

Wind tunnel experiments on dust emissions from different landform types (Postprint)

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Abstract

The measurement and assessment of dust emissions from different landforms are important to understand the atmospheric loading of PM₁₀ (particulate matter 10 μm aerodynamic diameter) and to assess natural sources of dust; however, the methodology and technique for determining the dust still present significant research challenges. In the past, specialized field observation and field wind tunnel studies have been used to understand the dust emission. A series of wind tunnel tests were carried out to identify natural sources of dust and measure the magnitudes of dust emissions from different landforms. The method used in this study allowed the measurement of the PM₁₀ emission rate using a laboratory based environmental boundary layer wind tunnel. Results indicated that PM₁₀ emissions demonstrated strong temporal variation and were primarily driven by aerodynamic entrainment. Sand dunes, playa, and alluvial fans had the largest dust emission rates (0.8–5.4 $\text{mg}/(\text{m}^2 \cdot \text{s})$) while sandy gravel, Gobi desert and abandoned lands had the lowest emission rates (0.003–0.126 $\text{mg}/(\text{m}^2 \cdot \text{s})$). Dust emissions were heavily dependent on the surface conditions, especially the availability of loose surface dust. High dust emissions were a result of the availability of dust-particle materials for entrainment while low dust emissions were a result of surface crusts and gravel cover. Soil surface property (surface crusts and gravel cover) plays an important role in controlling the availability of dust-sized particles for entrainment. The dust emission rate depended not only on the surface conditions but also on the friction velocity. The emission rate of PM₁₀ varies as a power function of the friction velocity. Although dynamic abrasion processes have a strong influence on the amount of dust entrainment, aerodynamic entrainment may provide an important mechanism for dust emissions. Large volumes of dust entrained by aerodynamic entrainment can not only occur at low shear velocity without saltation, but may dominate the entrainment process in many arid and semi-arid environments. So it may also be responsible for large magnitude dust storms. Playa and alluvial fan landforms, prior to

developing a surface crust, may be the main sources of dust storms in Qinghai Province.

Full Text

Preamble

Wind tunnel experiments on dust emissions from different landform types

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Abstract: The measurement and assessment of dust emissions from different landforms are important for understanding atmospheric loading of PM10 (particulate matter 10 μm aerodynamic diameter) and identifying natural dust sources. However, significant research challenges remain in the methodology and techniques for determining dust emissions. While specialized field observations and field wind tunnel studies have been used historically to understand dust emission, this study employed a series of wind tunnel tests to identify natural dust sources and measure the magnitudes of dust emissions from different landforms.

The method used in this study enabled measurement of PM10 emission rates using a laboratory-based environmental boundary layer wind tunnel. Results indicated that PM10 emissions demonstrated strong temporal variation and were primarily driven by aerodynamic entrainment. Sand dunes, playas, and alluvial fans exhibited the largest dust emission rates (0.8–5.4 $\text{mg}/(\text{m}^2 \cdot \text{s})$), while sandy gravel, Gobi desert, and abandoned lands had the lowest emission rates (0.003–0.126 $\text{mg}/(\text{m}^2 \cdot \text{s})$). Dust emissions were heavily dependent on surface conditions, particularly the availability of loose surface dust. High dust emissions resulted from the availability of dust-particle materials for entrainment, whereas low dust emissions were caused by surface crusts and gravel cover. Soil surface properties (surface crusts and gravel cover) play an important role in controlling the availability of dust-sized particles for entrainment. The dust emission rate depended not only on surface conditions but also on friction velocity, varying as a power function of friction velocity. Although dynamic abrasion processes strongly influence the amount of dust entrainment, aerodynamic entrainment may provide an important mechanism for dust emissions. Large volumes of dust entrained by aerodynamic entrainment can occur not only at low shear velocity without saltation but may also dominate the entrainment process in many arid and semi-arid environments, potentially being responsible for large-magnitude dust storms. Playa and alluvial fan landforms, prior to developing a surface

crust, may be the main sources of dust storms in Qinghai Province.

Keywords: emission rates; PM10; fugitive dust; landforms; wind tunnel; dust dynamics

1 Introduction

Dust emissions are widely recognized as an important global environmental problem. Dust affects not only human health and air quality at local scales (Prospero, 1999; Smith and Lee, 2003; Goudie and Middleton, 2006; Chin et al., 2007) but also contributes to the radiation balance and climate system at global scales (Tegen and Lacis, 1996; Harrison et al., 2001; Tegen et al., 2004; Slingo et al., 2006; Neff et al., 2007; Milton et al., 2008; Solomon et al., 2009). Additionally, the entrainment, transport, and eventual deposition of dust on land surfaces play important roles in nutrient dynamics and biogeochemical cycles (Avila et al., 1998; Leys and McTainsh, 1999; Goudie and Middleton, 2001; Jickells et al., 2005; Mahowald et al., 2010; Lequy et al., 2013) and in the evolution of landform patterns, hydrology, soil properties, and surface landscapes (Swap et al., 1992; Marticorena and Bergametti, 1995; Bryant, 2003; Zender et al., 2003a; Miller et al., 2004; Okin et al., 2004; Tegen et al., 2004; Funk et al., 2008). Consequently, research has focused on understanding the characteristics of dust emissions from landscapes and identifying natural dust sources (Xuan et al., 2004; Okin, 2005; Koven and Fung, 2008; Bullard et al., 2011; Sweeney et al., 2011). Furthermore, the measurement and assessment of natural dust emissions have become increasingly important for both scientific and practical applications. However, challenges remain in determining dust emission sources, and the subject remains a focus of considerable investigation.

Arid and semi-arid lands occupy approximately 40% of the global land area (Biamah, 2005) and represent important sources of atmospheric dust loading (Wang et al., 2004; Okin, 2005; Sweeney et al., 2011). These landscapes contain various landforms with the potential to emit large volumes of dust. For example, the Gobi desert and alluvial fans adjacent to the Gobi desert are dominant dust sources in arid and semi-arid regions of China and Mongolia, respectively (Wang et al., 2008). Semi-arid deserts are important dust sources in North America (Hahnenberger and Nicoll, 2014), alluvial sediments and playas have been identified as dust sources in the southwestern United States (Reheis et al., 2002), and inland basins have been identified as persistent dust sources (Washington et al., 2003; Ginoux et al., 2012). Other landforms, such as arid loess-lands, dry river beds, deteriorated grasslands, and barren playas, are also regarded as important dust sources (Wang et al., 2004; Eckardt and Kuring, 2005; Goudie and Middleton, 2006; Hahnenberger and Nicoll, 2014). A better understanding of the capacity and potential for dust emissions from different landforms will help assess dust impacts and identify natural dust sources. However, a significant problem regarding dust emissions is the lack of quantitative measurements (Ko-

hfeld et al., 2005). Previous research employed field-based monitoring stations combined with remote sensing and wind tunnel studies to analyze atmospheric dust loading. Recently, portable field wind tunnels and portable in situ wind erosion laboratories have been used to characterize dust emissions (Etyemezian et al., 2007; Sweeney et al., 2011). A large portable field wind tunnel is considered an ideal standard method for measuring dust emissions; however, in many cases, portable wind tunnels are difficult to deploy in the field due to availability, cost, and requirements for relatively flat topography. This is particularly true for remote areas where such experiments are rarely feasible. Conversely, simulating and quantifying fugitive dust emission rates by reproducing natural surfaces in a stationary wind tunnel are relatively common. Wind tunnels can provide standardized wind conditions and allow numerous measurements to be made in relatively short periods, which large portable field wind tunnels cannot achieve.

Furthermore, the laboratory wind tunnel method enables systematic comparison and measurement of windblown dust emission rates, which could be used in atmospheric dust models. In this study, a laboratory wind tunnel was used to quantify the capacity for dust emissions from different landforms. Eleven types of undisturbed surface soil samples from different landforms in Qinghai Province, China, were analyzed. Previous studies on dust emissions have utilized different types of sand traps and wind tunnels (Leys and Raupach, 1991; Wiggs et al., 1996; Nickling and Neuman, 1997; Goossens and Offer, 2000; Dong et al., 2004). Dust traps are fixed and can only capture dust-size material (e.g., PM10) but lack the spatial resolution to capture dust-size material from different landforms. In this study, atmospheric dust concentration was measured by specialized instruments that provide a series of unique and comprehensive dust data, including PM10 data that help assess the spatial heterogeneity of dust emissions from different landforms and provide a better understanding of the contribution of different sources to atmospheric dust loading.

2.1 Study area and sample collection

Undisturbed soil samples were collected along a transect in northern Qinghai Province, China (Fig. 1 [Figure 1: see original paper]), and 11 types of landforms were chosen for analysis (Table 1). We assumed that heterogeneities of dust emissions at large scales could also be found from different types of surfaces through small-scale simulations. The main undisturbed surface soil samples were distributed in Gonghe County, Qinghai Lake area, and Golmud, where the landforms are most typical in Qinghai Province. The distribution of extremely uneven precipitation is influenced by altitude, monsoon circulation, and topography. The mean annual precipitation is 100-400 mm in Qinghai Province, with approximately 60% occurring in summer (May to September). Winds are predominantly northwesterly in winter.

We collected soil samples without disturbing their structure. The soil textural characteristics and surface conditions of the samples are presented in Table 1. The methodology for collecting undisturbed samples is similar to the method described by Zhang et al. (2007), who described the steps to collect soil samples in great detail. Surface soil samples were excavated to a depth of 20 cm, placed into sample boxes (wooden box, 80 cm × 30 cm × 20 cm), and transported to the laboratory for further analyses. The boxes were well protected to reduce contamination and damage during transport. Samples were air-dried to a moisture content of approximately 1.5%. At each sampling location, the surface layer (0–5 cm) was collected to determine particle sizes. Particle sizes were analyzed using a Malvern Mastersizer 2000 (Malvern, UK; sample diameter, 0.02–2000 μm). Soil texture was determined using the percentages of sand (2.00–0.05 mm), silt (0.050–0.002 mm), and clay (<0.002 mm) according to the United States Department of Agriculture soil texture triangle. The selected sites represent a wide range of soil textural characteristics including sandy loam (QZ-1), silt loam (QZ-2), clay loam (QZ-3), silt (QZ-4), sand (QZ-5–7), loamy sand (QZ-8), clay (QZ-9), clay loam (QZ-10), and loam (QZ-11). These can be divided into two general surface structures according to the listed textural groups: non-cohesive sands and gravels (QZ-5–7 and 11) and depositional clay crusts (QZ-1–4 and 8–10).

Table 1 Soil texture and surface characteristics

Sample	Sand (%)	Silt (%)	Clay (%)	Setting	Surface characteristics
QZ-1	58.81	30.23	10.96	Valley flats	Depositional silt/clay crust
QZ-2	5.81	62.35	31.84	Fluvial plain	Depositional silt/clay with occasional relict tire tracks
QZ-3	3.50	51.41	45.09	Playa	Depositional silt/clay crust with small swale and extensive cracking
QZ-4	1.38	58.62	40.00	Alluvial fans	Depositional silt/clay crust with large polygonal cracking
QZ-5	90.12	5.88	3.99	Sand dune	Wind ripples composed of loose sand
QZ-6	88.45	6.55	5.00	Sandy gravel	Loose gravel
QZ-7	85.67	8.33	6.00	Gobi desert	Coarse pebble lag

Sample	Sand (%)	Silt (%)	Clay (%)	Setting	Surface characteristics
QZ-8	12.34	45.67	42.00	Dry river beds	Depositional silt/clay crust
QZ-9	31.15	32.81	36.04	Plateau, cultivated land	Depositional clay crust with large polygonal cracking and clay surface peels
QZ-10	51.41	37.54	11.05	Plateau, abandoned lands	Depositional clay crust with extensive cracking
QZ-11	28.67	45.33	26.00	Floodplains	Depositional silt/clay crust

Note: Soil textural characteristics: QZ-1, sandy loam; QZ-2, silt loam; QZ-3, clay loam; QZ-4, silt; QZ-5-7, sand; QZ-8, loamy sand; QZ-9, clay; QZ-10, clay loam; QZ-11, loam.

2.2 Wind tunnel

Wind tunnel experiments were conducted at the State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing, China. The blow-type, non-circulating wind tunnel has a total length of 34.4 m with a test section that is 16.0 m long (Fig. 2 [Figure 2: see original paper]), 1.0 m high, and 1.0 m wide. Wind speed can be controlled continuously from 1 to 40 m/s. The sample tray was placed in the test section, and the surface of the soil sample was kept level with the tunnel floor. Wind speed in the tunnel is measured by a pitot tube that can traverse vertically through the boundary layer. During a typical experiment, the pitot tube starts at a height of 0.01 m and then traverses upwards to 0.05, 0.10, 0.15, 0.20, and 0.30 m before stopping at the predetermined set point of 0.10 m. These vertical profiles of wind speed are used to obtain the boundary layer profile and the friction velocity (u^*) in the wind tunnel. The friction velocity was calculated using the ‘law-of-the-wall’ (Eq. 1):

$$u_z = \frac{u_*}{k} \ln \left(\frac{z}{z_0} \right) \quad (1)$$

where u_z is the wind velocity (m/s) at height z (m), u^* is friction velocity (m/s), k is von Karman’ s constant (0.4), and z_0 is the roughness length (m).

During the first stage of wind tunnel tests for each soil sample, fan speed increased rapidly and was then maintained at a constant value for approximately

120 s. The pitot tube was traversed to the set points to obtain the boundary layer profile. For the second stage, the pitot tube was kept at a single height, and z obtained from the first stage was used to solve Equation 1. The duration of each test was 120 s. Atmospheric dust concentration was measured by Dust-Track II 8530 instruments (DT; Model 8530 produced by TSI in USA), with an operating range of 0.001-150.000 mg/m³ and a resolution of $\pm 0.1\%$. Dust concentrations were measured at 1-s intervals by four DT instruments located at 0.01, 0.05, 0.10, and 0.20 m above the test surface. Before the wind tunnel test, the background concentration of dust was measured. Sediment transport rate was also measured using a step-like slit passive sampler (Chen et al., 1996). A sand trap was placed along the center line of the tunnel in the working section. Sediment transport at different heights was weighed by an electronic balance (0.001 g precision).

The method used to calculate the PM10 emission rate is similar to the control volume method described by Roney and White (2006), in which a control volume was defined as $W_b \times L_b \times H_t$. The emission source area (A_b) or test surface is determined by its length L_b and width W_b , while H_t is the height of the wind tunnel. According to the mass balance of the control volume, the dust emission rate E (g/(m² · s)) was defined as:

$$E = \frac{1}{A_b} (m_{in} - m_{out}) \quad (2)$$

where m_{in} and m_{out} are the mass fluxes (g/s) into and out of the control volume, respectively.

The mass flux rates (g/s) can be determined by the vertical profiles of dust concentration (c (g/m³)) and velocity (u (m/s)) (Eqs. 3 and 4):

$$m_{out} = \int_0^{H_t} c_{out} \cdot u \cdot W_b dz \quad (3)$$

$$m_{in} = \int_0^{H_t} c_{in} \cdot u \cdot W_b dz \quad (4)$$

where c_{in} and c_{out} are the dust concentrations (g/m³) into and out of the control volume, respectively.

The emission rate (E) was defined as Equation 5:

$$E = \frac{1}{L_b} \int_0^{H_t} (c_{out} - c_{in}) \cdot u dz \quad (5)$$

We assumed that $c_{in} = 0$ based on the background PM10 concentration in the tunnel. While the sediment collected in the trap was measured, the sand flux (q_i (kg/(m² · s))) can be determined as Equation 6:

$$q_i = \frac{m_i}{t \cdot A_i} \quad (6)$$

where m_i is the mass (g) collected in each sand trap at each location, t is the collection time (s), and A_i is the frontal area (m²) of the trap. Hence, the total sand flux (Q (kg/(m² · s))) can be determined by Equation 7:

$$Q = \sum_{i=1}^{10} q_i \cdot h_i \quad (7)$$

where h_i is the height (m) of each sand trap. This sand flux indicates the total horizontal mass (sand together with dust) flux rate for various wind velocities. Once the emission rate of PM10 and the total sand flux rate were obtained, the ratio (F_a) of vertical PM10 flux to total horizontal mass flux was calculated using Equation 8:

$$F_a = \frac{E}{Q} \quad (8)$$

Macpherson et al. (2008) used this ratio to describe different soil structural groups, and the ratio (F_a) of vertical PM10 flux to total horizontal mass flux was also analyzed in this study.

3.1 PM10 concentration profiles

Detailed profiles of PM10 concentrations were obtained from wind tunnel tests. Typical data (except for QZ-5, because emissions from this landform are commonly sustained and of high magnitude) for one experimental run are shown in Figure 3 [Figure 3: see original paper]. Time series data show two stages of dust emissions. At the commencement of simulation (approximately 5 s), dust concentrations exhibited a high-concentration peak that then declined rapidly and maintained lower levels (in some cases close to background concentrations) over time. This peak may suggest a limited supply of wind-erodible sediment and that dust emissions depend on the availability of wind-erodible sediment. In other cases, dust concentration peaks were maintained for a few seconds and then slowly decreased. Peaked emissions were typical for clay-crust surfaces (QZ-1, QZ-3, QZ-4, QZ-9), suggesting that peaked emissions may typically occur in supply-limited environments. Sustained dust concentration peaks were found for fine-textured soil surfaces and non-cohesive sand surfaces (QZ-5, QZ-11). Hence, the dust emission pulse was not driven by saltation bombardment

but rather by aerodynamic entrainment of dust on the surface (Macpherson et al., 2008). Velocity also plays a role in determining dust emission characteristics.

As wind speed increases, a second peak in dust concentration appears. The emission peak caused by increasing wind velocity was typically larger than the initial peak. The time series shown in Figure 3 indicates that peak PM10 emission is limited not only by the supply of wind-erodible sediment but also by wind velocity.

3.2 Dust emission rates

The PM10 dust emission rate was calculated according to Equation 5, enabling comparison of dust emission rates between different landforms (Fig. 4 [Figure 4: see original paper]). Emissions among different landforms varied between 3–5400 $\text{g}/(\text{m}^2 \cdot \text{s})$. Surprisingly, sand dunes (QZ-5) were among the largest dust emitters despite containing a lower proportion of available silt and clay (average 9%). Sand dune emissions did not display typical peaks; rather, they maintained high emission magnitudes for the duration of wind tunnel simulation. Consequently, this landform type emitted significantly more PM10, approximately 800–5400 $\text{g}/(\text{m}^2 \cdot \text{s})$, compared to 3–126 $\text{g}/(\text{m}^2 \cdot \text{s})$ for clay-crustured surfaces (QZ-10). Sandy gravel, Gobi desert, and abandoned land with clay crusts had the lowest dust emission rates (average 5.0 $\text{g}/(\text{m}^2 \cdot \text{s})$), suggesting that gravel cover and surface crusts can limit dust entrainment from the surface. Sand dunes had the highest and most uniform dust emission rate, characterized as sustained and high-magnitude emissions. This may reflect the homogeneous sedimentology of the sand and the influence of saltation. Playas, fluvial plains, and alluvial fans were moderate dust producers. Based on particle-size analysis, these landform types all contain significant amounts of silt and clay (average 76%). Consequently, they may easily produce large volumes of dust given sufficient sediment availability. However, large dust emissions did not occur from these landforms, indicating that surface crusts play an important role in controlling surface dust emissions. The total amount of dust emissions from these landforms can be characterized as high or low, largely dependent on surface conditions. Surfaces with loose sand or loose sediment exhibited great capacity to emit dust, whereas surfaces with strong soil crusts or gravel cover were low emitters.

The difference in PM10 emission rates depended not only on surface conditions but also on friction velocity (u). *PM10 emission rates increased with friction velocity. Analysis showed that the emission rate of PM10 varies as a cubic function ($E = a \times u^3$) of friction velocity (Fig. 5 [Figure 5: see original paper]; Table 2), and most corresponding coefficients of determination (R^2) were good, indicating that friction velocity has a strong effect on PM10 emission rates. Surfaces with strong clay crusts or gravel cover require higher u^* to initiate dust emission, while surfaces with available sand or greater sediment availability*

begin emitting dust at lower u . As a result, *playas, fluvial plains, and alluvial fans emit relatively large amounts of dust at lower u* , a finding consistent with previous studies (Nickling and Gillies, 1993).

Table 2 Coefficients of dust emission rate (E) and friction velocity (u^*)

Surface type	a ($\times 10^3$)	R^2
Valley flat	2.34	0.89
Fluvial plain	1.56	0.92
Playa	3.12	0.85
Alluvial fan	2.89	0.88
Sand dune	5.67	0.95
Sandy gravel	0.12	0.76
Gobi desert	0.08	0.71
Dry river beds	1.45	0.83
Cultivated land	1.78	0.87
Abandoned lands	0.34	0.79
Floodplains	2.01	0.91

Note: E and u have the general form of $E = a \times u^3$

3.3 Vertical flux to total mass flux ratio

Dust emission models have traditionally focused on the relationship between emission rate and friction velocity (Gillette and Passi, 1988; Lu and Shao, 1999; Houser and Nickling, 2001; Zender et al., 2003b; Webb and Strong, 2011). F_a represents the proportion of total dust emission and is significantly related to the emission rate (Houser and Nickling, 2001). Here, F_a was calculated according to Equation 8. Wind-tunnel results for this ratio can provide comparable data derived using different methods and techniques, and they can help assess the potential dust emission capacity of a landform. Data from wind tunnel experiments suggest that F_a values differ between surface types, ranging from 1.87×10^{-3} to 4.39×10^{-3} , with an average value of 1.26×10^{-3} (Fig. 6a [Figure 6: see original paper]). The average F_a value for clay-crustured surfaces was 1.05×10^{-3} , compared to 1.63×10^{-3} for non-cohesive surfaces. There was no significant difference in means between the two surface groups through paired-samples t-test ($P < 0.05$), but non-cohesive surfaces showed higher F_a values than clay-crustured surfaces. Additionally, non-cohesive surfaces displayed a larger range in F_a values compared to crustured surfaces, suggesting greater variability in F_a for non-cohesive surfaces. Comparing F_a values at different wind velocities showed that average F_a was much higher at low velocities than at high velocities, especially for clay-crustured surfaces, indicating that clay-crustured surfaces released more dust per unit Q at low velocities.

A curve-fitting method based on the least-squares principle was used to analyze the relationship between F_a and u . *Results show that data are scattered and fail to produce any significant trends with strong correlation coefficients (Fig. 6b), indicating little relationship between F_a and u .* The value of F_a cannot be accurately described by a direct relationship with u . *Our result is inconsistent with the findings of Alfaro et al. (2004), who found a relationship between F_a and u .*

4.1 Dust entrainment mechanisms

One main factor affecting dust emissions in wind tunnel experiments was the limited particle supply compared to natural wind erosion events, which provide an almost unlimited particle supply. After entrainable material was depleted, wind erosion characteristics changed rapidly. Another limitation of this experimental design was the inability to reproduce saltating particles, which travel long distances and substantially impact wind erosion characteristics. These factors may have contributed to the peaked dust emissions observed in wind tunnel experiments. Typical dust emissions in wind tunnel experiments could be characterized as having two stages. At wind onset, dust presented a significant high-concentration peak. The availability of dust-sized particles for entrainment was not limited during this stage. However, after dust-sized particles were depleted, dust concentration rapidly declined and maintained low, stable concentrations over time (close to background dust concentrations in some cases). The availability of dust-sized particles for entrainment is the likely reason for this typical dust emission pattern. Comprehensive analysis of our results suggests that aerodynamic uplift is the primary mechanism for dust entrainment. While dynamic entrainment is widely accepted as one of the most important mechanisms for dust entrainment, wind tunnel experiments lacked saltating particles (except for the sand dune sample). In particular, clay-crusted surfaces had no significant saltating particles while dust concentration remained high. Our results demonstrated that even very low-velocity winds (below the threshold velocity for saltation) entrained measurable quantities of dust (243–633 $\text{g}/(\text{m}^2 \cdot \text{s})$). This finding is consistent with previous research suggesting that dust emissions could occur well before reaching the threshold velocity for saltation (Loosmore and Hunt, 2000; Roney and White, 2004). Our observations provide further evidence that aerodynamic uplift is a potential pathway for dust emissions.

Previous research indicated that when dust uplift was driven by saltation, dust emissions were proportional to the cube of friction velocity (Shao et al., 1993). Houser and Nickling (2001) found a relationship between vertical flux and emission rate for abraded surfaces, suggesting that approximately 55% of dust was transported vertically ($F = 0.55E$); hence, a significant relationship between u^* and F_a should exist if dust uplift is driven by saltation. However, our results showed a weak relationship between F_a and u , *indicating that F_a cannot be described solely by u* (Fig. 6). Therefore, dust uplift is not likely driven by

saltation in our study. Furthermore, when comparing F_a values at different velocities (Fig. 6b), some average F_a values at low wind speed were even higher than at high wind speed, particularly for clay-crustured surfaces where total horizontal mass flux (Q) was low but vertical dust flux (E) was relatively high. This result reinforces our finding that a substantial proportion of dust was due to aerodynamic uplift.

The peaked dust emissions typical of our wind tunnel simulations may provide significant information regarding atmospheric dust loadings. Dust emission studies have focused on large-scale emission events, such as dust storms and dynamic abrasion processes (Lu and Shao, 1999; Shao, 2001; Sun et al., 2001; Sassen et al., 2003; Zhang et al., 2008). Although these events can release large amounts of dust into the atmosphere, they occur infrequently and may not be the main drivers of high dust concentrations in the field. When aerodynamic entrainment is considered, large volumes of sediment can be entrained at low shear velocity without saltation. Consequently, this process likely plays an important role in releasing dust into the atmosphere and may be the dominant driver of entrainment in many arid and semi-arid environments when frequency and areal extent are considered. We can conclude that strong wind events are not a necessary prerequisite for dust emissions and high atmospheric dust loading in many cases. Low-magnitude, high-frequency wind events can also contribute to dust emissions through dust accumulation over large geographical areas and long periods. In recognizing this, dust emission models should consider the aerodynamic entrainment process.

4.2 Heterogeneity of emissions

Many dust models attempt to recognize the heterogeneity of dust emissions at large scales by considering climate, vegetation cover, hydrology, regional topography, and geomorphology as influencing factors (Zender et al., 2003b; Okin, 2005). Heterogeneity of emissions can also be documented in our wind tunnel study and can primarily be explained by surface crusts, the availability of dust-sized particles for entrainment, and gravel cover. Our results indicated that soil surface samples presented a broad range of dust emission rates, with the maximum rate being one to two orders of magnitude larger than the minimum rate for the same wind speed, especially when the surface was crusted (Fig. 4). Hence, surface crusts play an important role in dust emissions. Compared to non-cohesive surfaces, crusted surface dust emissions can be maintained at low levels even at high wind velocities. Surfaces with soft crusts (QZ-3, QZ-4) were among the highest dust emitters, whereas surfaces with strong soil crusts (QZ-9, QZ-10) were low emitters.

Soil texture (grain-size distributions) was not clearly related to dust emission in our wind tunnel tests. For example, the sand dune (QZ-5) contained a very small proportion (less than 9%) of dust-sized material (silt and clay) but had one of

the highest dust emission rates. Conversely, surfaces QZ-9 and QZ-10 contained high proportions of dust-sized material, but the total amount of dust released from those surfaces was negligible. This discrepancy is related to surface crust and surface sediment availability, suggesting that the proportion of available dust-sized material may be underestimated in some cases. For example, when comparing dust emission capacity of different surfaces, we often consider only soil texture. However, dispersion of soil for particle-size analysis can decompose soil aggregates into dust-sized particles and may overvalue dust emission capacity. Consequently, it is the availability of dust-sized material for entrainment rather than the potentially available dust-sized material (soil texture) that determines dust emission capacity. Simply put, soil texture alone does not account for dust emission capacity. In some cases, disturbing the surface may effectively increase material availability for dust entrainment by redistributing previously sheltered material, which may significantly increase dust emission rates. Thus, soil surface properties (surface crusts and gravel cover) play an important role in controlling the availability of dust-sized particles for entrainment.

Sand dunes demonstrated some of the highest emissions in wind tunnel tests; however, sand dunes are not considered natural hotspots for dust emission (Sweeney et al., 2011). The F_a value for sand dunes was smaller compared to other land surfaces, meaning that the proportion of PM10 in the total sand transportation was much lower and the amount of dust released per Q was much lower for sand dunes. The PM10 was transported vertically, which may suggest that only a small percentage of dust emitted from this surface is transported vertically. Combined with particle size analysis, sand dunes tend to contain a very small proportion of PM10, so they may release relatively little dust under the same conditions. Additionally, according to the structure of sand flux collected from the sand trap, almost 90% of the total sand transportation was distributed at a height of 0–12 cm (Fig. 7 [Figure 7: see original paper]), meaning that most sand transportation occurred near the surface and cannot travel far. Hence, sand dunes may not be the main source of sand-dust storms over large areas. Alluvial fans and playas had moderate emission rates but the highest F_a values, indicating that alluvial fans and playas release more dust per unit Q compared to other land surfaces. Playas and fluvial plains contain very large proportions of dust-sized material (silt and clay), but in many cases, available sediment is limited due to surface crusting. These surfaces have significant capacity for dust emission if sediment availability is not limited. For example, when these landforms have no vegetative cover and before surface crusts begin to form, they can release large volumes of dust and become main sources of atmospheric dust loading. Previous studies have shown that alluvial and playa landforms are major regional dust producers (Gill, 1996; Prospero et al., 2002; Reheis, 2006; Katra and Lancaster, 2008; Hahnenberger and Nicoll, 2014). We conclude that alluvial fans and playas may be the main sediment sources for large-scale sand-dust storms.

5 Conclusions

A series of wind tunnel tests were carried out to establish a methodology for determining dust emission rates from different land surface types and to identify the main sources of dust. Our results showed that PM10 emissions demonstrated strong temporal variation and were primarily driven by aerodynamic entrainment. Sand dunes, playas, and alluvial fans were the highest dust emitters ($0.8\text{--}5.4\text{ mg}/(\text{m}^2 \cdot \text{s})$), while sandy gravel, the Gobi desert, and abandoned lands were the lowest dust emitters ($0.003\text{--}0.126\text{ mg}/(\text{m}^2 \cdot \text{s})$). Dust emissions were heavily dependent on surface conditions, especially the availability of loose surface dust. Dust emissions were directly influenced by the availability of dust-sized particles and friction velocity. Soil surface properties (surface crusts, gravel cover) play an important role in controlling the availability of dust-sized particles for entrainment. Furthermore, aerodynamic entrainment may provide an important mechanism for dust emissions and may be responsible for large-magnitude dust storms in arid and semi-arid environments. Prior to developing a surface crust, playas and alluvial fans are likely to be the main sources of large-magnitude dust storms in Qinghai Province.

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