New insights into the wind-dust relationship in sandblasting and direct aerodynamic entrainment from wind tunnel experiments

Sagar Prasad Parajuli\textsuperscript{1}, Ted M. Zobeck\textsuperscript{2}, Gary Kocurek\textsuperscript{1}, Zong-Liang Yang\textsuperscript{1,*}, and Georgiy L. Stenchikov\textsuperscript{3}

\textsuperscript{1}The University of Texas at Austin, Jackson School of Geosciences, 2225 Speedway, Stop C1160, Austin, Texas 78712-1692, USA

\textsuperscript{2}U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS), Lubbock, Texas, USA

\textsuperscript{3}King Abdullah University of Science and Technology (KAUST), Thuwal, KSA

* Corresponding Author. E-mail: liang@jsg.utexas.edu; Tel.: 512 471 3824; Fax: 512 471 9425
Abstract

Numerous parameterizations have been developed for predicting wind erosion, yet the physical mechanism of dust emission is not fully understood. Sandblasting is thought to be the primary mechanism, but recent studies suggest that dust emission by direct aerodynamic entrainment can be significant under certain conditions. In this work, using wind tunnel experiments, we investigated some of the lesser understood aspects of dust emission in sandblasting and aerodynamic entrainment for three soil types, namely clay, silty clay loam, and clay loam. First, we explored the role of erodible surface roughness on dust emitted by aerodynamic entrainment. Second, we compared the emitted dust concentration in sandblasting and aerodynamic entrainment under a range of wind friction velocities. Finally, we explored the sensitivity of emitted dust particle size distribution (PSD) to soil type and wind friction velocity in these two processes. The dust concentration in aerodynamic entrainment showed strong positive correlation, no significant correlation, and weak negative correlation, for the clay, silty clay loam, and clay loam, respectively, with the erodible soil surface roughness. The dust in aerodynamic entrainment was significant constituting up to 28.3, 41.4, and 146.4% compared to sandblasting for the clay, silty clay loam, and clay loam, respectively. PSD of emitted dust was sensitive to soil type in both sandblasting and aerodynamic entrainment. PSD was sensitive to the friction velocity in aerodynamic entrainment but not in sandblasting. Our results highlight the need to consider the details of sandblasting and direct aerodynamic entrainment processes in parameterizing dust emission in global/regional climate models.

Key points

- Surface roughness is shown to affect dust emitted by aerodynamic entrainment in a wind tunnel test
- Dust emission by aerodynamic entrainment can be even higher compared to that by sandblasting
- Sensitivity of emitted dust PSD to soil type and friction velocity depends on emission mechanism
1. Introduction

The main mechanism for dust emission is believed to be 'sandblasting', in which saltating sand-sized particles bombard a soil surface and transfer a fraction of kinetic energy to the soil bed causing dust entrainment [Bagnold, 1941; Shao et al., 1993]. Numerous parameterizations have been developed for predicting wind erosion based on field and wind tunnel experiments in which streamwise saltating mass flux and associated vertical dust flux are expressed in terms of wind shear stress [e.g., Bagnold, 1941; Gillette et al., 1974; Marticorena and Bergametti, 1995; Zender et al., 2003]. It is generally believed that mobilization of dust by 'direct aerodynamic entrainment' is not significant in comparison with sandblasting [Shao et al., 1993]. Dust emission by direct aerodynamic entrainment is not considered in saltation-based global/regional dust models [e.g., Zender et al., 2003], although some models [e.g., Gillette and Passi, 1988; Ginoux et al., 2001] account for the dust emitted by both mechanisms in terms of surface wind velocity. Several studies, however, have shown that under certain conditions, for example, in fine soils without crust [Loosmore and Hunt, 2000], silty agricultural soil [Kjelgaard et al., 2004], supply-limited desert surfaces [Macpherson et al., 2008], loess deposits [Sweeney and Mason, 2013], and under convective turbulence [Klose et al., 2014], the primary mechanism for dust emission is aerodynamic entrainment rather than sandblasting. In this work, we compare emitted dust concentrations and particle size distributions (PSD) in sandblasting to those in direct aerodynamic entrainment for a range of friction velocities in an attempt to understand the dynamics of dust emission in these two processes.

Most of the previous studies [e.g., Chepil, 1950; Marshall, 1971; Marticorena and Bergametti, 1995; Lopez et al., 1998; Chappell et al., 2010] recognize the suppressing effect of non-erodible roughness elements on dust emission by momentum absorption. However, little is known about how dust emission responds when the surface roughness consists of
erodible roughness elements. A few previous studies [e.g., Gillette et al., 1980; Baddock et al., 2011; Sankey et al., 2011] have found that disturbing soil enhances dust emission, but these have not explored the underlying reasons. In this work, we explicitly focused on investigating the effect of erodible surface roughness in dust emitted by direct aerodynamic entrainment. Surface roughness here refers to the mm-scale micro-relief or variable-scale physical roughness of the erodible soil surface.

The sensitivity of the emitted dust PSD to soil type has been investigated recently [e.g., Floyd and Gill, 2011; Shao et al., 2011a], but without considering the emission mechanism. With the exception of Alfaro et al. [1997], previous field and wind tunnel experiments [e.g., Gillette et al., 1974; Sow et al., 2009; Shao et al., 2011a] including a recent comparative study of past field and wind tunnel data [Kok, 2011] show that emitted dust PSD does not depend on wind friction velocity (hereinafter called friction velocity). In this work, we also investigated the sensitivity of the emitted dust PSD to soil type and friction velocity.

In summary, this work investigates dust emission in sandblasting and direct aerodynamic entrainment in a wind tunnel for three soil types: clay, silty clay loam, and clay loam, and explores the following specific research questions:

1. What is the role of soil surface roughness in dust emission by direct aerodynamic entrainment?

2. How does the concentration of dust emitted in direct aerodynamic entrainment compare to that in sandblasting for a range of friction velocities?

3. Is the PSD of the emitted dust in direct aerodynamic entrainment and sandblasting sensitive to soil type and friction velocity?
2. Background

2.1 Dust emission by sandblasting

Saltation is initiated when the wind friction velocity $u_*$ exceeds a critical threshold known as the threshold friction velocity $u_{*t}$ [Bagnold, 1941], which is often expressed as a function of soil particle size and moisture [Iversen and White, 1982; Gillette and Passi, 1988; Ginoux et al., 2001]. The resulting saltating mass flux and subsequent dust emission by sandblasting depend upon several factors including the erodibility of the underlying bed [Ho et al. 2011], height of the saltation layer [Bagnold, 1941; Owen, 1964], the distance at which equilibrium is reached in the saltation layer [Anderson and Haff, 1991; Shao and Raupach, 1992], soil clay content [Marticorena and Bergametti, 1995], soil crusting [Gillette, 1978; Rice et al., 1996; Rajot et al., 2003; O’Brien and McKenna Neuman, 2012], and compaction of the soil bed [Lu and Shao, 1999; Gordon and McKenna Neuman, 2009].

2.2 Dust emission by direct aerodynamic entrainment

Dust emission by aerodynamic entrainment is governed by several factors such as surface roughness [Sankey et al., 2011], soil disturbances [Gillette et al., 1980], particle size [Bagnold, 1941; Shao and Lu, 2000; Zobeck et al., 2013], crusting [Gillette, 1978], cohesion [Shao and Lu, 2000], fetch effect [Roney and White, 2006], carbonate content [Zobeck and Amante-Orozco, 2001; Mockford, 2013], and soil dry stability [Zobeck et al., 2013]. Surface roughness appears to be one of the main controlling factors of dust emission in direct aerodynamic entrainment. Roughness configuration can affect horizontal sediment flux and dust emission by modifying the threshold friction velocity [Greeley et al., 1991], wind momentum transferred to the soil surface [Marshall, 1971; Dong et al., 2002], proportion of a land surface over which $u_*$ exceeds $u_{*t}$ [Webb et al., 2014], and through sheltering effects by non-erodible roughness elements [Marshall, 1971; Zobeck, 1991; Raupach et al., 1993; Marticorena and Bergametti, 1995; Brown et al., 2008; Chappell et al., 2010]. Aerodynamic
roughness length \( z_0 \), which is the height in the wind profile at which the wind velocity theoretically becomes zero, is generally derived by measuring the wind profile in the turbulent boundary layer and usually treated as a constant. However, \( z_0 \) is extremely sensitive to the surface roughness [Dong et al., 2002], so it is important to characterize its value under the natural conditions at which saltation and dust emission take place. Surface roughness has been quantified with geometric indices such as roughness height distribution, ridge to height ratio, roughness density and micro-relief index [Allmaras et al., 1966; Currence and Lovely, 1970; Potter et al., 1990; Zobeck et al., 2003], and brightness of the surface which is directly related to the measured \( z_0 \) [Dong et al., 2002; Chappell et al., 2010; Shao et al., 2011b].

### 2.3 Particle size distribution (PSD) of emitted dust

Measurement of particulate matter such as PM10 and PM2.5 (particulate matter with an aerodynamic diameter of less than 10 and 2.5 µm, respectively) and their PSD during dust events are essential because of implications for Earth’s radiative forcing [Tegen and Lacis, 1996] and human health [Kellogg and Griffin, 2006]. Many global/regional climate models, including the Community Earth System Model (CESM) and the Weather Research and Forecasting Model coupled with Chemistry (WRF-Chem), use the parameterizations proposed by Ginoux et al. [2001] and Zender et al. [2003]. In these models, the calculated vertical dust mass flux is generally distributed log-normally in a certain range of particle size bins usually between 0.1 and 10 µm, which is based on observations during field campaigns [e.g., D’Almeida, 1987].

Although the PSD of emitted dust is mostly governed by the parent soil PSD, it can change drastically during the process of dust emission because of disaggregation [Gillette et al., 1974; Arriaga et al., 2006; Shao et al., 2011a]. In sandblasting, soil particles may be disaggregated because of the impact of saltating sand particles [Alfaro et al., 1997] and due to inter-particle collision [Crouvi et al., 2012], which, in turn, can affect the particle size
distribution of the dust emitted. In direct aerodynamic entrainment, smaller loose particles may be mobilized earlier although cohesion usually restricts their emission [Shao and Lu, 2000; Gordon and McKenna Neuman, 2009].

The PSD of emitted dust generally follows a lognormal distribution, which has been demonstrated by many wind tunnel studies [e.g., Gillette, 1978; Alfaro et al., 1997] and field studies [e.g., Patterson and Gillette, 1977; D’Almeida, 1987; Sow et al., 2009]. In the global dust-modeling context, simplified distributions such as lognormal distributions are preferred because of ease in computation, although more sophisticated methods such as log-hyperbolic and Weibull distributions have been proposed to describe real world PSDs [e.g., Christiansen et al., 1984; Zobeck et al., 1999]. The frequency function for a lognormal PSD can be written as

\[
\frac{dN}{d\log D} = \frac{N}{\sqrt{2\pi} \sigma_D} \exp \left[ -\frac{(\log D - \log D_m)^2}{2 \log^2 \sigma_D} \right]
\]

where \(D\) is particle diameter, \(N\) is the total aerosol number concentration, \(D_m\) is the mean modal diameter or geometric mean diameter, and \(\sigma_D\) is the geometric standard deviation [Hinds, 1982].

3. Materials and Methods

3.1 Soils/sand used

Three types of soil were used in this study (Figure 1). The first was a commercial, kaolinitic soil (H. C. Spinks Company, Inc., Paris, Tennessee) containing 77.1% clay, 22.2% silt, and 0.6% sand as determined by the hydrometer method. This soil was classified as clay and was extremely loose and powdery to the touch. The second and third soils were natural, loose, surface soils collected from rangeland near Las Cruces (Jornada), New Mexico. The second soil contained 30.1% clay, 52.9% silt, and 17% sand and was classified as ‘silty clay loam’. The third soil, classified as ‘clay loam’, contained 28.4% clay, 37.1% silt, and 34.4%
sand. The sand used as abrading material was a prewashed, well-sorted fine sand named Oklahoma #1 sand, which was virtually dust free (0.03% < 10 µm) [Van Pelt et al., 2010; Zobeck et al., 2013]. The soil types and size distribution of abrading sand used in this study were similar to those used in some past studies [e.g., Shao et al., 1993; Alfaro et al., 1997]. The dry PSDs of the soils and abrading sand are presented in Figure 2. They were obtained by using the dry system of a commercially available laser diffraction particle-sizer (Beckman Coulter Multisizer LS 13 320).

3.2 Wind tunnel set-up

Three sets of experiments outlined in section 3.7 were conducted in a wind tunnel facility of the United States Department of Agriculture-Agriculture Research Service (USDA-ARS)/Wind Erosion and Water Conservation Research Unit located in Lubbock, Texas. The wind tunnel is a suction-type, non-recirculating tunnel about 10 m in length with a cross-section of 0.5×1.0 m. Convergence and flow straightening takes place in the initial section of the tunnel after which a deep boundary layer is developed in the tunnel. More details on the wind tunnel are described elsewhere by Ravi et al. [2006] and Amante-Orozco [2000]. The wind tunnel has a non-erodible, rough bed made by gluing coarse sand on the floor. The maximum free stream wind velocity attainable is about 15 m s⁻¹. The soil was contained in a tray of dimensions 0.5 (length) × 0.1 (width) × 0.004 (depth) m, which was oriented with its length parallel to the wind direction as shown in the schematic diagram of the wind tunnel (Figure 3).

Reynolds number ($R_e$) and Froude number ($F$) were used to characterize the flow in the wind tunnel, which are given by $uH/v$ and $u^2/gH$, respectively, where $u$, $H$, and $v$ are free-stream wind velocity, height of wind tunnel, and kinematic viscosity of air, respectively. A threshold Reynolds number of 1400 [Bagnold, 1941, pp 46] and a Froude number upper limit of 20 [Pietersma et al., 1996] are suggested for a turbulent boundary layer to be developed.
3.3 Determination of friction velocity

The wind profile was determined by collecting wind velocity measurements with a hot-wire anemometer from eight different heights of 0.05, 0.055, 0.104, 0.203, 0.303, 0.402, 0.502, and 0.602 m at a wind-tunnel section immediately upstream of the soil bed. The wind profiles were measured at different target free-stream wind velocities of 3, 6, 9, 12, and 15 m s\(^{-1}\) by setting the fan speed to various levels. The average aerodynamic roughness length was then determined from these wind profiles by using the well-known semi-logarithmic equation:

\[
    u(z) = \frac{u_*}{k} \ln \frac{z}{z_0}
\]

(2)

where \(u(z)\) is wind velocity at height \(z\), \(u_*\) is friction velocity, \(k\) is Von Kármán’s constant (equal to 0.4), and \(z_0\) is aerodynamic roughness length.

The average aerodynamic roughness length derived using the wind profiles was then used to calculate the friction velocity corresponding to actual wind velocity measured at a central height of 0.50 m above the wind-tunnel floor during the experiment.

3.4 Roughness determination

Roughness of the soil surface was measured with an HDI Advance 3-d scanner from LMI Technologies, which can produce a digital elevation model of the surface being scanned at an accuracy of up to 45 \(\mu\)m. The 3-d scanner scans the intended surface for a few seconds using a pair of cameras, generating a few million points per scan. The scanning was done from outside the tunnel through the Plexiglas surface after the soil tray was positioned flush with the wind tunnel floor. Because of the physical limitations and positional constraints of the scanner, the field of view covered only about the central 56% of the total sample tray length, but covered the whole width (0.1 m).

We used a standard deviation index (SDI) \([Arvidsson and Bölenius 2006; García\]
Moreno et al., 2008], the standard deviation of the soil surface elevations, to characterize surface roughness. This index represents the effect of both random and oriented roughness [García Moreno et al., 2008]. It is given by

\[ SDI = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (Z_i - \bar{Z})^2} \]  

where \( Z_i \) is the elevation of \( i^{th} \) point, \( \bar{Z} \) is the mean elevation, and \( N \) is the number of points.

3.5 Emitted dust measurement

A portable optical laser spectrometer (GRIMM 1.109) designed to measure the dust particle number or concentration in 31 channels sized between 0.25 and 32 \( \mu \)m was used to measure the PSD of emitted dust. Dust concentration measured by the GRIMM is presented in terms of mass concentration \( dm/d\log d_p \) averaged over one minute for the sandblasting and the direct aerodynamic entrainment cases, where \( dm \) represents the fraction of dust mass concentration in a channel and \( d_p \) is the particle diameter. The air was sampled isokinetically from the entire vertical profile of the tunnel immediately downwind of the soil bed using a vertical slot sampler with a width of 3 mm. Because the sampling was done from the whole vertical section of the tunnel, the concentration measured by the GRIMM represents the average particle concentration of the vertical concentration profile [Stout and Zobeck, 1996]. More details about the GRIMM instrument are given by Amante-Orozco [2000] and Van Pelt et al. [2010].

3.6 Saltation measurement

The sand supplied from the hopper was introduced into the tunnel floor approximately 6.5 m upwind from the center of the soil tray through three drop tubes. The saltating flux was monitored using a SENSIT sensor, which counts particles hitting the sensor per unit time. The sensor of the SENSIT was located 22 cm downwind of the soil tray at a height of 2.5 cm above the tunnel floor off-center of the longitudinal axis of the soil tray. It is noted that the
SENSIT counted the sand particles that did not strike the soil bed at all, particles rebounded after hitting the soil bed, as well as soil particles ejected from the soil bed. Although the SENSIT does not directly provide the total streamwise saltating sand flux, it provides a good measure of relative change in the saltating sand flux at different friction velocities.

3.7 Experiments

Three sets of experiments were conducted in this study. The first set was the ‘roughness case’, which was designed to address the first research question given in section one. Similarly, the second and third sets were the ‘direct aerodynamic entrainment case’ and ‘sandblasting case’ designed to address the second and third research questions, respectively.

The purpose of the ‘roughness case’ was to investigate the effect of surface roughness on dust emission by direct aerodynamic entrainment. The experiment was conducted at two constant target free-stream wind velocities of 9 and 12 m s$^{-1}$ for all three soils without a supply of abrading sand. The soil within the section of the soil bed being scanned was roughened by a hand-held dressing tool (Figure 4) consisting of three wheels each with 10 points. Each wheel was 4 cm in diameter and 0.5 cm from the adjacent wheel. The initial geometric roughness of the soil bed (see Figure 4 for a sample picture) was measured with the scanner after which the soil bed was exposed to the target wind velocity in the wind tunnel. Twenty six measurement were collected at each target wind velocity and for each soil by running the dressing tool across the soil bed a variable number of times, thus creating variable surface roughness. The dressing tool was run only in transverse direction for consistency, which created oriented roughness perpendicular to the soil bed length. The wind tunnel was turned on and the emitted dust concentration was measured over a one minute period by the GRIMM. Total dust concentration was then used for analysis calculated by summing the dust concentrations in all bin sizes. A one minute averaging time was chosen to be consistent in all experiments, and because dust emission from the soil surface largely
stopped after about a minute.

In the direct aerodynamic entrainment case, the emitted dust concentration and PSD were measured at five different target wind velocities (3, 6, 9, 12, and 15 m s\(^{-1}\)) without a supply of abrading sand for all three soils. The experiment at each target wind velocity was repeated three times to check for reproducibility. The soil surface was roughened by running the dressing tool over it in order to enhance the dust signal. The dressing tool was run carefully a fixed number of times at each repetition to ensure consistency. The wind tunnel was then turned on, and the emitted dust concentration and PSD were measured immediately over the subsequent one minute period.

In the sandblasting case, the emitted dust concentration and PSD were measured for the three soils at only three target free-stream wind velocities of 9, 12, and 15 m s\(^{-1}\) because sand was deposited on the tunnel floor at wind velocities below 9 m s\(^{-1}\). The experiment at each target wind velocity was repeated three times to check for reproducibility. Abrading sand was introduced through the hopper at a constant rate of 459.6 \(\pm 6.3\) g min\(^{-1}\). The minimum friction velocity of \(\sim 0.45\) m s\(^{-1}\) (corresponding to 9 m s\(^{-1}\) free-stream wind velocity) was larger than the threshold friction velocity of 0.3 m s\(^{-1}\) calculated using an empirical equation from Shao and Lu [2000] for the mean diameter of the abrading sand. Visual examination confirmed that saltation took place without any deposition of the sand particles on the wind tunnel floor at all target wind velocities. The soil tray was filled with soil and leveled smooth after which it was installed in the wind tunnel flush with the tunnel floor. The wind tunnel was turned on and the background concentration was measured for an initial 30 seconds before the abrading sand was introduced from the hopper. The background dust measured was very low (see results section) compared to the dust emitted after the abrading sand was introduced. Therefore, it was reasonable to assume that dust emission was mainly due to sandblasting. An averaging time of one minute was chosen because the soil bed
eroded to the full depth of soil by sandblasting after about one minute when exposed to the highest target wind velocity.

Each set of experiments were conducted on the same day to limit daily variations in temperature and humidity. For all sets, a fresh test soil bed was used for each run. The wind velocity was brought up to the target wind velocity as quickly as possible in a consistent manner.

4. Results

4.1 Boundary layer measurements

The mean aerodynamic roughness length calculated from all five wind profiles at different target wind velocities was 0.15 mm. The friction velocities corresponding to target wind velocities of 3, 6, 9, 12, and 15 m s$^{-1}$ were 0.15, 0.30, 0.45, 0.61, and 0.73 m s$^{-1}$, respectively. The Reynolds number ranged from $1.91 \times 10^5$ to $9.57 \times 10^5$ and the Froude number ranged from 0.9 to 22.9 between 3 and 15 m s$^{-1}$ target wind velocities, respectively, indicating the development of a fully turbulent boundary layer even at the lowest target wind velocity.

4.2 Roughness case

Typical digital elevation models of the rough surfaces for the three soils are presented in Figure 5. The vertical stripes in Figure 5 are the oriented surface roughness features created by the dressing tool. It is noted that the SDI represents the standard deviation in elevation of the whole soil surface and not only that of the roughened surface.

The observed relationships between mean dust concentration and the SDI for the three soils at 9 and 12 m s$^{-1}$ are presented in Figure 6. The emitted dust concentration for the clay soil showed strong dependence on surface roughness with significant ($P<0.05$) correlation coefficients of 0.72 and 0.79 at 9 and 12 m s$^{-1}$, respectively. The emitted dust concentration
did not seem to depend upon the surface roughness for the silty clay loam at either wind velocities as the correlation was insignificant (P>0.05). Similarly, the dust concentration was inversely related to the SDI for the clay loam with significant (P<0.05) correlation coefficients of 0.47 and 0.49 at 9 and 12 m s\(^{-1}\), respectively.

### 4.3 Direct aerodynamic entrainment case

The concentrations of the emitted dust at different target wind velocities for the three soils in the direct aerodynamic entrainment case are presented in Figure 7. The low standard error in emitted dust PSD measurements represented by the shading shows that the rough surfaces created on the soil were consistent across the three repetitions. In general, dust concentration increased with increasing friction velocity for all the soils. One minute averaged dust concentrations summed over all bins for the clay soil at 9, 12, and 15 target wind velocities were 84, 211, and 219 µg m\(^{-3}\), respectively. Similarly, the dust concentrations were 69, 166, and 239 µg m\(^{-3}\) for the silty clay loam and 130, 395, and 848 µg m\(^{-3}\) for the clay loam at 9, 12, and 15 target wind velocities, respectively. All the soils had two unique peaks in the PSD, which may be related to the initial soil PSD (Figure 2).

The mean temporal profiles of dust concentration at different friction velocities for the three soils are presented in Figure 8. The dust concentration rose quickly after the wind tunnel was turned on and started decreasing after reaching the peak. The temporal profiles also confirmed the trend of increasing dust concentration with friction velocity for all the soils.

The results of two-sample t-tests for testing the sensitivity of the mean modal diameter of the emitted dust to the soil type are presented in Table 1 showing significant differences in the mean modal diameters (P<0.05) from different soils in certain cases. This suggested that the PSD was sensitive to soil type in the direct aerodynamic entrainment case.
Similarly, t-tests results (Table 2) revealed significant differences in the mean modal diameters (P<0.05) at certain friction velocities. This indicated that the mean modal diameters were sensitive to the friction velocity as well.

### 4.4 Sandblasting case

SENSIT count data (Figure 9) showed that saltation intensity generally increased with increasing friction velocity for all soils. There appears to be a consistent bias in the SENSIT count data of the three soils at each friction velocity. This could be due to differences in soil bed properties that can affect particle rebound. The bias could also be related to soil PSD, which can affect the number of counts registered by the SENSIT sensor as the smaller particles tend to follow the streamlines around the sensor and may not be registered.

Figure 10 shows the mean dust concentration by particle size at three different target wind velocities in the sandblasting case. The dust concentration generally decreased with increasing friction velocity. One minute averaged dust concentrations summed over all bins for the clay soil at 9, 12, and 15 target wind velocities were, 10,747, 8,985, and 772 μg m⁻³, respectively. Similarly, the dust concentrations were 1,509, 1,421, and 578 μg m⁻³ for the silty clay loam and 1,899, 1,876, and 579 μg m⁻³ for the clay loam at 9, 12, and 15 target wind velocities, respectively. Note that the dust concentration for clay soil was about one order of magnitude higher than for the silty clay loam and clay loam, unlike in the direct aerodynamic entrainment case where the clay loam had about three times the concentration as that of the clay and silty clay loam. The sharp reduction of dust concentration at 15 m s⁻¹ is noted and was consistent for all the soils, although the reduction was higher for the clay.

Figure 11 shows the mean temporal profiles of the emitted dust concentration in the sandblasting case. The sharp increase in dust concentration after about 30 seconds marks the impact of saltating particles on the soil bed. The dust concentration fluctuated more for the silty clay loam and clay loam than for the clay, possibly due to the soil texture differences;
the former two contained more soil peds. The emitted dust concentration quickly reached the maximum after which the dust emission rate did not change much.

The results of the two-sample t-tests (Table 3) showed that the mean modal diameters of the dust emitted from the three soils were significantly different from each other (P<0.05) at all friction velocities indicating that the PSD was sensitive to the soil type in the sandblasting case as well. However, the t-tests results showed that the mean modal diameters at different friction velocities were not significantly different (P>0.05) from each other for all the soils (not presented). The mean modal diameter of the emitted dust, therefore, did not depend upon friction velocity in sandblasting.

5. Discussion

5.1 Roughness case

One of the most commonly accepted theoretical explanations on the effect of non-erodible surface roughness in dust emission is given by the drag partitioning approach [Marshall, 1971]. The momentum extracted by non-erodible roughness elements is primarily controlled by roughness density, which is usually expressed in terms of lateral cover or frontal area index [Marshall, 1971; Marticorena and Bergametti, 1995; Chappell et al., 2010] as \( \lambda = \frac{nbh}{S} \), where \( n \) is the number of roughness elements within an area \( S \), and \( b \) and \( h \) are the width and height of roughness elements, respectively. The consequence of such drag partitioning is that dust emission decreases with increasing roughness density of the non-erodible elements due to the increase in apparent threshold friction velocity [Marticorena and Bergametti, 1995].

Although there were no non-erodible roughness elements in our soil bed, the ridges on the roughened soil surface may have absorbed some momentum, and may also have caused a sheltering effect, both of which would suppress dust mobilization. But these effects cannot explain the differences in the nature of the relationship between dust concentration and SDI.
observed (Figure 6) for the three soils as the method employed for soil surface roughening was similar for all the soils. It appears that the differences were, to some extent, due to differences in sand content in the three soils. Sand content was lowest in the clay soil (0.6%), thus most of the momentum was transferred to the silt/clay particles that were essentially the sources of dust. Thus the emitted dust concentration showed strong, proportional dependence upon surface roughness for the clay soil. The dry sand content was higher in the silty clay loam (17%) and less momentum was transferred to the silt/clay particles as compared to the sand particles when the SDI was higher. The increasing effect of dust mobilization in the silt/clay fraction was balanced by the suppression caused by more momentum transfer to the sand particles at higher SDI. Therefore the emitted dust concentration showed no dependence on SDI. Similarly, for the clay loam, sand content was even higher (34.4%) and even more momentum was transferred to the sand particles resulting in an inverse relationship between the dust concentration and the SDI.

5.2 Direct aerodynamic entrainment case

The dust concentration for all soils in aerodynamic entrainment generally increased with increasing friction velocity and the main mode of dust PSD was ~ 1-10 μm. The decrease in dust concentration after reaching the peak (Figure 8) may be due to the decrease in the degree of erodible surface roughness, which determine the availability of loose soils. The changing surface roughness caused changes in the threshold friction velocity [Greeley et al., 1991] and the momentum transferred to the particles [Marshall, 1971] which control particle mobilization. The temporal profile of dust emission was very similar to the results of a wind tunnel experiment for pure dust configuration reported in Shao et al. [1993].

The percentage of dust in aerodynamic entrainment as compared to sandblasting increased with the wind speed. The dust concentration in aerodynamic entrainment at 15 m s⁻¹ for the clay and silty clay loam were 28.3 and 41.4% of sandblasting, respectively. For
the clay loam, dust concentration in aerodynamic entrainment at 15 m s$^{-1}$ was even higher (146.4%) than in sandblasting. These results indicate that dust emitted by direct aerodynamic entrainment is significant and cannot be neglected in modeling dust emission. As the results of the roughness case (section 4.2) indicate, the aerodynamically entrained dust seemed to be affected by the erodible surface roughness suggesting that this effect should be further explored and accounted for in modeling dust emission. Results of the sensitivity tests (Tables 1 and 2) showed that emitted dust PSD was sensitive to both soil type and friction velocity in the direct aerodynamic entrainment case. In the dust modeling context, these results indicate that the soil type and friction velocity are important factors to be considered when prescribing the emitted dust PSD, although their detailed inclusion is often limited by computational constraint [Liu et al., 2012].

5.3 Sandblasting case

Unlike in the aerodynamic entrainment case, the emitted dust concentration from the clay was significantly higher than that from the other two soils in the sandblasting case. We believe that the higher emission from the clay soil was due to a higher sandblasting efficiency, because the clay soil was looser and had a greater proportion of silt and clay compared to the other two soils. In a test of 37 soils in a dust generator, Mockford [2013] also found an increase in airborne dust with increasing clay and silt content.

The main mode of emitted dust PSD observed in the sandblasting case was ~1-10 µm for all the soils, which was strikingly similar to that in the direct aerodynamic entrainment case despite the existence of different particle modes in the initial soil PSDs (Figure 2).

Results of the sensitivity test showed that emitted dust PSD was sensitive to soil type in sandblasting as well. The dust PSD did not show sensitivity to the friction velocity in sandblasting, which was consistent with many previous studies [e.g., Gillette et al., 1974; Shao et al., 2011a; Sow et al., 2009; Kok, 2011]. However, the previous studies did not
distinguish between sandblasting and aerodynamic entrainment.

The observed evolution of dust emission with time (Figure 11) was similar to that observed by Shao et al. [1993] in a wind tunnel experiment. However, our observations contrasted with theirs in the sense that we observed a decrease in dust concentration with increase in friction velocity. Our results cannot be compared directly to Shao et al. [1993] for a number of reasons. First, in their experiment, sand was supplied from a thick sand bed placed immediately upwind of the soil bed, which in our case, was supplied from a hopper at a constant rate. Because of the difference in the way the sand was supplied, supply limitation at higher wind velocity is less likely in their case as compared to ours. In contrast, because the tunnel length available for saltation development was shorter in their case, development of steady state saltation is less likely compared to ours, which can affect the saltating mass flux. Finally, the length of our soil bed was smaller compared to theirs, which can affect particle impact density and subsequent dust emission.

There are two potential mechanisms for the decrease in emitted dust concentration at higher wind velocities. First, a constant flux of sand supplied might have resulted in under-saturation at higher wind velocity [O’Brien and McKenna Neuman, 2012; Li and McKenna Neuman, 2012]. Although the saltation intensity generally increased with increasing friction velocity (Figure 9), the possible effect of supply limitation cannot be ruled out because the particles from the soil surface may have also contributed to the SENSIT counts. The second possibility is that the mean jump length (l) might have increased with increasing friction velocity [Sørensen, 1985; Alfaro et al., 1997; Ho et al., 2011], causing a decrease in dust emission due to reduced impact frequency. Such a reduction in particle impact frequency at higher friction velocity has not been well documented in aeolian research but it has been theoretically modeled and experimentally validated in many fluvial bedload-transport studies [e.g., Sklar and Dietrich, 1998; Sklar and Dietrich, 2004]. Although the mean volume of
sediment eroded per impact increases linearly with the increase in impact velocity as the flow velocity and bed shear stress increase, the maximum rate of bed erosion occurs at intermediate levels of excess shear stress due to the reduction in impact frequency [Sklar and Dietrich, 1998; Whipple and Tucker, 2002; Sklar and Dietrich, 2004]. We conducted two supplementary experiments, namely ‘supply limitation test’ and ‘impact frequency test’, in order to ascertain which of these two mechanisms affected our results.

We recorded the SENSIT counts without the soil bed in the supply limitation test. A flat wooden board with a similar surface to that of the wind tunnel floor was used in place of the soil bed, and the saltating sand rate over one minute period was measured at the three target wind velocities. These SENSIT counts are presented in Figure 12a and showed an increasing trend, indicating that the saltation flux increased with the increase in friction velocity. This result ruled out the possibility of a decrease in dust emission at higher wind velocity due to supply limitation.

In the second test, we measured sand impact frequency by using a Petri dish filled with water in place of the soil bed. The saltating sand particles striking the surface of the water in the Petri dish were not able to rebound and were effectively trapped. Trapped sand over one minute at the three target wind velocities was dried overnight and weighed. Figure 12b plots trapped sand mass against friction velocity, and clearly showed that impact frequency was reduced at higher wind velocity. These results support the interpretation that the reduction in dust concentration at higher wind velocity was due to the reduction in impact frequency. The SENSIT counts data in the impact frequency test are also presented in Figure 12a, showing an increasing trend as expected. It is noted here that the SENSIT measures the impact counts of the sands per second at a fixed point. While the SENSIT counts can be used as a proxy for saltating flux, it cannot be used as a proxy for impact frequency, which is the impact counts per unit horizontal surface area.
To illustrate the effect of the increased jump length on impact frequency, consider saltation of a single sand particle. Let the length of soil bed be \( L \), and the mean jump length of the saltating particle be \( l \). Assuming a perfectly elastic collision, when \( l = L/4 \), the sand particle is likely to hit the bed four times, when \( l = L/2 \) the particle is likely to hit the bed twice, and so on. Therefore the net flux of particles impacting the bed or impact frequency should be proportional to \( L/l \), which is what is accounted for in the bed erosion model of Sklar and Dietrich [1998].

In reality, the process of dust ejection after sand particle impact, known as splash entrainment, is much more complex. The above assumption that the emitted dust is proportional to the impact frequency may not be strictly true because some momentum is lost by the particle into the bed depending upon properties of soil bed such as crusting, particle size, plasticity, and soil moisture [e.g., Rice et al., 1996; Ginoux et al., 2001; O’Brien and McKenna Neuman, 2012]. The saltation length and height after impacting the soil bed also depends upon the lift-off velocity and turbulence [Shao and Li, 1999], and the coefficient of restitution of the bed [Anderson and Haff, 1988].

6. Conclusion

In this paper, we investigated three important aspects of dust emission in sandblasting and direct aerodynamic entrainment for three different soil types, namely clay, silty clay loam, and clay loam using wind tunnel experiments. First, we investigated the role of erodible roughness in dust emitted by direct aerodynamic entrainment. Second, we compared the concentration of emitted dust in sandblasting and direct aerodynamic entrainment under a range of friction velocities. Finally, we investigated the sensitivity of dust PSD emitted by sandblasting and direct aerodynamic entrainment to the wind friction velocity and soil type.

The dust emitted by aerodynamic entrainment showed strong positive correlation, no
significant correlation, and weak negative correlation for the clay, silty clay loam, and clay loam, respectively, with the erodible soil surface roughness at millimeter spatial scale. The soil surface roughness was quantified in terms of standard deviation in elevations of the soil bed as measured by a 3-d scanner. Because the surface roughness measurement method employed in this study is scale dependent and the results were sensitive to soil types, validity of this result should be tested at other scales of surface roughness and for other soil types.

Our results showed that dust emission by direct aerodynamic entrainment is significant and can be even higher compared to that by sandblasting under certain conditions. The dust emitted by aerodynamic entrainment at 15 m s\(^{-1}\) as compared to sandblasting was up to 28.3, 41.4, and 146.4\% for the clay, silty clay loam, and clay loam, respectively. We note that, in nature, because sandblasting and direct aerodynamic entrainment tend to occur simultaneously, the reduction in dust concentration at higher wind velocities during sandblasting as observed in this study may not be apparent.

As friction velocity increased, the concentration of dust emitted by direct aerodynamic entrainment generally increased while that by sandblasting decreased, with the increase in friction velocity. We found that the PSD of emitted dust was sensitive to soil type in both sandblasting and direct aerodynamic entrainment cases. Mean modal diameters of emitted dust were dependent on friction velocity in the direct aerodynamic entrainment case but not in the sandblasting case under the range of friction velocities tested. Further study should be done to fully establish the sensitivity of emitted dust PSD on other soil types and at other wind velocities, especially in the higher velocity range in which large-scale dust storms occur in nature.

Our results have implications for dust emission modeling suggesting that consideration of the details of sandblasting and direct aerodynamic entrainment processes while parameterizing dust emission can improve dust characterization in global/regional
climate models. Although our tests were done for only three soil types: clay, silty clay loam, and clay loam, these soils are representative of major disturbed dust sources like agricultural fields, urban settings, construction sites, and cattle grazing areas.

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This work was funded by the third-round grant from King Abdullah University of Science and Technology. We thank Dean Holder from USDA-ARS/Wind Erosion and Water Conservation Research Unit, Lubbock, Texas for providing technical assistance during the experiments. We are extremely grateful to the anonymous reviewers for providing many constructive comments, which have substantially improved the quality of the manuscript. The first author is grateful to Jasper Kok of UCLA, David Mohrig of UT-Austin, and John E Stout of USDA-ARS for providing critical insights into the experimental results. We also thank Adam Papendieck of UT-Austin for proofreading the manuscript. All the data used in this study can be obtained by contacting the first author by e-mail (psagar@utexas.edu).

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Lubbock, Texas.


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Table 1. Differences in mean modal diameter ($\mu m$) by soil type within target wind velocity for the direct aerodynamic entrainment case.

<table>
<thead>
<tr>
<th>Target Wind Velocity (m s$^{-1}$)</th>
<th>Soil Type</th>
<th></th>
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<tr>
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<td>Silty</td>
<td>Clay</td>
<td>Loam</td>
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<td>3.18b</td>
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<td>3.53b</td>
<td>3.74ab</td>
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</table>

*Means with the same letter within a target wind velocity are not significantly different (P>0.05) as determined by two-sample t-tests among comparisons by soil type.
Table 2. Differences in mean modal diameter ($\mu m$) by target wind velocity within soil type for the direct aerodynamic entrainment case.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Target Wind Velocity (m s$^{-1}$)</th>
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</thead>
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<tr>
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<td>Silty Clay Loam</td>
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<td>Clay Loam</td>
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</table>

* Means with the same letter within a soil type are not significantly different (P>0.05) as determined by two-sample t-tests among comparisons by target wind velocity.
Table 3. Differences in mean modal diameter ($\mu m$) by soil type within target wind velocity for the sandblasting case.

<table>
<thead>
<tr>
<th>Target Wind Velocity (m s$^{-1}$)</th>
<th>Soil Type</th>
<th></th>
<th></th>
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</tr>
</tbody>
</table>

*Means with the same letter within a target wind velocity are not significantly different ($P>0.05$) as determined by two-sample t-tests among comparisons by soil type.
Figure 1. Three soil types used in this study. Clay (left), silty clay loam (middle), and clay loam (right).
Figure 2. Dry particle size distribution of the clay, silty clay loam, clay loam soils, and abrading sand.
Figure 3. Schematic diagram of the longitudinal cross section of the wind tunnel.
Figure 4. Dressing tool used for roughening the soil surface (left) and a sample picture of the rough surface created for the clay soil (right).
Figure 5. Typical digital elevation models of the roughened soil surfaces in the roughness case for the (a) clay (b) silty clay loam, and (c) clay loam.
Figure 6. Relationship between standard deviation index (SDI) of elevations and one-minute averaged emitted dust concentration for the three soils at two different target wind velocities. Measured dust represents dust emitted by direct aerodynamic entrainment in the roughness case.
Figure 7. Emitted dust concentration by particle diameter at different friction velocities in the direct aerodynamic entrainment case for the three soils. Shading represents the standard error of the three repetitions. Note the difference in y-axis scales.
Figure 8. Temporal profile of mean emitted dust concentration in the direct aerodynamic entrainment case for the three soils. Note the difference in y-axis scales.
Figure 9. SENSIT counts data (sec⁻¹) averaged over one minute plotted against friction velocities for the sandblasting case. Error bars represent the standard deviation of the three repetitions.
Figure 10. Emitted dust concentration by particle diameter at different friction velocities in the sandblasting case for the three soils. Note the difference in y-axis scales. Shading represents the standard error of the three repetitions.
Figure 11. Temporal profile of mean emitted dust concentration in the sandblasting case for the three soils. Note the difference in y-axis scales.
Figure 12. (a) SENSIT counts data averaged over one minute in the supply limitation test and impact frequency test, (b) Mass of dried, trapped sand collected over one minute in the impact frequency test. Error bars represent the standard deviation of the three repetitions.