Definition and measurement of dust aeolian thresholds

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[1] Dust suspension and particle "saltation threshold" speeds were measured in an environmental boundary layer wind tunnel located at the University of California, Davis. The results indicate that dust suspension threshold speeds occur at substantially lower friction speeds than "saltation threshold" speeds. Many of the dust suspension threshold values are half of the "saltation threshold" values. For example, surface soils from the most erodible areas of Owens (dry) Lake were tested in the wind tunnel, and we found that dust suspension thresholds varied from 50 to 75% of conventional "saltation threshold" values. Current regulatory models relying on "visual threshold" for estimating suspended dust may be incorrect and may lead to substantial underestimates of suspended material yield over large, expansive, erodible areas. Wind environments with average wind speeds at or around the "saltation threshold" speed values are especially susceptible to underestimation. Though this study focuses only on Owens (dry) Lake soils, we believe that the witnessed effect will occur in any soil with an abundance of dust particles interspersed among sand-sized particles. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 0394 Atmospheric Composition and Structure: Instruments and techniques; *KEYWORDS:* dust threshold, PM_{10}, air quality

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1. Introduction

1.1. Owens (Dry) Lake, California, USA

[2] The city of Los Angeles Department of Power and Water started diverting Owens River water from Inyo County to Los Angeles County with the completion of the Los Angeles aqueduct in 1913. The primary source of water for Owens Lake was diminished, if not completely halted. Geologically, Owens Lake had slowly (thousands of years) been drying up naturally due to climatic conditions and desertification of the area; however, this slower process would have allowed a natural lake bed stability to be reached (i.e., proliferation of desert scrub to stabilize the soils). After the Owens River diversion the lake dried up in a matter of years, leaving unstable alkali soils that are susceptible to becoming airborne during windstorms. The desert climate produced by the rain shadow effect of the Sierra Nevada mountain range allowed evaporation of the remaining water. In addition, owing to the meteorology of the area, intense storm events create winds that blow either north or south through the Owens Valley over the lake playa. These storms create intense duststorms that transport high concentrations of PM_{10} (particulate matter of 10 μm or smaller aerodynamic diameter) into the atmosphere, with emissions estimated to be 100,000–400,000 t of particulate matter per year [*Ono and Schade*, 1997]. In fact, by one estimate, the figure is as high as 900,000–8,000,000 t per year [*Gill and Gillette*, 1991], making Owens (dry) Lake the single largest point source of airborne particulate in North America. These airborne particles are small enough to travel great distances and can be inhaled deeply into the human respiratory tract, creating a potential health hazard as well as affecting local air visibility.

[3] Owing to the need for mitigation of the duststorms, the University of California, Davis (UCD) became active in many of the research projects [*White and Cho*, 1994; *Cahill et al.*, 1996; *Kim et al.*, 2000] aimed at solving the problem of dust mitigation. In this paper we describe a study aimed at better understanding the threshold friction velocity for dust suspension of soils from Owens (dry) Lake. Through behavior analysis of the soils in a laboratory wind tunnel, a quantification of the minimum conditions for PM_{10} entrainment for Owens (dry) Lake loose soils is estimated.

1.2. Threshold Friction Velocity

[4] The threshold friction velocity u_{*t}(m s^{-1}) is defined as the velocity at which particles (~50–1000 μm) on the

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surface begin to continuously move, either by creep or suspension. The friction velocity u_* is defined as $(\tau_w/\rho_a)^{1/2}$, where τ_w is the shear stress on the surface and ρ_a is the air density. The threshold friction velocity thus represents the minimum value at which erosion occurs. Sediment entrainment occurs when the forces acting on a stationary particle, lift and drag, are able to overcome the forces resisting the sediment movement: inertial, cohesive, and adhesive forces. The exact nature of this initial movement is debated, but generally, it is described in one of the following two ways: (1) once the critical threshold shear velocity is reached, stationary surface grains begin to roll or slide along the surface by the direct pressure of the wind [*Bagnold*, 1941; *Malina*, 1941; *Chepil*, 1959]; or (2) the grains begin to vibrate back and forth before leaving the surface almost vertically, as if ejected [*Bisal and Nielsen*, 1962; *Lyles and Krauss*, 1971]. *Iversen and White* [1982] suggested that this initial movement is caused by instantaneous air pressure differences that act as lift, spinning the particle into the airstream.

[5] The *Bagnold* [1941] equation is used as one prediction of the threshold friction velocity:

$$u_{*_t} = A\sqrt{\frac{\left(\rho_p - \rho_a\right) \cdot gD}{\rho_a}}, \tag{1}$$

where
- u_{*t} fluid threshold velocity;
- ρ_p relative density of the grains;
- ρ_a relative density of the air;
- D mean grain diameter;
- g gravitational constant.

A is the empirical coefficient equal to 0.1 for particle friction Reynolds number $Re_p > 3.5$:

$$Re_p = \frac{u_{*t} D}{\nu}, \tag{2}$$

where ν is the kinematic viscosity of air. For $Re_p > 3.5$ the grains protrude into the airflow and the surface is termed aerodynamically rough, so drag acts directly on the grains. More complete forms of equation (1) have been developed to account for the behavior of beds of smaller particles, where cohesive forces play an important role [*Fletcher*, 1976a, 1976b; *Iversen and White*, 1982; *Shao and Lu*, 2000]. These relationships between grain diameter and threshold friction velocity have been confirmed by many researchers [*Horikawa and Shen*, 1960; *Chepil and Woodruff*, 1963; *Belly*, 1964; *Iversen et al.*, 1976a, 1976b]. However, although the fluid threshold can be prescribed for uniform sediments >100 μm, it is not as easily defined for most natural sediments because they usually contain grain sizes and shapes that vary in grain density and packing. Therefore experimental measurements of the threshold friction velocity are necessary to estimate the threshold for emissions of natural soils. Past experimental measurements have relied on visual detection [*Bagnold*, 1941; *Gillette et al.*, 1982]; however, in this study we aim to rigorously determine the "first movements" of natural soils with emphasis on dust (PM_{10} materials). For a more complete review of the traditional definitions of the threshold friction velocity, see *Lancaster and Nickling* [1994].

1.3. Dust Suspension/Resuspension

[6] This work describes direct measurements of suspension and resuspension of dusts (particles of aerodynamic diameter <20 μm) in natural soils. At Owens (dry) Lake, this aspect is crucial in estimating the overall flux of PM_{10} on a yearly basis. Traditional models indicate that for homogenous beds of dust particles the friction velocities required for removal create an upturn in the threshold friction velocity curve at ~100 μm particle sizes as cohesive forces such as van der Waals forces, capillarity, and cementation play a crucial role. In this range, $Re_p < 3.5$, the grains lie in the viscous sublayer, with the drag more or less evenly distributed along the aerodynamically "smooth" surface, and suspension occurs without saltation. Wind tunnel studies performed in this range for homogenous beds [*Bagnold*, 1941; *Chepil*, 1945; *Loosmore and Hunt*, 2000] confirm that high wind speeds are required to entrain fine-grained materials. Previous experimenters have shown that in aerodynamic suspension, once threshold conditions have been exceeded, an initial transient dust release falls off quickly to negligible or zero flux in minutes [*Bagnold*, 1941; *Chepil and Woodruff*, 1963; *Shao et al.*, 1993]. *Loosmore and Hunt* [2000] indicate that after the transient response, there is a small sustained flux of dust continuously above threshold that is missed by "visual threshold" techniques. Again, for natural soils, these results are not applicable as distributions of larger particles make the surface aerodynamically "rough," changing the overall surface dynamics. However, dust particle concentrations are important in threshold measurements of natural soils since they add to emissions.

2. Experimental Methods

2.1. Soil Collection Rationale and Preparation

[7] For an accurate assessment of emissions' characteristics of soils, field soils must be used. Accordingly, in September 1999, 5 t of soils were collected at Owens (dry) Lake for use in wind tunnel simulations at the University of California, Davis. Previous field studies by *Niemeyer et al.* [1999], *Cahill et al.* [1996], the Great Basin Unified Air Pollution Control District in 1997, and the California Air Resources Board in 1997 indicated the locations of the dry lake which appeared to be most emissive. These areas were targeted for soil collection, and a GPS instrument was used to precisely identify the areas from which each soil sample was taken. Soil was collected at four separate locations, as indicated and labeled on the map in Figure 1. The exact GPS coordinates and types of soil are described in Table 1.

[8] At each location, the top surface, ~2.5 cm, was removed and soil was collected to depths of ~10–25 cm to ensure that material most susceptible to erosion was collected. Initial visual observations indicated that the soils collected were loose elastic materials for the entire collection depth. During "emissive soil" collections (soil 1 and soil 4) the 2.5 cm layer was discarded since it corresponds to the hard crust, which must be broken mechanically if the loose soils below are to be exposed to wind [*Gillette*, 1978; *Gillette et al.*, 1982]. During sand collection (soil 2 and soil 3), there was no need to remove crusts since these soils

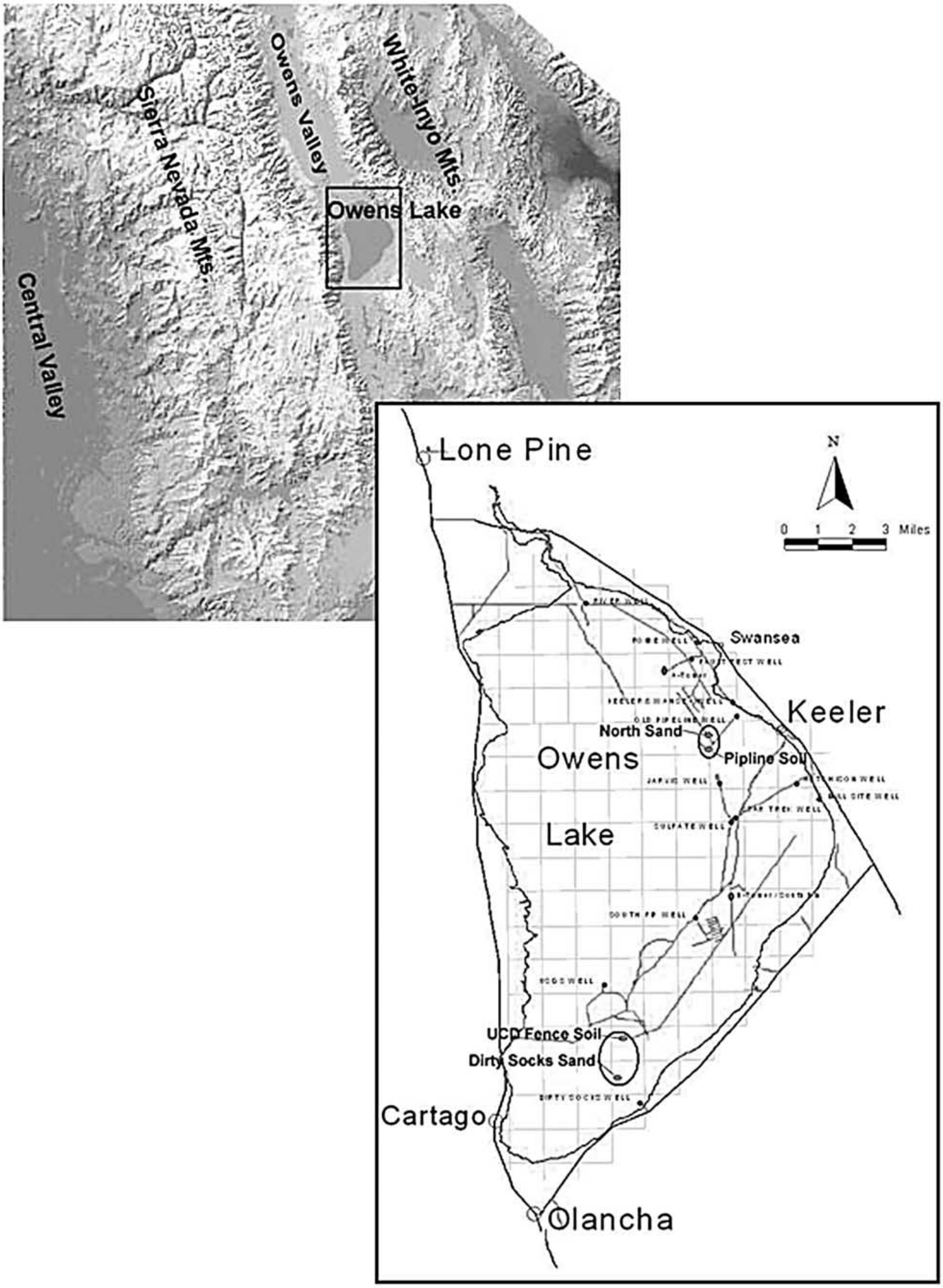

Figure 1. Owens (dry) Lake, California, USA. The mountainous topography strongly influences the meteorology. Soil collection sites are marked by circled dots on the map.

Table 1. Summary of All the Wind Tunnel Measured and Calculated Threshold Friction Velocities for the Four Soils Collected at Owens (Dry) Lake[a]

Soil Designation	Soil Description	GPS N Latitude, deg, min	GPS W Longitude, deg, min	Mean Diameter, mm	u_{*t}, m s^{-1}
		Electrometer Measurements			
1	old pipeline, emissive	36, 28.808	117, 54.649	0.35 ± 0.03	0.35 ± 0.04
2	north sand, sand	36, 29.194	117, 54.655	0.31 ± 0.03	0.38 ± 0.04
3	Dirty Socks dune, sand	36, 20.391	117, 57.681	0.39 ± 0.03	0.40 ± 0.04
4	UCD fence, emissive	36, 21.411	117, 57.467	0.35 ± 0.03	0.36 ± 0.04
		DustTrak® Measurements			
1	old pipeline, emissive	36, 28.808	117, 54.649	0.35 ± 0.03	0.33 ± 0.03
2	north sand, sand	36, 29.194	117, 54.655	0.31 ± 0.03	0.33 ± 0.03
3	Dirty Socks dune, sand	36, 20.391	117, 57.681	0.39 ± 0.03	0.37 ± 0.04
4	UCD fence, emissive	36, 21.411	117, 57.467	0.35 ± 0.03	0.30 ± 0.03
		DustTrak® First Movement Measurements			
1	old pipeline, emissive	36, 28.808	117, 54.649	0.35 ± 0.03	0.18 ± 0.03
2	north sand, sand	36, 29.194	117, 54.655	0.31 ± 0.03	0.28 ± 0.03
3	Dirty Socks dune, sand	36, 20.391	117, 57.681	0.39 ± 0.03	0.20 ± 0.03
4	UCD fence, emissive	36, 21.411	117, 57.467	0.35 ± 0.03	0.18 ± 0.03
		Slope-Method Calculation			
1	old pipeline, emissive	36, 28.808	117, 54.649	0.35 ± 0.03	0.39 ± 0.08
2	north sand, sand	36, 29.194	117, 54.655	0.31 ± 0.03	0.43 ± 0.11
3	Dirty Socks dune, sand	36, 20.391	117, 57.681	0.39 ± 0.03	0.41 ± 0.28
4	UCD fence, emissive	36, 21.411	117, 57.467	0.35 ± 0.03	0.40 ± 0.22

[a]In addition, the collection location, the soil description, and the calculated mean diameter particle size of each soil is shown. UCD, University of California, Davis.

were already loose. Our hypothesis is that loose soils should be tested in the wind tunnel since they are likely to be the major contributor to fugitive dust at Owens Lake. This hypothesis is based on observational studies at the Owens (dry) Lake site performed by previous researchers [*Cahill et al.*, 1996].

[9] The soils were transported back to the University of California, Davis to be used in the wind tunnel studies. Laboratory testing (sieve analysis and other property testing done by an independent laboratory) verified that for each soil, there was no significant stratification of soil properties through the collection depth. As expected, this initial testing also indicated that there were distinct differences between the four soils. All four soils were air dried during low-humidity conditions and then were kept in sealed containers when not in use. The one soil that initially had significant moisture contained some clumping when dried. The clumps were eliminated with a course screen acting as a sieve, and there was likely some pulverizing into finer materials as the clumps and aggregates were passed through the sieve. The other three materials were tested as collected at Owens (dry) Lake with the exception of the initial air drying. Leveling of the soil bed for wind tunnel testing was done with boards and did not appear to create any additional fines. No wind tunnel tests were run on extremely high humidity days since emission reductions would be expected from the soils absorbing moisture from the air.

2.2. Wind Tunnel

[10] All measurements were made in the Saltation wind tunnel (SWT), an environmental boundary layer wind tunnel at the University of California, Davis [*Kim et al.*, 2000]. This open-circuit wind tunnel is designed to simulate particle flows or saltation movement and thus is ideal for simulating the emission of dust from the surface of Owens (dry) Lake. The inlet has an array of flow-straightening tubes to ‘‘filter’’ the incoming air of any large-scale turbulence resulting from objects in the surrounding room. Following the inlet, the tunnel has a long section to develop a turbulent boundary layer characteristic of the surfaces of desert playas. A set of small pebbles were affixed to the bottom surface in the first 5 m of the development section of the tunnel. These pebbles were evenly spaced but randomly oriented such that a well-developed, two-dimensional boundary layer formed prior to impinging on the 5-m-long soil bed. Within the sections containing the soil of interest the boundary layers were closely matched due to similar roughness characteristics. In these sections, to maintain an even depth, a trough 0.025 × 0.30 m wide was used; its side surfaces contained rough sand paper to match the roughness of the soils (Figure 2). Lastly, the diffuser section opened to the outside atmosphere, expelling any suspended dust or sand.

[11] The wind tunnel measurement instrumentation consisted of two TSI DustTraks to measure PM_{10} aerosol concentrations (‘‘fugitive dust’’), a traversing total pressure probe to measure the vertical velocity field, a Pitot-static probe to measure the mean free stream velocity, an electrostatic probe to measure threshold, and stackable isokinetic sand traps [*White*, 1982] to measure the horizontal sand saltation flux.

2.3. Roughness Height z_0, Friction Velocity u_*, and Coefficient of Drag C_d

[12] Every surface has a physical characteristic roughness height z_0, which can be determined from conditions prior to ‘‘saltation threshold.’’ After threshold, saltating particles will affect the surface characteristics. In addition, the shear velocity u_* for any given flow can be calculated. Both z_0

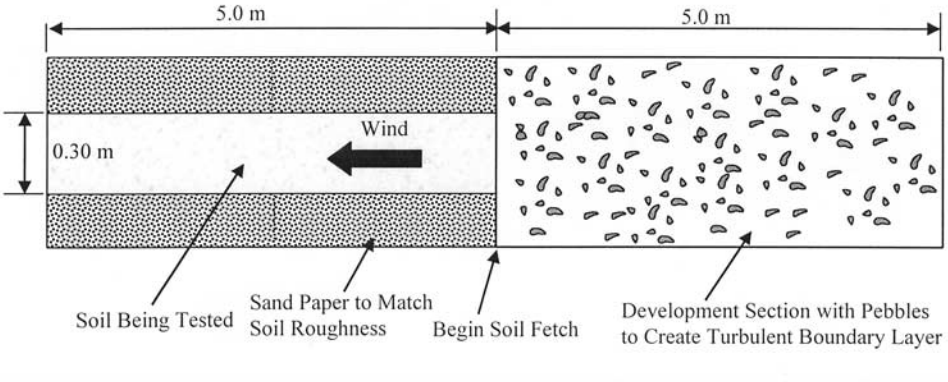

Figure 2. Schematic of the wind tunnel test bed for testing various Owens (dry) Lake soils.

and u_* are determined by using mixing length theory, as prescribed by the following equation:

$$\frac{u(z)}{u_*} = \frac{1}{k}\ln\left(\frac{z}{z_0}\right) \quad (3)$$

and

$$u_* = \sqrt{\frac{\tau_w}{\rho}}, \quad (4)$$

where $u(z)$ is the mean velocity at height z above the surface, u_*; is the friction or shear velocity, k is the von Kármán constant equal to 0.418, z_0 is the aerodynamic roughness, and τ_w is the wall or surface shear stress. This well-known equation was originally developed by Prandtl for any two-dimensional turbulent boundary layer and was later modified to incorporate roughness elements. The premise of the equation is that the turbulent flow is characterized by the surface, which creates a logarithmic velocity profile. Likewise, if one measures the velocity profile, it is possible to obtain the aerodynamic characteristics of the surface. In order to obtain both z_0 and u_*, experiments must be used in combination with mixing length theory. By obtaining a series of velocity profiles at different wind speeds below threshold, z_0 is obtained [*Bagnold*, 1941]. By obtaining the slope of the each curve, u_* was obtained for each case, including the saltation or "postthreshold" cases. However, for the "postthreshold" cases, z_0 is not constant and is replaced with z_0', which varies with increasing wind speed:

$$\frac{u(z)}{u_*} = \frac{1}{k}\ln\left(\frac{z}{z_0'}\right). \quad (5)$$

[13] The experimental method was as follows: First, a specific soil was placed in the test bed; second, a specific free stream velocity U_{ref} below threshold was reached in the tunnel, as indicated by the free stream Pitot-static tube; and finally, a traversing probe was used to record the velocity as a function of height. The traversing probe was used to measure the streamwise velocity at 19 sampling positions above the surface. These locations were spaced logarithmically, and at each location, measurements were taken for 10 s at a sampling rate of 100 Hz. The resulting 1000 data points at each location were averaged together to produce the velocity profile (Figure 3). This procedure was repeated for up to four more free stream velocities below measured threshold. This method was repeated for various combinations of the different soils. The values z_0 and u_* were then calculated using the above theory. Lastly, the coefficient of drag C_d may be calculated from the "prethreshold" linear relationship of u_* versus U_{ref} as follows:

$$u_* = C_d^{1/2} U_{ref} \quad (6)$$

$$C_d = \left(\frac{u_*}{U_{ref}}\right)^2. \quad (7)$$

2.4. Threshold Measurements

[14] An electrostatic probe attached to a Keithley Electrometer Model 602 was placed in the diffuser section of the

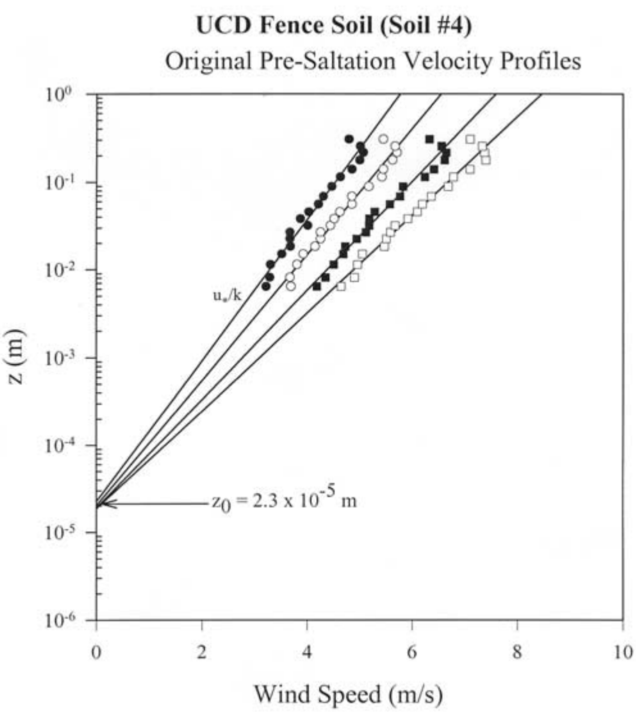

Figure 3. Velocity profiles measured above a single soil type for four different free stream wind tunnel speeds prior to saltation. These types of curves are used to obtain aerodynamic surface characteristics of the different soil beds.

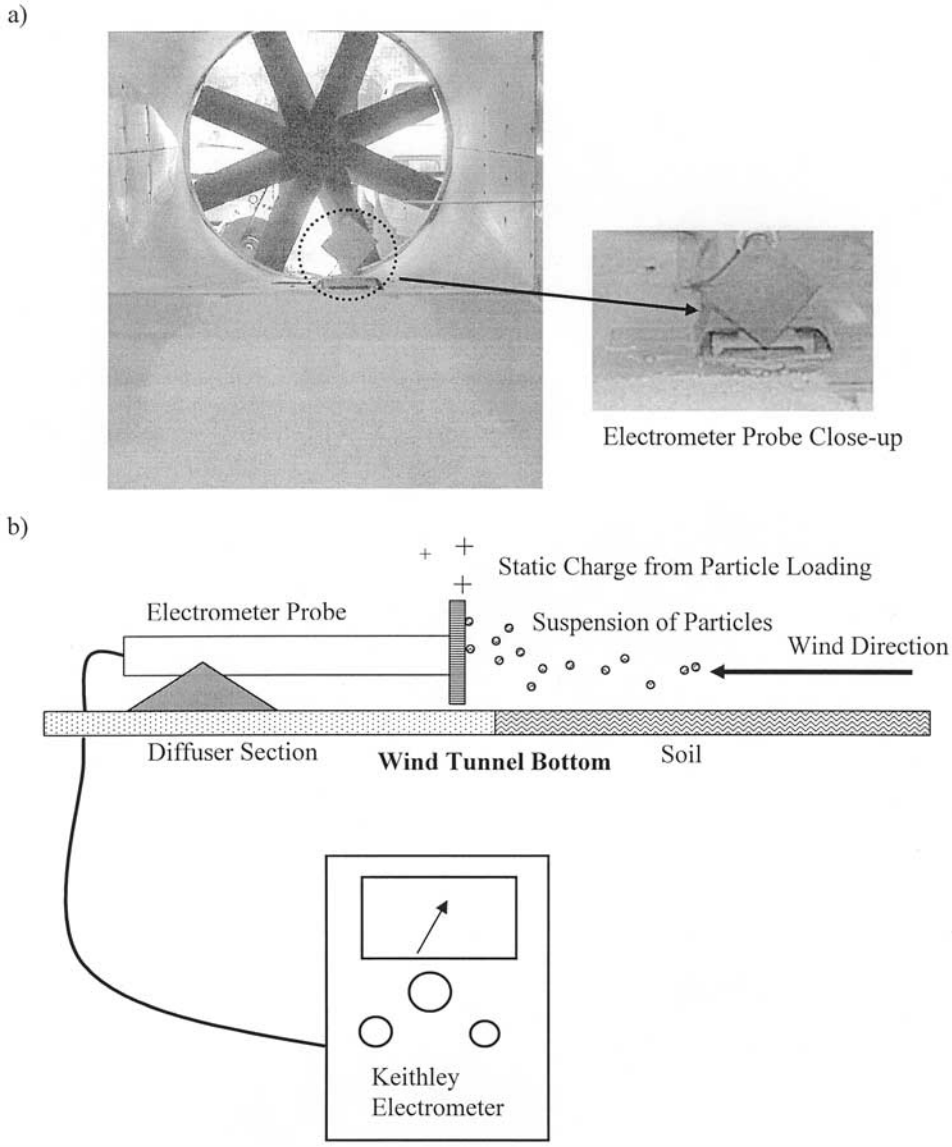

Figure 4. (a) Location of the electrometer in the wind tunnel. (b) Schematic showing the basic principle used to obtain a threshold velocity for each soil.

wind tunnel, where it outputs a positive voltage when particles impact the metal plate. The electrometer does not necessarily measure the strength of the impact, but with great sensitivity, it detects the amount of dust in the airstream through the voltage created by the static discharge of the airborne particles, thus providing an accurate and repeatable threshold measurement [*Wilson et al.*, 1997, 1998]. The metal plate was perpendicular to the wind velocity, as shown in Figure 4. The voltage from the electrometer and the free stream velocity U_{ref} were measured simultaneously. The velocity corresponding to a rapid increase in the voltage was taken as the threshold velocity. This velocity was then converted to threshold friction velocity using equation (6).

[15] The DustTraks were used to obtain another measurement of threshold. The TSI DustTrak® can sample an intake volume of air and return a concentration value every second. An aerosol sample is drawn into the sensing chamber in a continuous stream, where the monitor uses light-scattering technology to determine mass concentration in "real time," sending a concentration value in mg m^{-3} to the LCD screen as well as to the computer data acquisition system, where it is recorded. In addition, the DustTrak has specialized orifices to selectively choose the size range of particles reaching the sampler. There are orifices specifying the following size ranges: particles <10 μm, particles <2.5 μm, and particles <1.0 μm. The 10 μm orifice was used for these experiments. The aerosol sampling tubes were placed near the surface of the soil ~4.38 m from the beginning of the soil bed and at a height of z = 0.0064 m (Figure 5). The tubes attached to DustTraks are relatively small and rounded and do not impede the flow significantly in the vicinity of the surface. The diameter of the tubes is 0.00127 m and the wind tunnel width is ~0.5 m, making the tubes generally invisible to the flow field. Likewise, the suction of the DustTrak pump at the height where measure-

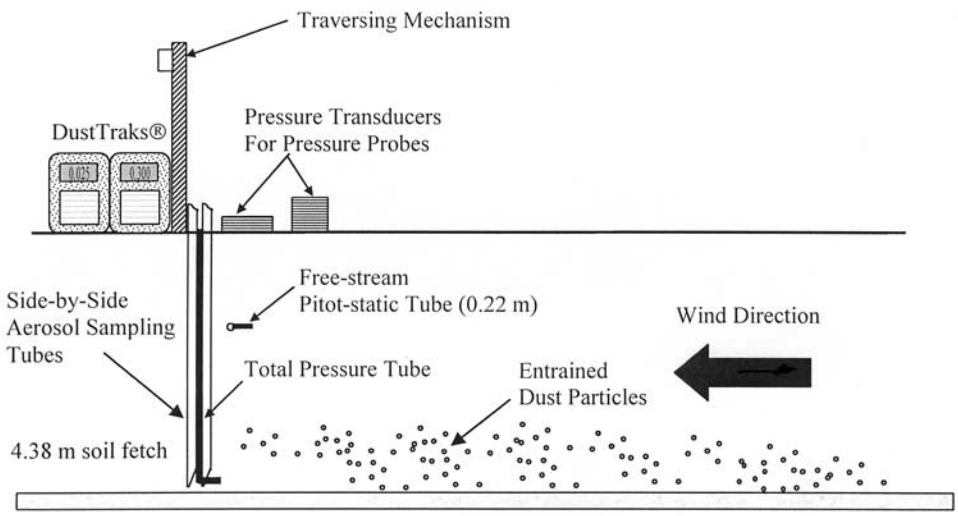

Figure 5. Schematic for DustTrak® testing of "dust" threshold, with the sampling tubes located at approximately z = 0.0064 m from the surface of the soil.

ments were made does not have the capacity to suck fines from the surface. This suction effect was tested experimentally by traversing the height of the tunnel from top to bottom with no wind flow; concentrations near the surface of the soil were essentially the same as those found at other heights and in the ambient air, 14–18 μg m^{-3}. These values are also typical of the ambient air on any given day in Davis. To obtain the threshold values, the reference velocity was slowly increased over a range of velocities and the PM_{10} was simultaneously recorded. Rapid sustained increases in the dust concentrations indicated threshold.

[16] Lastly, a third method of obtaining the threshold can be obtained analytically from the experimental data of friction velocity u_* correlated with the reference velocity U_{ref}. This correlation shows a bimodal relationship with two distinct regions, "prethreshold" and "postthreshold," as also shown in other wind tunnel studies [*Alfaro et al.*, 1997] and as measured in the field at Owens (dry) Lake by *Gillette et al.* [1998]. The divergence from a linear regime is an indication of "threshold." *Alfaro et al.* [1997] presents a bimodal system with two linear regions; however, owing to stress partitioning [*Rasmussen*, 2002; *Owen*, 1964] of the flow during soil movement, it is not completely accurate to fit the "postthreshold" region with a linear fit.

3. Results

[17] Initially, for verification of the electrometer measurements, a UCD fence soil (soil 4) bed was cycled through various U_{ref} velocities, and the corresponding electrometer voltages were recorded, as shown in Figure 6. The sharp increases in voltage indicated threshold. For this single bed of soil the cycle was repeated four times, and with satisfactory repeatability the same U_{ref} value was obtained: $\sim$8 m s^{-1}. The voltage increase corresponded to U_{ref} values slightly before "visual threshold"; the voltage began to substantially increase before the bed could actually be seen moving. The initial electrometer readings indicating threshold may correspond only to suspended dust mass, or they may be a combination of very small sand particle and dust movements that are not detectable to the human eye.

[18] The threshold velocity of each of the four soils was obtained by correlating with the free stream velocity U_{ref} in the tunnel for (up to) three trials. A typical experimental result for one of the soils is shown in Figure 7. In Figure 7 the normalized voltage V/V_{max} of the electrometer is plotted versus the free stream velocity U_{ref}; the threshold velocity is indicated by a sharp sustained increase in the normalized voltage. For all the soils the threshold velocity was found to be similar, $\sim$8.0 ± 0.3 m s^{-1}, as measured at a 0.22 m height above the surface. This suggests that the surfaces of the loose soils are aerodynamically similar, and the initial movement of the surface follows a similar physical mechanism. Wind passing over the stationary bed is retarded at the base by the friction imparted on the air by the soil particles. As the velocity increases in the tunnel, both the frictional velocity and the shear stress increase. At some critical point, dust and subsequently sand on the bed starts to move. *Bagnold* [1941] has shown that the bed movement depends on the mean grain diameter of the soil, and since the effective mean grain diameter of all four soils is similar (Figures 8 and 9), the threshold velocity should be about the same for the four soils. The mean grain diameter for the four soils was found from the sieve analysis using the method described by *Friedman et al.* [1992] and shown in Table 1. Using *Bagnold*'s [1941] equation (1) and assuming quartz particles, these mean diameter values correspond to threshold friction velocities of 0.27 ± 0.01 m s^{-1}, 0.26 ± 0.01 m s^{-1}, 0.27 ± 0.01 m s^{-1}, and 0.29 ± 0.01 m s^{-1}, respectively. As noted earlier, an assumption of the *Bagnold* [1941] equation is uniform grain sizes, and thus it is not entirely appropriately applied to this situation; however, it provides a comparison to the experimentally determined values for each soil.

[19] In order to obtain the threshold friction velocity u_{*t} from the experimental cases (electrometer and DustTrak), the relationship in equation (7) was used to relate the value

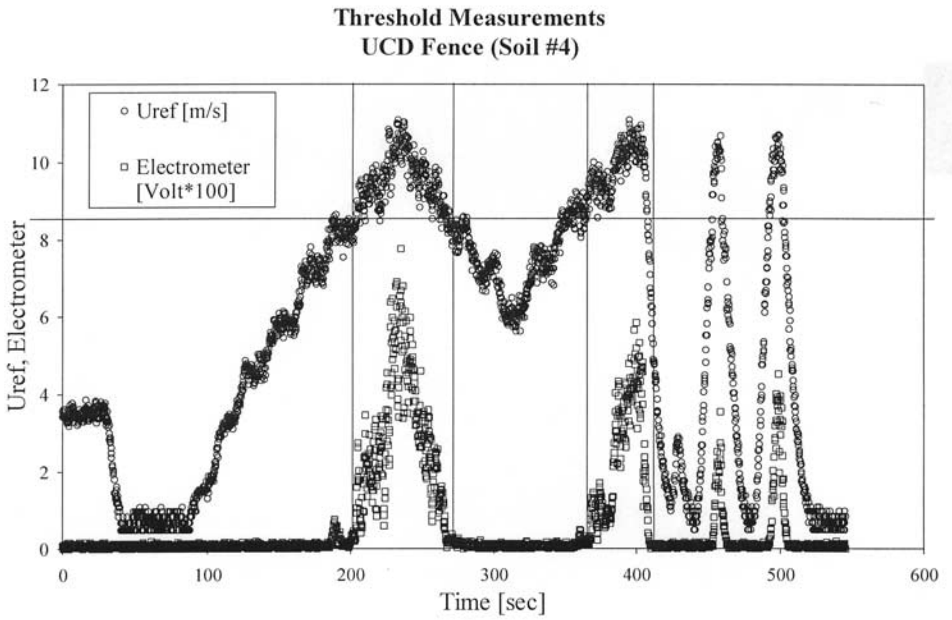

Figure 6. Repeatability of the threshold measurement as the digital acquisition system records the reference velocity and the electrometer voltage simultaneously. A steep rise in voltage indicates that threshold for bed movement has been exceeded.

of U_{ref} at threshold to the corresponding friction velocity. The slope $C_d^{1/2}$ was obtained with a linear regression, as described in section 2.3 and shown in Figure 10. The threshold friction velocity is more relevant when relating the experimental wind tunnel data to the values observed on the dry lake since this value is independent of the height at which the reference velocity is taken. For the electrometer measurements the values of threshold friction velocity corresponding to each of the soils are shown in Table 1. The values calculated using *Bagnold*'s [1941] equation are

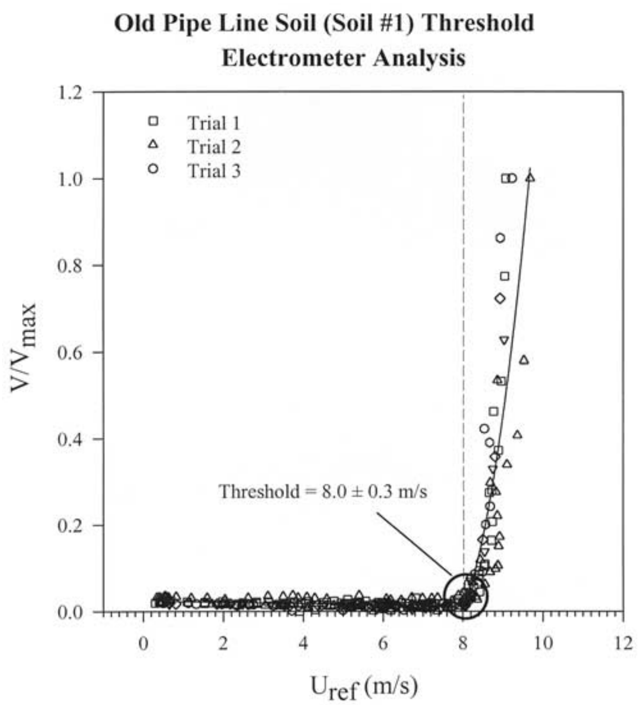

Figure 7. Dust threshold estimated using the electrometer for one of the four soils tested. A distinct threshold is seen on each plot.

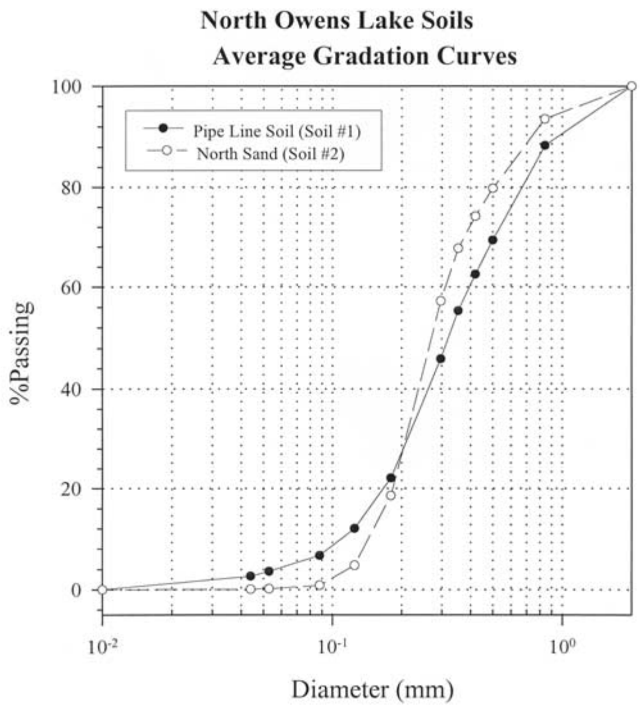

Figure 8. Cumulative size distribution for north soils in terms of percentage of particles of given diameter passing through a sieve stack in a sonic sifter.

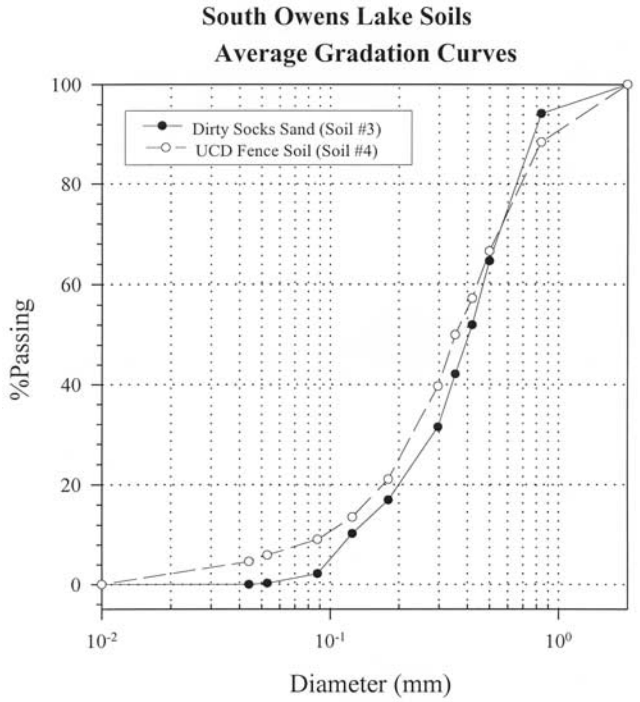

Figure 9. Cumulative size distribution for south soils in terms of percentage of particles of given diameter passing through a sieve stack in a sonic sifter.

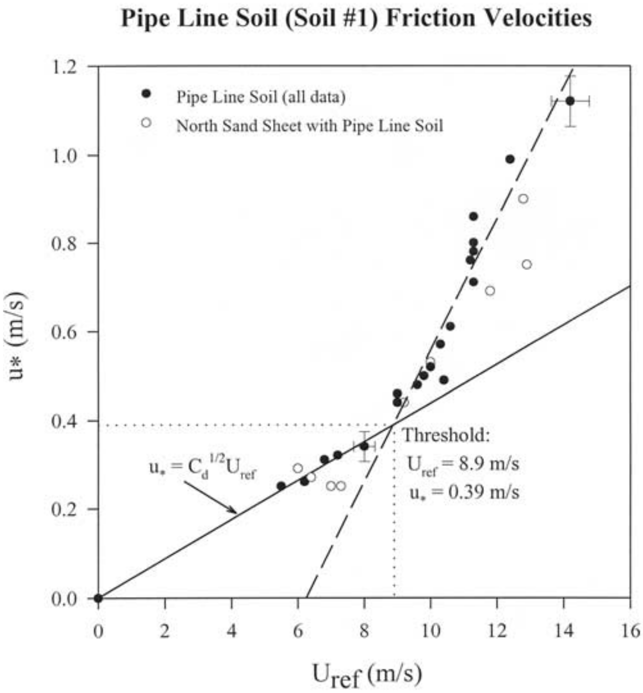

Figure 10. Calculated friction velocity plotted versus the reference velocity. The threshold velocity for each soil is then estimated using the bimodal slope method. The plots indicate two distinct regions, "prethreshold" and the "saltation" region. The intersection of the fits indicate threshold. The surficial coefficient of drag C_d is calculated from the slopes of these curves.

much less than the measured values. There are two possible reasons: First, rougher surfaces raise threshold speeds and, second, smaller particles interspersed among the large particles provide additional cohesive forces in the "real" soil, resulting in higher threshold conditions.

[20] A similar series of tests was performed using the DustTraks. Again, three trials with two DustTraks were performed for each of the four soils, as shown in Figure 5. PM_{10} concentrations were taken continuously every second as U_{ref} was slowly increased; the plots show the normalized PM_{10} concentrations C/C_{max} plotted versus U_{ref} (Figure 11). Room background concentrations were subtracted, and for the same trials the DustTrak data were averaged together to give one curve. A running time average of every 20 s was used to smooth out the minor data fluctuations (i.e., "nonsustained" fluctuations). For each soil tested with the DustTrak, there was the possibility of two distinct thresholds, as shown on the plots and termed "saltation threshold" and "PM_{10} threshold." The DustTrak seems to be more sensitive in its detection technique and registered slight continuous increases in dust concentration starting at much lower U_{ref} values (i.e., 4 m s^{-1}) for soils 1, 2, and 4. Eventually, at some critical velocity a rapid increase in concentrations occurred similar to those measured with the electrometer. The U_{ref} value of rapid increase was termed "saltation threshold"; however, this threshold velocity value was consistently lower than the electrometer measurements of threshold for all four soils.

[21] The "PM_{10} threshold" for soil 2 (the north sand) was estimated to be 6.0 m s^{-1}, substantially higher than those of the other soils. We offer two reasons for these differences:

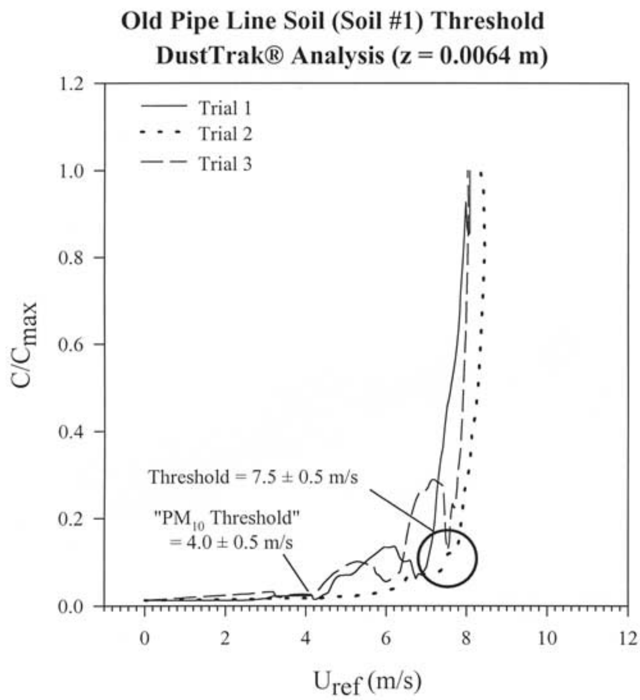

Figure 11. Threshold and "PM_{10}" threshold velocity for each soil estimated using the DustTrak. The plots indicate that an earlier threshold can occur before a more obvious sustained threshold. Some plots also indicate nonsustained dust events.

First, the gradation curves (Figure 8) and later emissions testing indicate that soil 2 has the least amount of smaller particles (particle diameters D_p < 100 μm); second, the gradation curves indicate that soil 2 has a smaller grain size in the "sand" region (fine sand) than the other soils. Thus smaller amounts of "dust" are likely to be secured between the fine grains of sand at the lower velocities.

[22] Using the same velocity profiles to obtain $C_d^{1/2}$, the threshold friction velocity u_{*t} for the DustTrak experiments was obtained. For the DustTrak measurements the values of threshold friction velocity corresponding to each of the soils are shown in Table 1. The values corresponding to the "first movement" or PM_{10} threshold friction velocity are also shown in Table 1. Again, the equivalent threshold values are higher than those obtained using the *Bagnold* [1941] equation, likely due to reasons previously stated. The "first movement" thresholds were noticeably lower than the *Bagnold* [1941] calculations.

[23] Finally, the threshold friction velocity was determined by the "slope method." The intersection of the fits on the $u*$ versus U_{ref} plots for "prethreshold" and "postthreshold" are shown in Figure 10, providing a third estimate of the threshold conditions. For the "slope method" calculations the values of threshold friction velocity corresponding to each of the soils are shown in Table 1. *Gillette et al.* [1998] used field measurements at Owens (dry) Lake near Keeler to determine the threshold friction velocity with the "slope method." For the three sites in which measurements were made, site 5010, 5011, and 5012, the values were 0.42 m s^{-1}, 0.42 m s^{-1}, and 0.42–0.47 m s^{-1}, respectively. Thus the field measurements compare reasonably well with the electrometer method and with the slope method employed in the wind tunnel.

[24] A summary of the results for all three methods is provided in Table 1. In addition, a plot of the results showing the thresholds for each soil type is shown in Figure 12. The threshold conditions indicated by the sustained rapid increase of the electrometer and the DustTraks and the slope method are all comparable. The slope method gives slightly higher (up to 33% greater) threshold values than the other two methods for all four soils; however, when the uncertainty in the slope method values is considered, the values fall in the range of the other two methods. These higher values are not unexpected as it is the least sensitive method to suspended particle movement. The slope method "response" is to the saltating movement that determines the fit in the "postthreshold" region. Since "dust" suspension without saltation does not appear to substantially affect the shear velocity near threshold, this method can only be used to detect "saltation threshold."

[25] Of the three methods, the DustTraks indicate the lowest sustained thresholds for the soils. The DustTraks size select PM_{10} and can measure concentrations as low as 0.001 mg m^{-3}; the result is the direct measurement of "dust" movement. The suspended dust increases substantially before the whole bed begins to move, indicating sustained dust movement occurs prior to "visual threshold." More importantly, the DustTrak measurements indicate noticeable PM_{10} dust well below "visual" or "saltation threshold." In this way the DustTrak records the "first movement," as bracketed in Figure 12. Concentrations from "first movement" to just before the "saltation threshold"

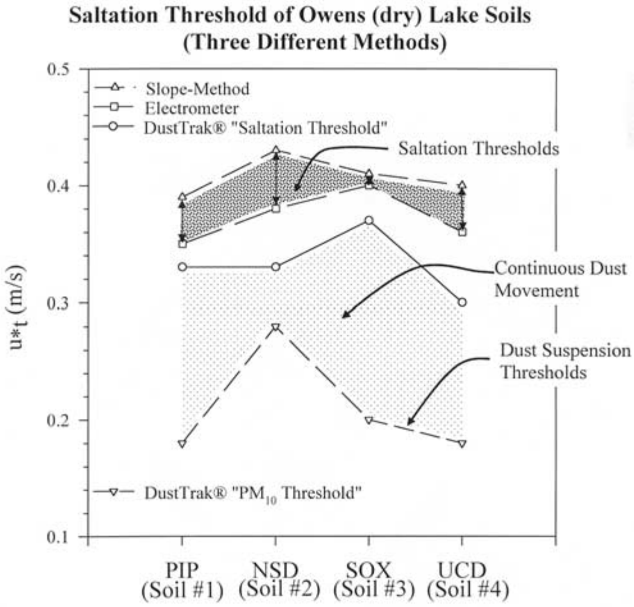

Figure 12. Measurements of "saltation threshold" for the three different methods. The "saltation thresholds" measured by these methods are very similar. In addition, an earlier "PM_{10} threshold" is shown at values lower than the threshold for saltation movement; at this value, continuous dust movement begins.

are, on average, 5–30% of the values at "saltation threshold." The average percentages of the emissive soils, soil 1 and soil 4, are 20% and 30%, respectively, while the values for the sands, soil 3 and soil 2, are 5% and 10%, respectively. The maximum percentage for a single run is 49% for an emissive soil, while the lowest value for a single run is around 0% for a sandy soil.

[26] The electrometer threshold values fall between those of the other two due to sensitivity of the instrumentation. The electrometer requires a critical amount of suspended mass to register a voltage increase, and smaller PM_{10} particles, though picked up by the DustTrak, are not in sufficient numbers to affect the electrometer until slightly greater friction velocities. However, the electrometer does register the suspended mass before the bed begins to visually move.

[27] In the work of *Gillette et al.* [1982] the threshold friction velocities of different desert soils are determined with a portable wind tunnel using "visual threshold" (the observation of first movement). Threshold values for disturbed soils were determined for three different Owens Lake soils along with many desert soils; measured "visual threshold" friction velocities were 0.20 m s^{-1} for a wind-deposited soil, 0.40 m s^{-1} for a sandy soil, and 0.49 m s^{-1} for a nonhomogenous sand. The latter two cases are most representative of the testing performed in UCD wind tunnel studies. These values agree reasonably well with the "slope method" values, suggesting that the "slope method" is equivalent to the "visual threshold" technique.

4. Conclusions

[28] Dust (PM_{10}) movement occurs before "visual threshold" for Owens Lake soils as recorded by DustTrak and

electrometer measurements. This suggests that dust loading occurs well before visual bed movement and, possibly, before saltation. Dust threshold values do not compare well with theories for homogenous particle beds, and thus there is a need for experimental wind tunnel measurements. The measured threshold provides a standard where one might expect to observe substantial PM_{10} loading of the atmosphere due to movement of the soils filled with small particles such as those at Owens (dry) Lake. The slope method is most likely a good indicator of ''visual threshold'' and in the absence of the more rigorous threshold measurements could be used as an indicator of PM_{10} threshold conditions. The values obtained with the slope method agree well with the field measurement made by *Gillette et al.* [1998].

[29] In addition, there are sustained ''first movements'' of PM_{10} at lower friction velocities as measured by the DustTrak. These additions could have policy implications in accounting for total dust loading in PM_{10} inventories. Typically, it has been assumed that there are no dust emissions below ''visual threshold''; however, these experiments indicate that some PM_{10} is being suspended well below ''visual threshold.'' Average concentrations from ''first movement'' to just before the ''saltation threshold'' are 5–30% of what they are at ''saltation threshold,'' with maximum values over 40% for individual tests. In an environment like Owens (dry) Lake, where the emissions are already quite large and the primary source of loading is crustal material, this amount below the ''visual threshold'' could be consequential. In places where crustal material is an additional source of PM_{10}, there could be implications to State Implementation Plans (SIPs). If mineral dust sources become airborne at substantially lower wind velocities than previously thought, an additional source of PM_{10} would be unaccounted for in the SIPs. Ultimately, the possible effect is continued violation due to this unknown source.

[30] The likely source of the dust before ''visual threshold'' or ''saltation threshold'' is the suspension without saltation mechanism; however, in the long term the saltation mechanism also plays a role. In the case of a ''real'' soil the dust particles are loosely packed throughout the bed, with an abundance of small particles throughout the surface, and thus a source of particles is readily available for turbulent structures and shear to suspend them. Armoring, initial sand-sized grain sorting at ''prethreshold'' conditions, is discounted as the mechanism of dust entrainment for two reasons. First, the electrostatic discharge created by the nonsustained sand particle movement would surely have been picked up by the electrometer measurements, and second, the mixture of dust and sand significantly decreases the elasticity of the bed at low speeds, making sand-sized particle movement unlikely.

[31] If erosion continues indefinitely at steady state conditions, eventually all available small particles (dust/PM_{10}) disappear; that is, the top layer of the bed becomes entirely particles of sand, and there are no longer any sources of small particles. However, if the entire bed is erodible, once saltation is initiated, more small particles again become available near the surface as the surface is scoured. If the wind returned to a state below the ''visual threshold'' friction velocity after scouring, small particles would continually be suspended through the mechanism of ''first movement.'' On the basis of the measurements made in this paper, Owens (dry) Lake is likely one environment where the mechanism of dust entrainment as described occurs.

[32] Likewise, this problem can be extended to other fugitive dust scenarios: On an unpaved road a continuous source of particles near the surface is provided by road traffic pulverizing the surface into dust, and in agricultural activities the source of particles is likely to be due the grinding action of plowing. All these small particles are then subject to wind erosions at friction velocities well below the traditional ''visual'' or ''saltation threshold,'' and thus one method of ascertaining suspension rates is the wind tunnel testing protocol described in this study.

[33] Lastly, we conclude with our definitions of threshold as interpreted from these experimental results. ''Visual threshold'' is the first visually observed sustained movement of particles on a soil bed due to blowing wind. ''Saltation threshold'' is when sand-sized particles begin sustained movement on the soil bed due to blowing wind; movements of sand-sized particles likely occur just before they are visually detectable, leading to dust emissions as detected by the electrometer and the DustTrak. ''Dust or PM_{10} threshold'' is when there is a ''first movement'' that leads to sustained suspension of dust occurring up to ''saltation threshold,'' as measured by the DustTrak.

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