

# The significance of Gobi desert surfaces for dust emissions in China: an experimental study

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**Abstract** A series of experiments to determine the direct emission of dust-sized particles from Gobi surfaces by clean wind (wind without sand), and the potential for aeolian abrasion of Gobi surfaces and beds of gravel and mobile sand to produce fine (<100  $\mu\text{m}$ ) and dust-sized (<10  $\mu\text{m}$ ,  $\text{PM}_{10}$ ) particles under sand-laden winds were conducted. Parent material was obtained from Gobi areas of the Ala Shan Plateau, the region with high dust emissions in arid China. The fine particles produced by aeolian processes were collected using sand traps and sieved the captured materials to exclude particles >100  $\mu\text{m}$  in diameter and then  $\text{PM}_{10}$  by sedimentation was acquired. The Gobi surface provided most of the emitted fine particles during the initial dust emission processes, but subsequently, release of the clay coatings of particles by abrasion becomes the dominant source of fine materials. Under sand-laden winds,  $\text{PM}_{10}$  production rates produced by aeolian abrasion of Gobi surfaces ranged between 0.002 and 0.244% of blown materials. After removal of sand, silt, or clay with low resistance to erosion from the Gobi surfaces by the wind, the  $\text{PM}_{10}$  production rates caused by aeolian abrasion were similar to those from gravel and sand beds. The results also indicated that after the dust-sized particles with low resistance to erosion were removed, the production of dust-sized particles was unrelated to wind

velocity. Under aeolian processes, Gobi deserts in this region therefore play a major role in dust emissions from arid and semiarid China.

**Keywords** Production of dust-sized particles · Aeolian abrasion · Gobi desert · Wind-tunnel experiment · China

## Introduction

Global dust emissions play a significant role in global climate cycles (Arimoto et al. 2006; Goudie and Middleton 2006), provide fine particles that participate in loess formation (Liu 1985; Pye 1987), and become part of deep-ocean sediments (Duce et al. 1980; Duce and Tindale 1991). Some dust components, such as iron, play a major role in regulating phytoplankton growth in the ocean (Bishop et al. 2002; Tsuda et al. 2003) and can affect nitrogen-fixing bacteria and the biomass-specific rate of photosynthesis, thereby modifying the global  $\text{CO}_2$  cycle (Petit et al. 1999; Jickells et al. 2005). As one of the world's primary potential dust source areas, the arid and semiarid regions of China and southern Mongolia also generate large quantities of mineral dust that is carried by winds over large areas of Asia and across the Pacific to North America (Husar et al. 2001; Sassen 2002) and even to the Arctic (Bory et al. 2002).

Based on an improved understanding of dust emission processes, many global dust emission models and simulations (e.g., Marticorena and Bergametti 1995; Mahowald and Luo 2003; Tegen et al. 2004) have been developed to simulate global and regional dust cycles. For instance, dust emission rates for a range of geomorphologic conditions have been estimated in arid and semiarid China and Mongolia using a model developed by the U.S.

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Environmental Protection Agency (e.g., Xuan and Sokolik 2002; Xuan et al. 2004). In addition, Laurent et al. (2005) used roughness lengths to predict the dust emission frequency in Chinese and Mongolian deserts. Shao and Dong (2006) reviewed the major modeling and simulation results for global dust emissions in detail. However, as has been the case in studies of Saharan dust, nearly all these determinations were for dust storms that did not originate in the major source areas (Goudie and Middleton 2001), and as a result of differences in study areas and methods, there have been significant differences in conclusions about the dust sources and emission quantities in arid and semiarid China and Mongolia.

In addition to arguments over the identities of potential dust source areas such as Gobi deserts, sandy deserts, alluvial fans, and degraded lands (Wang et al. 2006), there is debate over the key aeolian dust emission processes, such as suspension, creep, saltation, and reptation of particles (Shao and Raupach 1993; Livingstone and Warren 1996), which lead to transport of fine particles (usually defined as  $<100\ \mu\text{m}$ ; very fine sand in the Soil Science Society of America size scale) at regional or global scales. The formation of these fines during aeolian and other geomorphologic processes was discussed by Whalley et al. (1987), Wright et al. (1998), and Wright (2001), and the definitions and characteristics of these processes, and their roles in producing dust-sized particles (usually  $<10\ \mu\text{m}$ ,  $\text{PM}_{10}$ ) through aeolian abrasion, have been reviewed in detail by Bullard et al. (2004, 2007) and Bullard and White (2005). The elaborate experiments of Bullard et al. have shown that in dunefields, the clay coatings on the grain surfaces of the natural dune sands serve as one of the main sources of  $\text{PM}_{10}$  (Bullard and White 2005). However, there have been few experiments to quantify emissions of Chinese dust: determinations have instead been obtained through analyses of mineral compositions (e.g., Sun et al. 2000), of aerosols (e.g., Zhang et al. 2003), of particle size distributions (e.g., Wang et al. 2005), of remote sensing data (e.g., Zou and Zhai 2004), of dust storm frequency (e.g., Zhou and Zhang 2003; Wang et al. 2006), and of the geomorphologic setting (e.g., Wang et al. 2008).

In regions of China and southern Mongolia with high dust emissions, Gobi deserts, sand sheets, and wadis are usually interlaced, which complicates the task of determining which component of the geomorphologic setting in the region is most responsible for dust emissions. Although some research has highlighted the importance of playas as dust sources (e.g., Prospero et al. 2002), these are not always the most significant contributors to dust emissions because of their resistance to wind erosion (Rice and McEwan 2001; Argaman et al. 2006), which can be created by the development of surface biological and salt crusts (e.g., Houser and Nickling 2001; Hu et al. 2002). Several

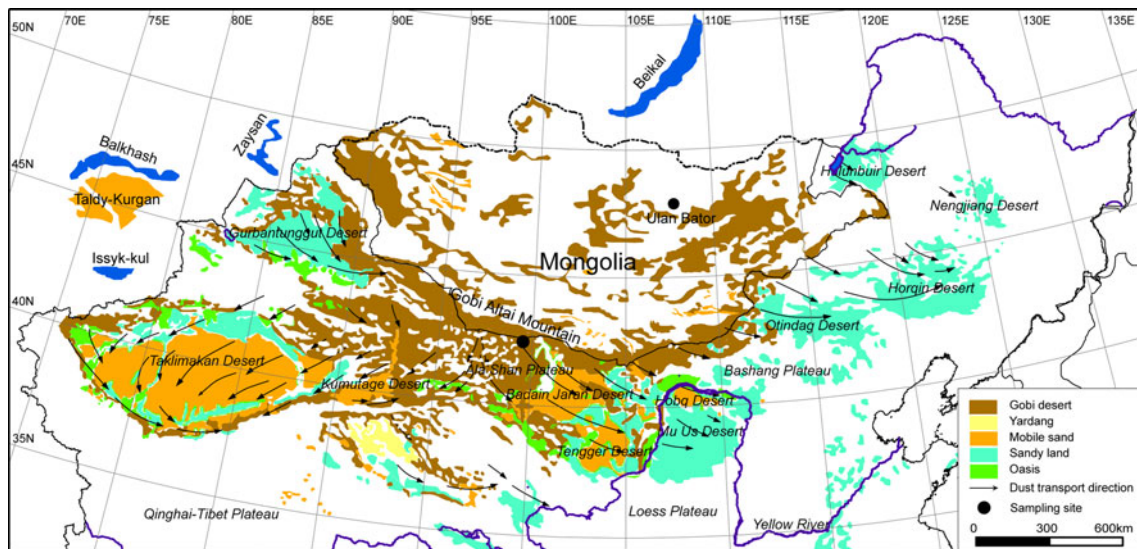
recent studies have suggested a wider range of dust sources, such as sand dunes and floodplains (Bullard et al. 2008; Lee et al. 2009). This suggests that within regions of interlaced geomorphologic types, it is important to study the relative contributions of the different types to dust emissions. Especially in arid and semiarid China, the quantities of dust emissions from Gobi desert and from other aeolian processes such as abrasion are still poorly understood.

All of these factors can clearly affect the accuracy of simulations of Chinese and Mongolian dust production and, consequently, of global dust cycles. Therefore, in this study, field sampling combined with wind-tunnel and particle-separation experiments was performed to quantify dust emissions from Gobi surfaces, to determine the rates of production of dust-sized particles by aeolian processes (especially abrasion), and to determine their significance for dust emission rates in the potential dust source areas of arid and semiarid China. These experiments may increase understanding of dust sources, provide a stronger basis for improving global dust models and assessing the effects of climate change on future dust emissions, and facilitate the interpretation of paleoclimate records based on the dust contained in ocean and lake sediments and ice cores (Prospero et al. 2002) where these sediments have been affected by Chinese and Mongolian dust.

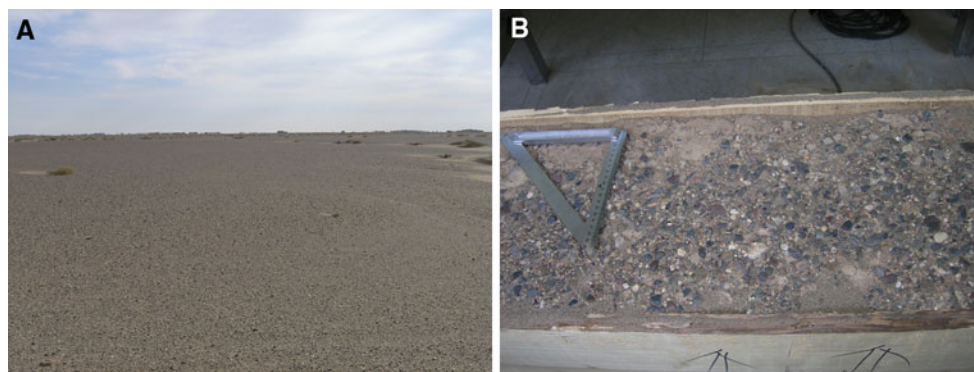
## Methodology

### Study area and sample collection

The sampling site was located in the Ala Shan Plateau ( $40^{\circ}18'N$ ,  $101^{\circ}8'E$ ; Fig. 1), an arid area of China with high dust emissions. The regional environment was described by Wang et al. (2005), and the characteristics of aerosols that originate in this region have been discussed in many previous studies (e.g., Mori et al. 2002; Kim et al. 2003). Extensive areas of Gobi desert cover most of the Plateau, although there are also scattered areas of mobile sands, wadis, and deteriorated farm fields that account for about 10% of the area. The Gobi surfaces in this region can be defined as “exposed surfaces comprising intricate mosaics of coarse particles, set on or in deposits of sand, silt or clay” (Cooke 1970); they have been given this name because they are adjacent to the Gobi Altai Mountains, which enrich the Gobi surfaces with fine particles that are carried into the Gobi deserts by intermittent floods that carry away particles created in the mountains by physical and chemical weathering processes. On the Gobi surfaces, the sizes of the clasts range between 1 and 20 mm, and their cover usually varies between 50 and 80%; gaps between the clasts are filled by silts and clays. Under the



**Fig. 1** Sampling location in this study, and the dominant dust transport directions in arid and semiarid China



**Fig. 2** Geomorphologic settings of the sampling sites: **a** overall view of the Gobi desert at the sampling site and scattered patches of mobile sands. **b** Close-up view of the Gobi surface after erosion by sand-laden wind

Gobi surfaces, there are interlaced layers of silts and gravels. However, due to high sand transport rates and the effects of the geomorphologic setting, scattered mobile sand sheets are also found on the Gobi surfaces, and these areas also produce dust-sized particles for potential emission as a result of aeolian processes.

Although all Gobi surfaces are covered by gravels interlaced with sand, silt, and clay particles, the surfaces differ as a result of variations in the contents of fine materials, in the arrays and roundness of the gravels, and in the solidity of the surface (i.e., the cohesion between the gravels and the fine materials). Because of the difficulties of quantitative analysis of surface differences during fieldwork, five undisturbed samples of the Gobi surfaces at the sampling site were obtained (Fig. 2) using 120 × 30 × 30 cm sample boxes, and these samples were brought to laboratory for further analysis. The intervals between samples were from 100 to 200 m and were decided based on differences in the gravel cover of the Gobi

surfaces (i.e., samples that covered a wide range of gravel abundance were obtained). Approximate visual estimates and photos suggested that for the five Gobi surface samples the gravel cover ranged from 50 to 80%. After selecting sampling sites, undisturbed samples of the Gobi surface were extracted as follows: the sample box was placed on the surface, the soils around the sampling sites removed, and then excavated downward for about 80 cm without disturbing the sampling faces. A sheet was then inserted horizontally below the box to serve as the bottom of the box. The box was then covered, and to ensure that its contents did not change during transportation, steel wires were used to wrap the box.

In addition to sampling of the Gobi surfaces, a total of about 500 kg of gravels and 1,000 kg of mobile sands were also collected. These samples were used in the wind-tunnel experiments described in section “Wind-tunnel experiments”. In this region, there are significant variations in the mineral contents and particle size distributions of surface

samples. The results of analysis showed that the major minerals within the mobile sands included quartz (20–45%), plagioclase (<0.3–35%), silica-rock debris (2–25%), and quartzite debris (3–15%); the fractions <100  $\mu\text{m}$  in diameter within the mobile sands varied between 0.2 and 4% of the total, versus a range of between 3 and 38% in the Gobi samples. Before experiments, the gravels and mobile sands used in the wind tunnel experiments to remove fractions <100  $\mu\text{m}$  in diameter were sieved so that these fractions would not affect the amount of dust-sized particles produced during the abrasion experiments.

### Wind-tunnel experiments

Wind-tunnel experiments were carried out at the Key Laboratory of Desert and Desertification, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences. The sizes and operation of the wind tunnel have been described in several previous papers (e.g., Dong et al. 2003), and the design of the experiment is illustrated in Fig. 3. Two sets of experiments were carried out: the first used the natural (undisturbed) Gobi surfaces, and the second used the sieved sands and gravels. Each series of experiments under two conditions were carried out: clean wind (wind without sand) and sand-laden wind. The aims of this experimental design were to understand the dust emission rates from natural Gobi surfaces under both wind environments (experiment 1), and the amounts of dust emission caused by abrasion of the gravels by blowing sand and of particles within the cloud of blowing sand (experiment 2). For each of the undisturbed Gobi surface samples, the sample in the working section of the wind tunnel, with the surface at the same level as the bottom of the wind tunnel was positioned, then fixed it in place. At a distance of 30 cm downwind from the sample, a sand trap 30 cm wide (i.e., the same width as the surface samples) by 30 cm tall to collect the windblown particles was installed. After

completing the wind-tunnel experiments for all five Gobi surface samples, a similar approach to study 1.5-m lengths of the sieved gravels and mobile sands (with all particles <100  $\mu\text{m}$  removed) was placed in a bed so that their surface was level with the bottom of the wind tunnel.

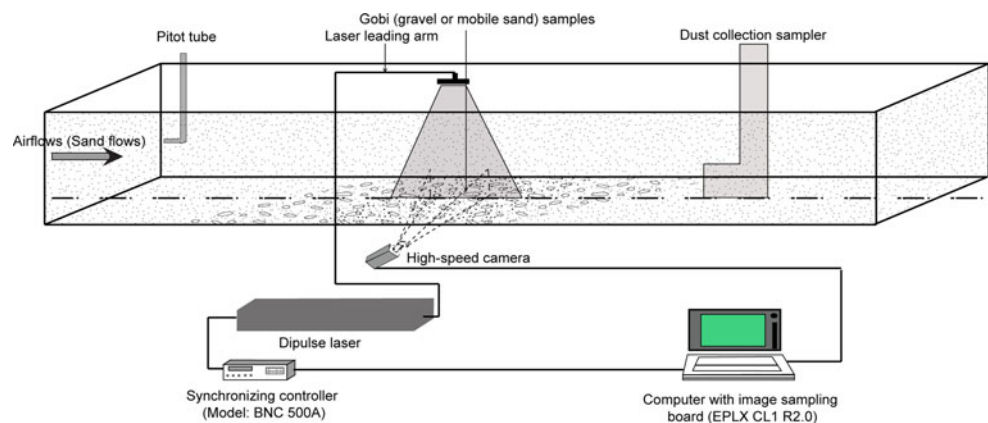
To simulate dust emission processes under natural conditions, the experiments were started with a wind velocity of 8  $\text{m s}^{-1}$  and then progressively increased the velocity to 22  $\text{m s}^{-1}$  at increments of 2  $\text{m s}^{-1}$ . The same surface sample for each new wind velocity was used. However, due to the experimental process and the sample conditions, data for certain wind speeds in certain trials could not be obtained. First, clean wind was used to determine the direct emission rates of dust-sized particles ( $\text{PM}_{10}$ ) from the undisturbed Gobi surfaces and then sand-laden winds above the Gobi surfaces and the beds of sieved gravel and mobile sand were used to determine the characteristics of the dust-sized particles generated by abrasion.

During the experiments, a high-speed camera connected to a synchronizing controller and a computer with an image-sampling board to monitor the aeolian processes was used. The duration of the experiment using clean wind depended mainly on the results of monitoring of particle motion. For each wind velocity, the sampling was stopped when there was no more particle motion visible on the computer screen, and then the samples collected within the sand trap were retrieved for further analysis. Under the sand-laden wind, the duration depended mainly on the wind velocity, the sediment supply, and the capacity of the sand trap. The resulting durations ranged from 1 to 10 min.

### Sample treatment and analysis

After all the wind-tunnel experiments were finished, the samples collected by the sand trap were used for further analysis. Before the wind tunnel experiments, the fractions <100  $\mu\text{m}$  in diameter were removed from the gravel and sand samples by sieving; therefore, these fractions within the collected samples originated entirely from the aeolian

**Fig. 3** Schematic diagram of the wind tunnel and particle image velocimetry apparatus used in the dust emission experiments



**Table 1** The proportion of total sediments with a diameter <100 μm trapped under a clean wind for the Gobi surface samples

Wind velocity (m s <sup>-1</sup> )	Content (% by weight)				
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
8	92.713	25.627	25.661	6.865	13.287
10	–	24.538	21.700	16.224	17.353
12	25.006	21.401	20.988	20.983	17.454
16	24.589	25.947	26.888	26.102	26.328
20	24.291	28.060	29.020	30.941	29.296
22	25.124	26.382	26.433	25.447	25.246

Short line within the table indicates the data were absent

**Table 2** The proportion of total sediments with a diameter <10 μm trapped under a clean wind for the Gobi surface samples

Wind velocity (m s <sup>-1</sup> )	Content (% by weight)				
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
8	4.604	0.107	0.409	0.115	0.149
10	–	0.221	0.225	0.359	0.217
12	0.307	0.231	0.207	0.527	0.193
16	0.266	0.275	0.189	1.608	0.149
20	0.297	0.209	0.225	1.756	0.196
22	0.303	0.367	0.401	0.659	0.271

Short line within the table indicates the data was absent

processes. During the wind-tunnel experiments, the total weight of the collected samples ranged between 0.92 and 10,319.48 g (with wind erosion rates ranging between 0.65 and 7,447.90 g/min.); the value was determined by the surface type and the wind conditions during the experiments (clean or sand-laden winds). First, the collected samples were sieved to determine the fractions ≥100 μm and <100 μm, which were weighed using a balance with a precision of 1%. Second, the fraction <10 μm was separated from the fraction <100 μm by means of sedimentation in deionized water, then dried, and its weight was measured. This analysis allowed us to calculate the rates of production (by weight) of dust-sized particles (the <100 and <10 μm fractions). Third, 37% HCl solution was used to check the mineral composition (i.e., acid-soluble vs. acid-insoluble minerals) of the fraction <10 μm after the abrasion experiments were finished. Finally, scanning electron microscope (SEM) micrograph analyses were carried out at the Key Laboratory of Desert and Desertification, Chinese Academy of Sciences, to measure the shapes and morphology of the particles.

**Results**

Rate of production of dust-sized particles under a clean wind

Under the clean wind at 8 m s<sup>-1</sup>, the <100 μm fraction emitted from Gobi surfaces accounted for 6.865–92.713% of

the total blown materials for that wind speed, with a mean of 32.831% (Table 1). However, this fraction changed to between 16.224 and 24.538% (with a mean of 19.954%) under the 10 m s<sup>-1</sup> clean wind. The variation among the five Gobi surfaces decreased as wind velocities increased during the subsequent experiments, with the rates of production of the <100 μm fraction ranging between 17.454 and 30.941% under wind velocities of 12–22 m s<sup>-1</sup>. In addition, the <10 μm fraction accounted for 0.409–4.604% of the total under a clean wind at 8 m s<sup>-1</sup>; as the wind velocity increased, it varied between 0.200 and 1.800% (Table 2).

The emission rates of the <10 μm fraction from the five Gobi surface samples were not always consistent with the wind velocity (Table 2), even though the average results were positively correlated with wind speed. One of the major reasons is the variation in gravel cover among the Gobi surfaces (ranging from 50 to 80%), which resulted in differences in the sand, clay, and silt contents, in gaps between the gravels, in the characteristics of the gravel arrays, and in the resistance of the surface to wind erosion. In addition, turbulence differences due to differences in the spacing and burial depth of the gravels may also have played a major role in determining the emission rates from the five samples. Limitations on the supply of fine materials may be the major control, since that explanation would be consistent with field observations: in the Gobi desert of the Ala Shan Plateau, where the highest aerosol concentration always appeared during the initial period of a dust outbreak, and as limitations on the availability of fine particles increased, the aerosol concentration decreased.

### Rates of production of dust-sized particles under a sand-laden wind

After completing the experiments under a clean wind, sand-laden winds were used to test dust emission from the Gobi surfaces and from the gravel and sand beds. Because the previous experiments had removed most of the sands, silts, and clays with low resistance to wind erosion from the Gobi surfaces, most of the dust-sized particles produced at this stage were produced by aeolian processes such as abrasion.

During the initial stage (i.e., under the  $8 \text{ m s}^{-1}$  wind), the rates of production of dust-sized particles were higher than those that occurred under higher wind velocities (Table 3). For instance, at a wind velocity of  $8 \text{ m s}^{-1}$ , the rates of production of the  $<100 \mu\text{m}$  fraction for the five Gobi samples ranged between 1.056 and 1.925% of the total blown materials, but accounted for 3.418% for the gravel bed. In subsequent experiments (with wind velocity increasing from 10 to  $20 \text{ m s}^{-1}$ ), the concentrations varied between 0.232 and 1.146%. Similar to the pattern for the  $<100 \mu\text{m}$  fraction, the  $<10 \mu\text{m}$  fraction was highest under the  $8 \text{ m s}^{-1}$  wind velocity, and accounted for

0.007–0.244% of the total for the Gobi surface samples, versus 0.033% for the gravel bed. At higher wind velocities, it varied between 0.002 and 0.009% for the Gobi samples and between 0.020 and 0.030% for the gravel beds (Table 4). In addition, under sand-laden winds, the rates of production of the  $<10 \mu\text{m}$  fraction differed significantly between the Gobi samples and the gravel beds. As the wind velocity increased from 10 to  $20 \text{ m s}^{-1}$ , the rates of production of the  $<10 \mu\text{m}$  fraction from the Gobi surfaces ranged between 0.002 and 0.009%, versus a range of 0.002–0.003% from the gravel beds. These results suggest that at least part of this fraction is an original  $<10 \mu\text{m}$  fraction that is present on the Gobi surfaces and that is only entrained by the wind rather than being produced by abrasion of the clay coatings of particles.

Under a sand-laden wind, results showed that rates of production of the  $<100$  and  $<10 \mu\text{m}$  fractions from the sand beds ranged between 0.388 and 0.592% of the total and between 0.001 and 0.004% of the total, respectively. The results also showed that in addition to abrasion between blowing particles and the gravels and sands, aeolian abrasion among the blowing particles played a potentially significant role in the production of dust-sized

**Table 3** The proportion of total sediments with a diameter  $<100 \mu\text{m}$  trapped under a sand-laden wind for the Gobi surface samples and for the sand and gravel beds

Wind velocity ( $\text{m s}^{-1}$ )	Content (% by weight)						
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Gravel bed	Sand bed
8	1.668	1.056	1.925	1.902	1.062	3.418	–
10	0.684	0.782	0.340	0.505	0.519	0.353	0.388
12	0.611	0.626	0.263	0.460	0.427	0.425	–
14	1.146	0.441	0.269	0.442	0.309	0.487	–
16	0.724	0.611	0.357	0.424	0.605	0.359	–
18	0.542	0.849	0.351	0.435	0.363	0.657	–
20	0.232	0.886	0.337	0.638	0.425	–	0.592

Short lines within the table indicate the data were absent

**Table 4** The proportion of total sediments with a diameter  $<10 \mu\text{m}$  trapped under a sand-laden wind for the Gobi surface samples and for the sand and gravel beds

Wind velocity ( $\text{m s}^{-1}$ )	Content (% by weight)						
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Gravel bed	Sand bed
8	0.007	0.011	0.244	0.028	0.023	0.033	–
10	0.004	0.009	0.004	0.005	0.004	0.002	0.002
12	0.002	0.003	0.003	0.005	0.004	0.002	–
14	0.004	0.003	0.002	0.005	0.003	0.002	–
16	0.003	0.003	0.003	0.004	0.003	0.002	–
18	0.004	0.003	0.003	0.006	0.003	0.003	–
20	0.002	0.004	0.002	0.006	0.003	–	0.002

Short lines within the table indicate the data were absent

**Table 5** Mean rates of production of dust-sized particles by aeolian processes

Fraction ( $\mu\text{m}$ )	Rate of production (% by weight) at a wind velocity ( $\text{m s}^{-1}$ ) of										
	8	10	12	14	16	18	20	22			
Gobi surface, clean wind	32.831 (34.443)	19.954 (3.862)	21.167 (2.676)	-	25.971 (0.851)	-	28.322 (2.480)	25.7270 (0.632)			
	1.077 (1.975)	0.256 (0.069)	0.293 (0.138)		0.497 (0.623)		0.537 (0.683)	0.400 (0.153)			
Gobi surface, sand-laden wind	1.523 (0.435)	0.566 (0.172)	0.478 (0.149)	0.521 (0.358)	0.544 (0.150)	0.508 (0.205)	0.503 (0.261)	-			
	0.063 (0.102)	0.005 (0.002)	0.004 (0.001)	0.003 (0.001)	0.003 (0.001)	0.004 (0.001)	0.003 (0.001)				
Gravel bed	3.418	0.353	0.425	0.487	0.359	0.657	-				
	0.033	0.002	0.002	0.002	0.002	0.003					
Sand bed	-	0.388	-	-	-	-	0.592				
		0.002					0.002				

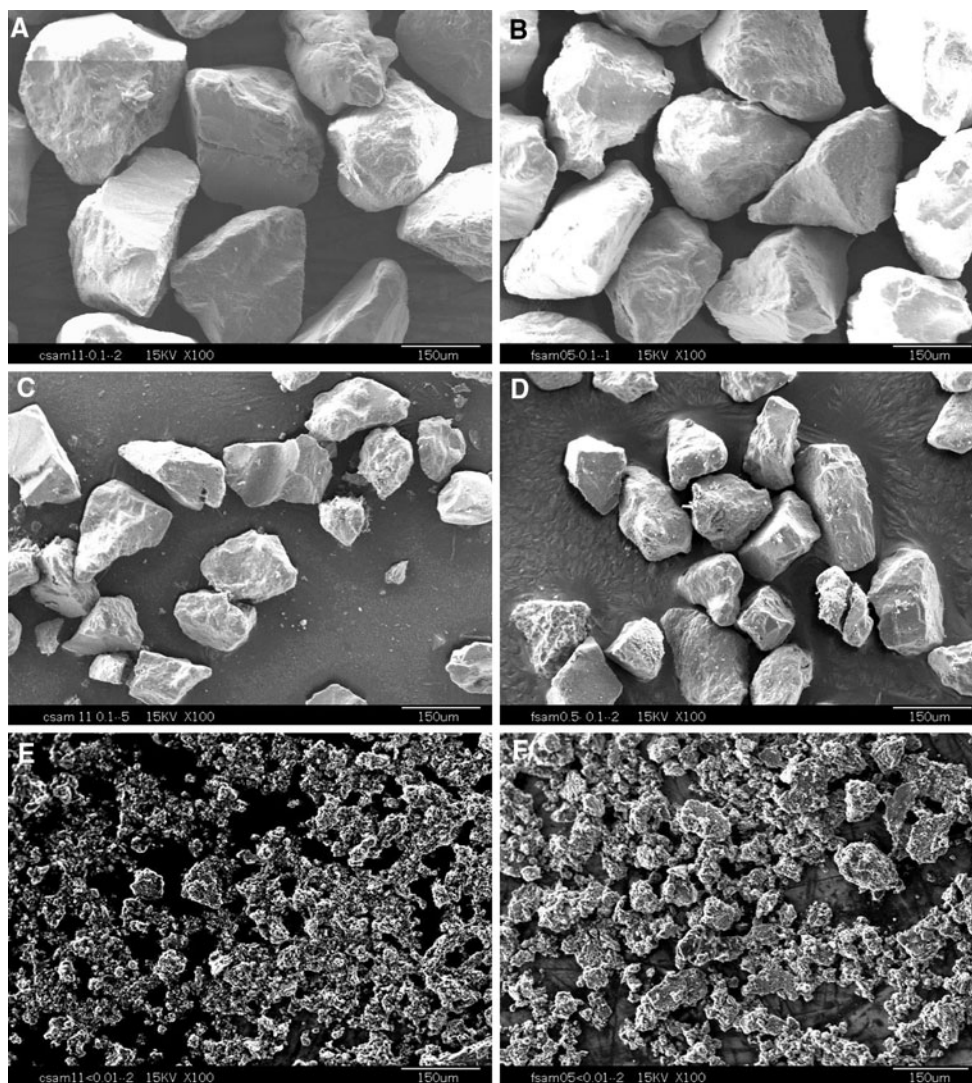
The results for the Gobi surface represents the mean of five samples, and values within brackets are the standard deviation. Short lines within the table indicate the data were absent

particles. In addition, the mean results for the five Gobi samples show that under a sand-laden wind, the rates of production of dust-sized particle are not closely related to wind velocity even after the dust-sized particles with low resistance to erosion have been removed by the wind (Table 5). This shows that the rates of production of dust-sized particles appear to be controlled by many factors and that the wind velocity is only one of the factors that control abrasion rates during aeolian processes.

SEM micrographs and particle size distributions

The coatings of particles, which include desert varnish, are mostly composed of clay minerals, and are ubiquitous on rock and gravel surfaces in dry regions (Potter and Rossman 1977). The SEM micrographs show significant differences in the fine and dust-sized particles produced by the abrasion experiments (Fig. 4). There were evident fractures and impact craters on the surfaces of the particles <100  $\mu\text{m}$  in diameter, and some even crumbled (Fig. 4a) as a result of the aeolian abrasion. The high clay content within the <10  $\mu\text{m}$  fraction made the SEM analysis difficult because of high adhesion among the particles (Fig. 4c, d). This provides additional evidence that the <10  $\mu\text{m}$  fraction mainly came from the clay coatings. For example, because most of the large particles were quartz, which is highly resistant to abrasion, few quartz particles within the <10  $\mu\text{m}$  fraction were found after treatment with the 37% HCl solution. These results show that although there may have been other sources, most of the <10  $\mu\text{m}$  fraction was produced from the clay coatings deposited on the larger particles, and very little resulted directly from impacts on the main body of the larger particles during the abrasion experiments. In the Ala Shan Plateau, the clay coatings produced by abrasion of gravels and sands enriched the dust component of the emissions during the initial aeolian processes, as was described by Bullard et al. (2007). In addition, experiments showed that clean winds have a relatively minor effect on the clay coatings of particles in this region (i.e., these coatings were still present after the wind tunnel tests with the clean wind). Under a sand-laden wind, the hardness of the gravels and sand particles reduced the amount of subsequent abrasion and therefore resulted in decreased dust emission.

There were also significant differences in the particle size distributions of the fine particles after the aeolian abrasion experiments. Because many factors affect the particle size distributions, and because of limitations on the number of collected samples and the treatment processes, only the results acquired under a single wind velocity of 16  $\text{m s}^{-1}$  for Sample 3 have been compared (Table 6). The results show that under the sand-laden wind, the contents of the fine particles (<100  $\mu\text{m}$ ) were significantly higher than



**Fig. 4** SEM micrographs showing the shapes of the particles <100  $\mu\text{m}$ , and <10  $\mu\text{m}$  in diameter after the abrasion experiments were finished (**a** and **c** are from the gravel bed, and **b** and **d** are from

sample 3 of the Gobi surface, respectively). **a**, **b** fractions <100  $\mu\text{m}$ , and **c**, **d** fractions <10  $\mu\text{m}$ , acquired after the abrasion experiments under sand-laden winds

**Table 6** Particle size distributions (% of total number of particles, measured using the SEM, with size values representing the largest axis of the particles) of fine particles collected in the dust sampler after abrasion and related aeolian processes (16  $\text{m s}^{-1}$  winds; A, under a clean wind; B, under a sand-laden wind)

Particle size ( $\mu\text{m}$ )	Proportion of total (%)											
	<50	50–60	60–70	70–80	80–90	90–100	100–110	110–120	120–130	130–140	140–150	>150
Sample 3 (A)	0.00	0.00	0.00	0.63	0.63	3.77	5.03	5.66	11.32	9.43	12.58	50.94
Sample 3 (B)	2.82	4.23	5.63	5.63	1.41	2.82	4.23	4.23	4.23	2.82	5.63	56.34
Gravel bed	0.00	0.00	0.00	0.00	1.56	1.56	3.13	0.00	3.13	9.38	14.06	67.19

those acquired under the clean wind. In addition, these values were also higher than those for the gravel bed. The results show that most of the fine and dust-sized particles collected above Gobi surfaces are produced from silts in and on the Gobi surfaces during aeolian processes.

## Discussion

In the Ala Shan Plateau, the results of aerosol monitoring suggest that the highest rate of dust emission usually occurs during the initial stages of a dust outbreak (e.g., Mori et al.



2002), and this has been confirmed by field investigations in this region. However, as the particles with low resistance to wind erosion become depleted, direct emissions from the Gobi surfaces decrease due to source limitations (Macpherson et al. 2008), and these surfaces may not provide enough dust-sized particles to produce large and sustained dust emissions. Instead, under sand-laden winds, the dust-sized particles produced by aeolian processes such as abrasion of surface particles and among blowing particles become the major sources of dust emissions. In addition, the five Gobi surface samples analyzed in the present study showed marked differences in the rates of production of dust-sized particles due to differences in the gravel cover of the surfaces, which determined the characteristics of the particle arrays, the contents of fine particles at the surface, and other properties of the surfaces, even though these samples were obtained from adjacent sites and tested under the same wind conditions. Because the Gobi surface characteristics did not be precisely characterized in present study, it will be necessary to obtain more data on these characteristics in future research.

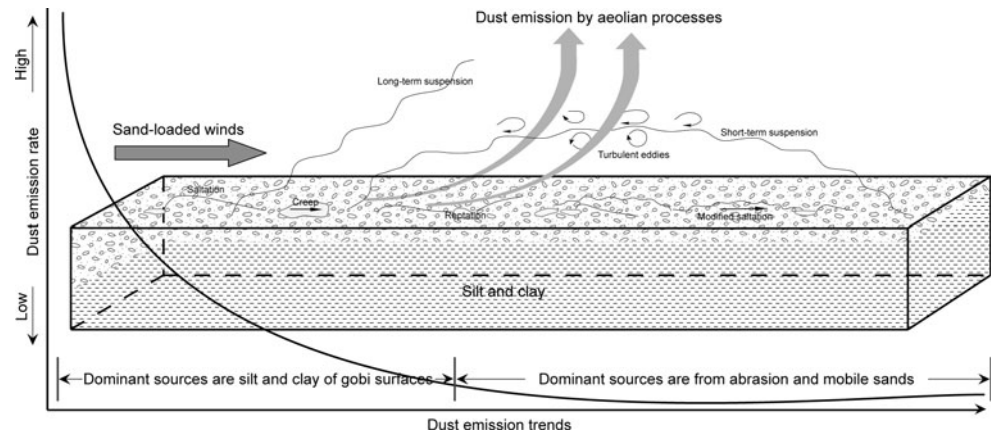
After the dust-sized particles with low resistance to erosion were removed by the wind, aeolian processes such as abrasion played a major role in subsequent dust emissions. The factors that affect this variation include the array of gravels, their roundness, the geomorphologic setting, atmospheric circulation, vegetation cover (Macpherson et al. 2008; Wang et al. 2008), and the formation of a clay coating on the particle surfaces. For instance, the abrasion experiments of Bullard et al. (2004, 2007) suggested that removal of the surface coatings of the particles is the main source of fine material  $<10\ \mu\text{m}$ , that the dust produced by this mechanism had a modal size of  $2\text{--}5\ \mu\text{m}$ , and that  $\text{PM}_{10}$  comprised up to 90% of the particles produced; these results were controlled by the original particle size of the sediments, their mineralogical composition, the extent of the original clay coating, the sorting of the particles, and their angularity. The results showed that the rates of production of dust-sized particles ( $<10\ \mu\text{m}$ ) under clean winds averaged about 0.500% of the total blown materials (mean value for the five Gobi samples), and under the sand-laden winds, the quantities produced by abrasion and other aeolian processes averaged about 0.012% of the total (after the erodible particles had been blown away in the tests with clean wind, all wind speeds combined), indicating that the dust-sized particles produced by aeolian abrasion amount to about 2.300% of the total directly emitted from the Gobi surfaces. Although the results show marked variation among samples in the amounts of dust-sized particles that are produced by these processes, the process of aeolian abrasion clearly makes the surfaces of Gobi deserts potentially significant sources of dust-sized particles at a global scale (Bullard et al. 2004).

In the Ala Shan Plateau, the locations of the major dust emission areas remain uncertain because of the range of aeolian geomorphologic forms that have developed in this region. Gobi desert covers more than 80% of the area and therefore appears to be the dominant dust source even if the other geomorphologic forms also have high dust emissions per unit area. However, only the Gobi desert appears to receive ongoing enrichment of the fine particles that are the source of dust emissions during the early stages of a dust outbreak as a result of transport from nearby mountains after intermittent floods. Despite this replenishment, emissions from these areas rapidly decrease due to depletion of these fine materials. After one dust outbreak ends, and before the next dust outbreak begins, fine materials are carried into the Gobi areas from the Gobi Altai Mountains by intermittent floods, and are regenerated in these mountains by physical and chemical weathering processes (Cooke and Smalley 1968; Goudie 1999; McFadden et al. 2005). This replenishes the dust-sized particles that will become the source for future emissions (Wang et al. 2008).

In the Ala Shan Plateau, sand-laden winds also provide potential dust-sized particles to serve as sources for emissions from other aeolian geomorphologic forms such as mobile dunes, vegetated dunes, and wadis. Although the present study did not directly measure the rates of emission of dust-sized particles from natural mobile sands, fine materials in this region have  $<50\ \mu\text{m}$  fractions amounting to only 0.100–0.400% of the total by weight, and the  $<10\ \mu\text{m}$  fraction has even lower values, which usually do not exceed 0.010% of the total (Wang et al. 2005). Although the wadis and vegetated dunes of this region also contain fine materials in huge quantities, the strong protection provided by salt, biological crusts, and vegetation cover reduces the vulnerability of these surfaces to wind erosion (e.g., Argaman et al. 2006) and therefore limits their emissions of dust-sized particles. In addition, the sporadic distribution and limited extent of these geomorphologic forms further suggest that they are not major dust sources.

Based on these previous results and those of the present study, a conceptual model of dust emissions from the Ala Shan Plateau has been proposed (Fig. 5). The dominant dust sources during the early stages of a dust outbreak appear to be direct emissions from Gobi surfaces due to the high contents of dust-sized particles that have accumulated on and between the coarse materials. Subsequently, these emissions end as the source materials are depleted, and are replaced by dust produced by other aeolian processes such as abrasion, which produce large quantities of mineral dust as a result of the long durations of dust events, even though the dust emission rates are low because of the hardness of the coarse materials. In addition, the experiments showed that under a sand-laden wind, the rate of production of

**Fig. 5** A conceptual model of dust emissions from Gobi surfaces as a result of aeolian processes in the Ala Shan Plateau



dust-sized particles appears to be unrelated or weakly related to wind velocity after the original fine materials are exhausted. This suggests that the production of dust-sized particles is not only related to the wind conditions, but also appears to be related to the materials that comprise the Gobi surfaces, to the array of the gravels, and to many other factors that have neither been discussed nor measured.

Finally, the experiments include some uncertainties that cannot be ignored. For instance, some fine materials may not have been captured by the sand trap due to their diffusion throughout the wind tunnel. In addition, monitoring using the high-speed camera revealed no regular patterns of particle motion, possibly due to the irregularity of the arrays of the gravels in the Gobi surfaces and variation in other factors that control sand transport. Despite these limitations, the results show that aeolian abrasion can produce at least 0.002–0.006% of particles  $<10\ \mu\text{m}$  (based on the total weight of captured blown materials) that are potentially transported to East Asia, the North Pacific, and North America. This suggests that in arid and semiarid China, modeling and simulation of global dust cycles must account for the dust produced by abrasion and related processes.

## Conclusions

The Gobi deserts of the Ala Shan Plateau are major sources of dust emissions due to their enrichment in silt and clay between the gravels. The wind-tunnel experiments showed that under clean winds, the rates of production of dust-sized particles ( $<10\ \mu\text{m}$  fraction) may reach 0.500% of the total blown materials (average by weight). At a certain wind velocity, after the easily erodible silts and clays have been removed from the Gobi surfaces, other aeolian processes such as abrasion play a major role in sustaining dust emissions. In addition, the clean winds have a relatively minor

effect on the clay coatings of particles, whereas sand-laden winds can abrade these clay coatings, resulting in emission of dust within a short period, even at low wind velocities. After the dust-sized particles with low resistance to erosion have been removed, the amount of dust-sized particles produced by abrasion decreases markedly because of the resistance of the gravels and sand particles to abrasion. However, the large areas covered by Gobi deserts in the study area produce large total quantities of dust despite the low emission rates per unit area. In addition, the results also show that after the dust-sized particles with low resistance to erosion were removed, the amount of dust-sized particles produced by abrasion and related processes is not related to the wind velocity. Although there are some uncertainties resulting from experimental procedure, the results nonetheless show that aeolian abrasion and related processes produce sufficient dust that this source must be considered in modeling of the dominant sources of dust emissions from Gobi areas in arid and semiarid parts of China.

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## References

- Argaman E, Singer A, Tsoar H (2006) Erodibility of some crust forming soils/sediments from the southern Aral Sea Basin as determined in a wind tunnel. *Earth Surf Proc Land* 31:47–63
- Arimoto R, Kim YJ, Kim YP, Quinn PK, Bates TS, Anderson TL, Gong S, Uno I, Chin M, Huebert BJ, Clarke AD, Shinozuka Y, Weber RJ, Anderson JR, Guazzotti SA, Sullivan RC, Sodeman DA, Prather A, Sokolik IN (2006) Characterization of Asian dust during ACE-Asia. *Global Planet Change* 52:23–56
- Bishop JKB, Davis RE, Sherman JT (2002) Robotic observations of dust storm enhancement of carbon biomass in the North Pacific. *Science* 298:817–821

- Bory AJM, Biscaye PE, Svensson A, Grousset FE (2002) Seasonal variability in the origin of recent atmospheric mineral dust at NorthGRIP Greenland. *Earth Planet Sci Lett* 196:123–134
- Bullard JE, White KH (2005) Dust production and the release of iron oxides resulting from the aeolian abrasion of natural dune sands. *Earth Surf Proc Land* 30:95–106
- Bullard JE, McTainsh GH, Pudmenzky C (2004) Aeolian abrasion and modes of fine particle production from natural red dune sands: an experimental study. *Sedimentology* 51:1103–1125
- Bullard JE, McTainsh GH, Pudmenzky C (2007) Factors affecting the nature and rate of dust production from natural dune sands. *Sedimentology* 54:169–182
- Bullard JE, Baddock M, McTainsh GH, Leys J (2008) Sub-basin scale dust source geomorphology detected using MODIS. *Geophys Res Lett* 35:L15404. doi:10.1029/2008GL033928
- Cooke RU (1970) Stone pavement in deserts. *Ann Assoc Am Geogr* 60:560–577
- Cooke RU, Smalley IJ (1968) Salt weathering in deserts. *Nature* 220:1226–1227
- Dong Z, Wang H, Liu X, Wang X (2003) The blown sand flux over a sandy surface: a wind tunnel investigation on the fetch effect. *Geomorphology* 49:219–230
- Duce RA, Tindale NW (1991) Chemistry and biology of iron and other trace metals. *Limnol Oceanogr* 36:1715–1726
- Duce RA, Unni CK, Ray BJ, Prospero JM, Merrill JT (1980) Long-range atmospheric transport of soil dust from Asia to the Tropical North Pacific: temporal variability. *Science* 209:1522–1524
- Goudie AS (1999) Experimental salt weathering of limestones in relation to rock properties. *Earth Surf Proc Land* 24:715–724
- Goudie AS, Middleton NJ (2001) Saharan dust storms: nature and consequences. *Earth Sci Rev* 56:179–204
- Goudie AS, Middleton NJ (2006) Desert dust in the global system. Springer, New York
- Houser CA, Nickling WG (2001) The factors influencing the abrasion efficiency of saltating grains on a clay-crusting playa. *Earth Surf Proc Land* 26:491–505
- Hu C, Liu Y, Zhang D, Huang Z, Paulsen BS (2002) Cementing mechanism of algal crust from desert area. *Chin Sci Bull* 47:1361–1368
- Husar RB, Tratt DM, Schichtel BA, Falke SR, Li F, Jaffe D, Gassó S, Gill T, Laulainen NS, Lu F, Reheis MC, Chun Y, Westphal D, Holben BN, Guymard C, McKendry I, Kuring N, Feldman GC, McClain C, Frouin RJ, Merrill J, DuBois D, Vignola F, Murayama T, Nickovic S, Wilson WE, Sassen K, Sugimoto N, Malm WC (2001) Asian dust events of April 1998. *J Geophys Res* 106(D16):18317–18330
- Jickells TD, An ZS, Andersen KK, Baker AR, Bergametti G, Brooks N, Cao JJ, Boyd PW, Duce RA, Hunter KA, Kawahata H, Kubilay N, LaRoche J, Liss PS, Mahowald N, Prospero JM, Ridgwell AJ, Tegen I, Torres R (2005) Global iron connections between desert dust, ocean biogeochemistry, and climate. *Science* 308:67–71
- Kim KH, Choi GH, Kang CH, Lee JH, Kim JY, Youn YH, Lee SR (2003) The chemical composition of fine and coarse particles in relation with the Asian dust events. *Atmos Environ* 37:753–765
- Laurent B, Marticorena B, Bergametti G, Chazette P, Maignan F, Schmechtig C (2005) Simulation of the mineral dust emission frequencies from desert areas of China and Mongolia using an aerodynamic roughness length map derived from the POLDER/ADEOS 1 surface products. *J Geophys Res* 110:D18S04. doi:10.1029/2004JD005013
- Lee JA, Gill TE, Mulligan KR, Acosta MD, Perez AE (2009) Land use/land cover and point sources of the 15 December 2003 dust storm in southwestern North America. *Geomorphology* 105:18–27
- Liu T (1985) Loess and environments. China Ocean Press, Beijing
- Livingstone I, Warren A (1996) Aeolian geomorphology: an introduction. Longman, Singapore
- Macpherson T, Nickling WG, Gillies JA, Etyemezian V (2008) Dust emissions from undisturbed and disturbed supply-limited desert surfaces. *J Geophys Res* 113:F02S04. doi:10.1029/2007JF000800
- Mahowald NM, Luo C (2003) A less dusty future? *Geophys Res Lett* 30:1903. doi:10.1029/2003GL017880
- Marticorena B, Bergametti G (1995) Modeling the atmospheric dust cycle: 1. Design of a soil-derived dust emission scheme. *J Geophys Res* 100(D8):16415–16430
- McFadden LD, Eppes MC, Gillespie AR, Hallet B (2005) Physical weathering in arid landscapes due to diurnal variation in the direction of solar heating. *GSA Bull* 117:161–173
- Mori I, Nishikawa M, Quan H, Morita M (2002) Estimation of the concentration and chemical composition of kosa aerosols at their origin. *Atmos Environ* 36:4569–4575
- Petit JR, Jouzel J, Raynaud D, Barkov NI, Barnola JM, Basile I, Bender M, Chappellaz J, Davis M, Delaygue G, Delmotte M, Kotlyakov VM, Legrand M, Lipenkov VY, Lorius C, Pépin L, Ritz C, Saltzman E, Stevenard M (1999) Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* 399:429–436
- Potter RM, Rossman GR (1977) Desert varnish: the importance of clay minerals. *Science* 196:1446–1448
- Prospero JM, Ginoux P, Torres O, Nicholson SE, Gill TE (2002) Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 total ozone mapping spectrometer (TOMS) absorbing aerosol product. *Rev Geophys* 40(1):1002. doi:10.1029/2000RG000095
- Pye K (1987) Aeolian dust and dust deposits. Academic Press, London
- Rice MA, McEwan IK (2001) Crust strength: a wind tunnel study of the effect of impact by saltating particles on cohesive soil surfaces. *Earth Surf Proc Land* 26:721–733
- Sassen K (2002) Indirect climate forcing over the western US from Asian dust storms. *Geophys Res Lett* 29(10). doi:10.1029/2001GL014051
- Shao Y, Dong CH (2006) A review on East Asian dust storm climate, modelling and monitoring. *Global Planet Change* 52:1–22
- Shao Y, Raupach MR (1993) Effect of saltation bombardment on the entrainment of dust by wind. *J Geophys Res* 98(D7):12719–12726
- Sun J, Liu T, Lei Z (2000) Sources of heavy dust fall in Beijing, China on April 16, 1998. *Geophys Res Lett* 27:2105–2108
- Tegen I, Werner M, Harrison SP, Kohfeld KE (2004) Relative importance of climate and land use in determining present and future global soil dust emission. *Geophys Res Lett* 31:L05105. doi:10.1029/2003GL019216
- Tsuda A, Takeda S, Saito H, Nishioka J, Nojiri Y, Kudo I, Kiyosawa H, Shimoto A, Imai K, Ono T, Shimamoto A, Tsumune D, Yoshimura T, Aono T, Hinuma A, Kinugasa M, Suzuki K, Sohrin Y, Noiri Y, Tani H, Deguchi Y, Tsurushima N, Ogawa H, Fukami K, Kuma K, Saino T (2003) A mesoscale iron enrichment in the western Subarctic Pacific induces a large centric diatom bloom. *Science* 300:958–961
- Wang X, Dong Z, Yan P, Yang Z, Hu Z (2005) Surface sample collection and dust source analysis in northwestern China. *Catena* 59:35–53
- Wang X, Zhou Z, Dong Z (2006) Control of dust emissions by geomorphic conditions, wind environments and land use in northern China: an examination based on dust storm frequency from 1960 to 2003. *Geomorphology* 29:292–308
- Wang X, Xia D, Wang T, Xie X, Li J (2008) Dust sources in arid and semiarid China and southern Mongolia: impacts of geomorphologic setting and surface materials. *Geomorphology* 97:583–600

- Whalley WB, Smith BJ, McAlister JJ, Edwards AJ (1987) Aeolian abrasion of quartz particles and the production of silt-size fragments: preliminary results. In: Forstick L, Reid I (eds) Desert sediments: ancient and modern, vol 35. Geology Society of America Special Publication, London, pp 129–138
- Wright J (2001) Making loess-sized silt: data from laboratory simulations and implications for sediment transport pathways and the formation of 'desert' loess deposits associated with the Sahara. *Quatern Int* 76(77):7–19
- Wright J, Smith B, Whalley B (1998) Mechanisms of loess-sized quartz silt production and their relative effectiveness: laboratory simulations. *Geomorphology* 23:15–34
- Xuan J, Sokolik N (2002) Characterization of sources and emission rates of mineral dust in Northern China. *Atmos Environ* 36:4863–4876
- Xuan J, Sokolik IN, Hao J, Guo F, Mao H, Yang G (2004) Identification and characterization of sources of atmospheric mineral dust in East Asia. *Atmos Environ* 38:6239–6252
- Zhang XY, Gong SL, Zhao TL, Arimoto R, Wang YQ, Zhou ZJ (2003) Sources of Asian dust and role of climate change versus desertification in Asian dust emission. *Geophys Res Lett* 30(24):2272. doi:[10.1029/2003GL018206](https://doi.org/10.1029/2003GL018206)
- Zhou Z, Zhang G (2003) Heavy dust events in North China, 1954–2002. *Chin Sci Bull* 48:1224–1228
- Zou XK, Zhai PM (2004) Relationship between vegetation coverage and spring dust storms over northern China. *J Geophys Res* 109:D03104. doi:[10.1029/2003JD003913](https://doi.org/10.1029/2003JD003913)