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Dustfall in China's western loess plateau as influenced by dust storm and haze events

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Abstract

Over a period of 12 h, the deposition rates of airborne dust during three dust storm and haze events in March and April 1999 at Lanzhou (36°N, 104°E) decreased successively from 0.43–2.23 $\mu g\,cm^{-2}\,min^{-1}$ in initial 2-h intervals to 0.05–0.08 $\mu g\,cm^{-2}\,min^{-1}$ in final intervals. Simultaneously, the mass median diameter of the falling dust decreased from 33.3–40.2 to 24.2–32.1 μm. The rate of dust deposition during dust storm and dust haze events was 10–25 times higher than the annual average (0.025 $\mu g\,cm^{-2}\,min^{-1}$), and a single dust storm or haze event contributed about 3% to the annual dust deposition flux ($1.33 \cdot 10^4\,\mu g\,cm^{-2}\,yr^{-1}$). However, particulate matter $<10\,\mu m$ (PM_{10}) in the deposited dust was normally below 10% by number frequency and <0.1% by weight, indicating that dust storm and haze events contributed little PM_{10} to silt accumulation on the western loess plateau. Most of the fine, PM_{10} particulates were transported further southeastward and exert more extensive impact on the atmospheric environment of the north hemisphere.

Keywords: Dustfall; Dust storm and dust haze; Loess Plateau; PM_{10}

1. Introduction

Since the geologist von Richthofen studied the origin of loess, there has been much research concerning the mode of the massive fine silt accumulation in China (Richthofen, 1882; Liu and Chang, 1962; Liu, 1965). The traditional aeolian-genesis hypothesis has been gradually confirmed by observations on the mechanism of loess accretion (Burbank and Li, 1985; Liu, 1985; Zhang et al., 1997). Historical 'Yutu' (Dust rain) and 'Chenmai' (Dust haze) have been repeatedly recorded in Chinese chorographies (Zhang, 1984). But consecutive and event-based observations on the dynamics of dust deposition in continental China are rare. Therefore, whether the loess was deposited largely during dust-storm events or, as is frequently assumed, by steady accumulation under normal atmospheric conditions, is still of great interest (Liu et al., 1981; Derbyshire et al., 1998; Chen et al., 1996).

Deposition of air-borne dust is dynamic and episodic due to variations in the frequency and magnitude of dust storm occurrences (Pye, 1987; Goudie, 1983). No earlier study has investigated dust deposition during sufficiently short intervals and over long periods to permit quantitative determination of the intra-event dynamics

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of particle size distribution and the mass contribution of a single dust storm or haze event to annual dust accumulation. We present here the results of 2-h-interval successive dustfall measurements during typical dust storm and haze events in March and April 1999, together with monthly dust deposition data that extended over a 2-year period, from May 1998 through April 2000, in Gaolan County, Lanzhou, Gansu Province. The observation site, at 36°13′N, 103°47′E, is located on the top of a loess hill about 10 km north of Lanzhou City, near a 330-m thick loess sequence (Burbank and Li, 1985). With 263 mm mean annual rainfall, this site experiences 7 strong-wind days and 11 dust storm and haze days per year (Li and Liu, 2003).

2. Methods

Dust samples were collected by the gravimetric method. During a dust storm and haze event, 10 plastic basins (68 cm diameter and 20 cm depth) were used to trap dust for each 2-h interval. The dust was collected in a dry state with fine hairbrushes. Three cylindrical glass vessels (15 cm diameter and 30 cm depth) with distilled water were set on a wooden trestle table 1.2 m high above the ground to trap monthly deposited dust. The weight of all dust samples was determined after oven drying at 105°C. Comparability of the two data sets was established through in situ comparative measurements.

Accompanied by intense Siberian/Mongolian cold fronts, dust storms in eastern Asia move out of the Gobi and sand desert regions of China along varied southeastward trajectories (Duce et al., 1980; Qiu et al., 2001; Sun, 2002). Aeolian dust settled out during dust-storm and haze events was used as a reference of dust fall associated with highly 'turbulent' atmospheric convection or impending dust pall, and the monthly dust fall data were used to estimate seasonal and annual dust accumulation under both 'turbulent convection' and normal steady atmospheric conditions. The rate of dust deposition is expressed as the mass of dust settled per unit area and unit time.

Particle size is an important indicator of physical properties associated with dust emission, transportation and deposition (Bagnold, 1941). Original particle size can hardly be obtained through conventional analysis methods due to the breakdown of the dust aggregates. In this study, SEM photographs of dry dust storm samples were taken at the Institute of Desert Research, Chinese Academy of Sciences (one such photograph is shown in Fig. 1), and the particle size parameters, were determined by measuring the long and the medium axes. The dimension of the dust particles, with median diameter normally larger than 3 μm, can be readily and reliably determined with photo processing methods. The mass medium diameter (MMD) was obtained through calculating the arithmetic mean of the medium axes of about 250 particles for each dust sample.

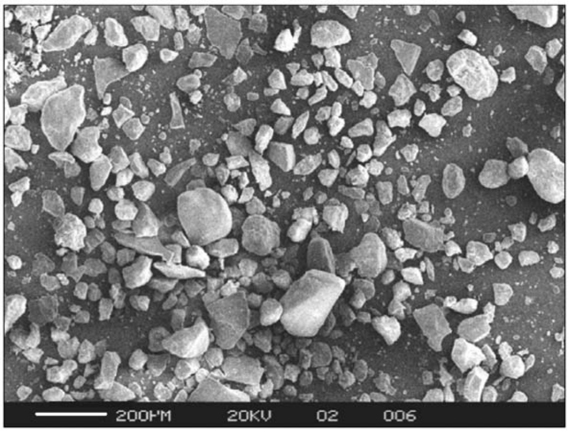

Fig. 1. Photomicrograph of a dust-storm dust sample at Lanzhou. The dust particles, angular and sub-rounded in shape, with 50–60% fine sand and 40–50% silt, are typical of the sandy loess in the northwest loess plateau.

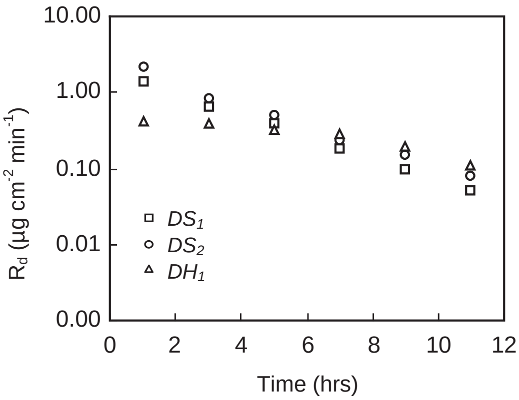

Fig. 2. Rate of dust deposition (R_d) at different 2-hour intervals during dust storm and haze events at Lanzhou. DS_1 was a dust storm on 7, March 1999, with maximum wind speed (10 m high above ground), $U_m = 15.8\,m\,s^{-1}$; DS_2 was another dust storm on 15, March 1999, $U_m = 18.2\,m\,s^{-1}$; and DH_1 was a dust haze event on 24, April 1999, $U_m = 2.1\,m\,s^{-1}$. The starting time 0 h, was chosen as the beginning of each dust storm or dust haze event. The deposition rate, for each 2-hour interval, was an average of 10 replicates.

3. Results and discussion

Fig. 2 presents the 2-h-interval dust deposition rates during dust storm and dust haze events. The rates of dust deposition during DS_1, DS_2, and DH_1, were 17, 25, and 10 times higher, on average respectively, than the long-term annual mean (as discussed below). Over twelve hours, dust deposition rates decreased monotonically from 1.43 to 0.05 $\mu g\,cm^{-2}\,min^{-1}$ during DS_1, from 2.23 to 0.08 $\mu g\,cm^{-2}\,min^{-1}$ during DS_2, and from 0.43 to 0.11 $\mu g\,cm^{-2}\,min^{-1}$ during DH_1. During the dust storm and haze events, the short-term dust deposition rates exhibited exponential decay

$$R_d = Ae^{-\lambda t} \quad R^2 = 0.90-0.99, \tag{1}$$

where A is the dust deposition rate at the initial interval of dust storm and haze events, and λ is the exponential decay constant characteristic for each dust-storm or haze event. The drastic decrease of dust deposition, which might be governed by dust concentration and particle size characteristics, has been rarely observed previously. In the dust samples, few black carbon and other components were observed. Nevertheless, we found the short-term decrease of dust deposition appears to be consistent with a similar decrease of soil erosion rate by wind due to rapid depletion of the erodible particles and aggregate armouring of the surface soil in the assumed source area (Chepil, 1950; Liu et al., 2003). Hence, the observed time-dependent behaviour of air-borne dust deposition ultimately may be controlled by the processes of dust emission in the source areas. Under strong wind conditions (with $\geqslant 17\,m\,s^{-1}$), the dust emission process from the source soil surface normally lasts from 0.5 to slightly more than 1 h (Chepil, 1950), while the dust deposition process in the loessial region and eastern China can usually persist from several hours to a few days. And the rate of dust emission could be higher, by two orders of magnitude, than the rate of dry dust deposition (Liu et al., 2003).

The observed MMD decreased from 35.8 to 28.6 μm during DS_1, from 40.2 to 32.1 μm during DS_2, and from 33.3 to 24.2 μm during DH_1 (Fig. 3). The decrease of MMD, against time, obeyed a linear decay correlation:

$$\mathrm{MMD} = -Ct + D_o \quad R^2 = 0.87-0.98, \tag{2}$$

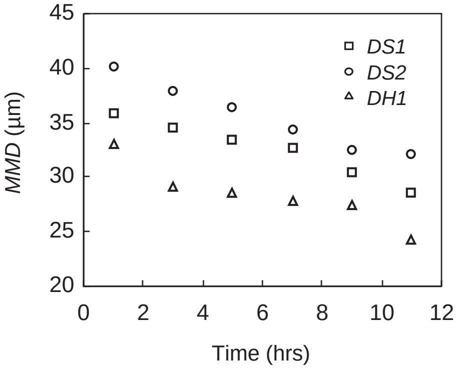

Fig. 3. The mass medium diameter (MMD) of settled dust at different intervals of dust storm and haze events at Lanzhou.

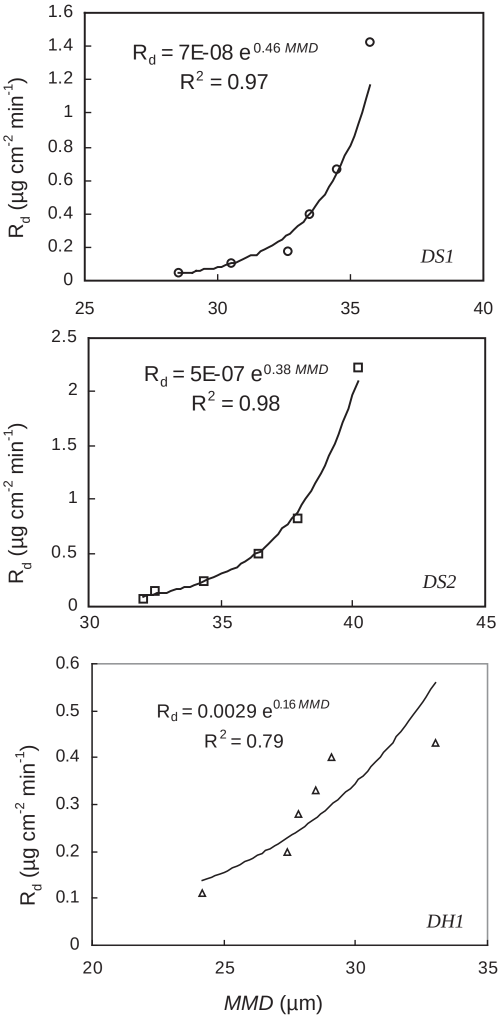

Fig. 4. The relationship between dust deposition rates and the mass medium diameter (MMD) of the settled dust at different intervals of dust storm and haze events at Lanzhou.

where D_o is the MMD at the initial interval of dust storm and haze events, and C is the linear decay constant. During each observation interval, the relationship between dust deposition rate and MMD could be written as

$$R_d = Ee^{\kappa \mathrm{MMD}}, \quad R^2 = 0.79-0.98, \tag{3}$$

where E is regression coefficient, and κ is an exponential constant (Fig. 4). Thus the dramatic decrease in dust deposition rate could be explained by the constant decrease in MMD on the basis of knowledge about the relationship between the particle size and corresponding terminal falling speeds (Bagnold, 1941). At Lanzhou, 80–90% of the settled dust was found in particles with diameters between 10 and 60 μm, and the MMD of the settled dust was 6–10 times larger than that of a dust event in Japan and 12 to 60 times larger than that in Enewetak of the tropical north Pacific (Duce et al.,

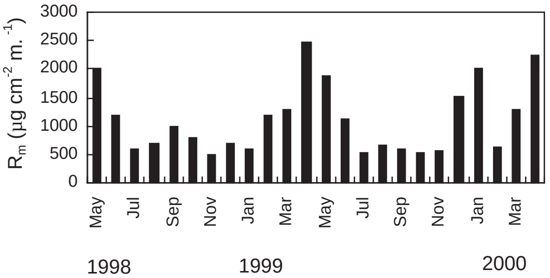

Fig. 5. Monthly rate of dustfall at different months over a 2-year period at Lanzhou.

1980). This was presumed to be due to Lanzhou being closer to the source area than Japan and Enewetak. The large dust particles associated with the exceptional dust deposition rate may hold implications for the mechanism of the massive accumulation of loess in China. In the samples of the observed dust events, particles with diameters $<10\,\mu$m were generally 6–10% by number frequency and 0.03–0.06% by weight, implying that dust storm and haze events contributed little PM_{10} to silt accumulation in the western loess plateau, and most of the finer particulates must have been transported further southeastward.

Our monthly dust observations through the two-year period yielded a cumulative annual average dust deposition rate of $1.33 \times 10^4\,\mu g\,cm^{-2}\,yr^{-1}$ (Fig. 5). This result is less than an earlier estimate of $2.4 \times 10^4\,\mu g\,cm^{-2}\,yr^{-1}$ based on dust fall during a single dust storm of April 1980 in Beijing (Liu et al., 1980). However, it is similar to the averaged annual dust rate of $1.2 \times 10^4\,\mu g\,cm^{-2}\,yr^{-1}$ at Lanzhou, from 1988 to 1991 (Derbyshire et al., 1998). The seasonal distribution of dust deposition, with 42% in spring, 18% in summer, 15% in autumn, and 25% in winter, supports the currently view that loessial dust accumulates on the loess plateau mainly in winter and spring (Zhang et al., 1994). The peaks in the spring season are consistent with the seasonality of dust storm activity and strong winds in the arid regions of China.

The cumulative dust deposition was $340\,\mu g\,cm^{-2}$ during DS_1, $480\,\mu g\,cm^{-2}$ during DS_2, and $210\,\mu g\,cm^{-2}$ during DH_1. This implies that DS_1, DS_2, and DH_1, contributed about 2.6%, 3.6%, and 1.6%, respectively, to the annual total flux. If these were typical dust storm and haze events, of which there are 11 per year on the average in the past two decades, dust fall during dust storm and haze events would be $3{,}800\,\mu g\,cm^{-2}$ on average, making up almost 30% of the annual total dust flux (Li and Liu, 2003). Because dust-fall samplers tend to underestimate catch in high wind speeds, the contribution of dust storm and haze events to annual dust flux in Lanzhou may be considerably underestimated (Hall et al., 1994).

4. Conclusions

This study observed a dynamic decreasing dust deposition phenomenon during dust storm and haze events, which was consistent with a similar decrease of soil erosion rate by wind from source soil surfaces. The deposition rate of airborne dust, however, was much less than the rate of dust emission from a soil surface, while the process of dust deposition was more persistent than the process of particulate entrainment by deflation. Dust storm and haze events contribute enormous amounts of large particles but quite little PM_{10} to western Loess Plateau. Most of the finer particulates are assumed to be transported further southeastward and exert a more extensive impact on the atmospheric environment of the north hemisphere.

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