chen et al., 2007) and quartz $\delta^{18}O$ (Yan et al., 2014). Similarly, mixing of dust from different sources may account for similar U–Pb age spectrums of zircon in Chinese loess deposits (Pullen et al., 2011; Che et al., 2013; Stevens et al., 2010). Alternatively, meteorological methods, including satellite images and air mass back trajectory modeling have been used to monitor the DS activities and dust transport routes, which could preclude irrelevant source candidates (e.g. Fang et al., 2004; Li et al., 2007; Yuan et al., 2008; Feng et al., 2008; Li et al., 2009; Lee et al., 2010a; Lee et al., 2010b; Tsai et al., 2014). To ascertain DS activities affecting certain sink areas, a robust source-to-sink linkage should be supported by satellite images that prove dust entrainments in the sources, air mass trajectories that pass through dust plumes in the sources and arrive at the sink, and similar physiochemical characteristics of the dust particles. Previously, only Lee et al. (2010a,b) tried to integrate these three methodologies to trace the provenance of local dust aerosols. The representativeness of daily air mass trajectories in the studies, however, fell short in constraining possible source candidates for the studied DS events.

In this study, we conduct a multidisciplinary investigation on the provenance of DS events occurring in Xi'an, southern Chinese Loess Plateau, in the spring of 2012. Our investigation is based on the three methodologies described above with a better representativeness of air movements by hourly back trajectory modeling. We collected daily dust fall, determined the flux variation time series, and identified eight DS events based on meteorological comparison and extreme detection algorithm. We discussed the transport routes of the spring DS events through air mass back trajectory modeling. Combining satellite images and accompanying real-time hourly air mass back trajectories, we separated the DS events into four natural and four anthropogenic DS events, analyzed the influences of natural dust sources and anthropogenic activities on them, and further constrained the dust sources of the four natural DS events to the Taklimakan desert, Gurbantunggut desert, and the northern Chinese deserts. Additional proxy comparisons, including quartz crystallinity index and oxygen isotope, confirmed the material linkage between the natural DS samples and the northern Chinese deserts, suggesting the northern Chinese deserts as the primary sources for natural DS events in Xi'an in the spring of 2012.

2. Sampling and methodology

2.1. Sampling daily dust fall in Xi'an

In this work, we adopted the wet collection method (Qian and Dong, 2004) to collect daily dust fall in Xi'an, which lies on the southern CLP, downwind to the well-known natural dust sources in East Asia (Fig. 1). The sampling site is situated at the southwestern part of Xi'an, which is surrounded by commercial and residential districts, and some manufacturing factories. To avoid fugitive dust from the ground, four glass dust collectors were placed adjacently 1 m above the roof of a four-storied building with bottoms covered by sufficient water during the sampling intervals. 86 dust samples were collected at 14 O'clock everyday from March 8 till June 1, 2012. No obvious dust pollution had been observed from surrounding districts during the whole sampling campaign.

Dust samples were sifted using a 100 mesh sieve to remove the fallen leaves and insects, dried at 40 °C, and then weighed. The daily dust flux was calculated using the following formula:

$$\text{Flux} = \text{weight}/(\text{area}*\text{time})$$

where weight is in gram, area is in m^2, and time is in day.

To analyze the relationship of dust deposition and meteorological factors, daily maximum wind speed and rainfall were acquired from the global weather profile dataset provided by the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). The CLIM-X-DETECT algorithm (Mudelsee, 2006), a robust time-dependent extreme detection method, was applied on the time series of the dust flux to discern the DS events.

2.2. Dust storm detection using MODIS images

Satellite image is the best choice for large-scale and long-term dust storm detection (Akhlaq et al., 2012). There are four most commonly used satellite imaging devices, i.e. MODIS (MODerate resolution Imaging Spectroradiometer), AVHRR (Advanced Very High Resolution Radiometer), GOES (Geostationary Operational Environmental Satellites), and SEVIRI (Spinning Enhanced Visible and Infrared Imager). Both GOES and SEVIRI provide 15-min temporal resolution with no less than 1000-m spatial resolution, while AVHRR provides 1-day and 1000-m resolutions. MODIS, however, provides a spatial resolution of 250–1000 m with the same 1-day temporal resolution. MODIS also provides global monitoring in 36 spectral bands, whose wavelengths range from 0.415 μm (visible) to 14.235 μm (infrared), while the others have no more than 12 spectral bands. Since the one-day temporal resolution is enough, we adopted MODIS because of its better spatial resolution and more information channels. All MODIS images were acquired from the Goddard Space Flight Center, NASA (http://ladsweb.nascom.nasa.gov), provided by the Earth Observing System Terra and Aqua satellites.

Robust extraction of DS coverage from infrared and/or visible bands using a variety of algorithms remains challengeable. In our test runs, we found that BTD_{11-12} (bright temperature difference between 11 and 12 μm bands, Ackerman, 1997), and TIIDI (thermal infrared integrated dust index, Liu and Liu, 2011) can not accurately