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The emission and vertical flux of particulate matter <10 µm from a disturbed clay-crusted surface

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ABSTRACT

Arid and semi-arid environments are important sources for the atmospheric loading of PM_{10} (particulate matter <10 µm), although the emission of this material is often limited by surface crusts. This study investigates the emission and vertical flux of PM_{10} from a clay-crusted playa, with and without saltating grains to abrade the surface. Using a portable field wind tunnel, it was found that, despite disturbance to the surface, the emission of PM_{10} decays rapidly without abrasion. Only in the presence of saltating grains was PM_{10} continuously liberated from the surface, such that the emission rate (the total amount of PM_{10} emitted from the surface expressed as a horizontal flux) varied linearly with the saltation transport rate. Although the emission of PM_{10} was found to depend on saltation abrasion, past studies have tended to focus on the relationship between the vertical flux of PM_{10} (the amount of PM_{10} being transported vertically through the boundary layer) and the shear velocity. In this study, the vertical flux of PM_{10} was found to vary with the shear velocity to the power of 2·14. Although the vertical PM_{10} flux is a proportion of the emission rate (the horizontal flux), no statistically significant relationship was observed between the emission rate and the shear velocity. The disparity of these results is explained by the lack of a consistent relationship between the shear velocity and the saltation transport rate in this supply-limited environment. This suggests that the observed relationship between the vertical PM_{10} flux and the shear velocity is a spurious correlation, resulting from the use of shear velocity to calculate the vertical dust flux. It is thus concluded that shear velocity is not an appropriate variable for emission modelling in supply-limited environments and that improvements in dust emission modelling will only be realized if the abrasion process is the focus of a concerted research effort.

Keywords Emission rate, PM_{10}, saltation transport, vertical dust flux.

INTRODUCTION

The entrainment, transport and deposition of dust-sized sediment can have a severe impact on the natural environment and human activity. Dust has been linked to climate modification and is itself a major consequence of climate change (Idso, 1981). As dust-sized material occupies a large percentage of the soil, its transport can be a source of significant long-term land degradation in agricultural areas (Fryrear, 1981). The more immediate impacts of dust activity include disruption of communication systems (Clements *et al.*, 1963; Pye, 1987), reduced visibility (Houseman, 1961), transmission of disease (Hyers &

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Marcus, 1981) and respiratory afflictions (Pye, 1987). Consequently, the entrainment and subsequent transport of dust-sized sediment remains an important and challenging focus of research for both scientific and practical applications.

Dust particles can be entrained by aerodynamic forces or the impact forces of saltating grains, a process termed dynamic entrainment. The entrainment of dust particles by aerodynamic forces is inherently difficult, because of the strong cohesive forces associated with these small particles (Greeley & Iversen, 1985). As first identified by Bagnold (1941) and more recently demonstrated by Shao *et al.* (1993), the interparticle forces are more easily disrupted by the impact force of saltating grains than by aerodynamic forces. The importance of saltation bombardment has also been recognized in studies by Fairchild & Tillery (1982) and Borrmann & Jaenicke (1987). Fairchild & Tillery (1982) found that the resuspension rate (the fraction of surface material removed in unit time; g s^{-1}) increased by a factor of two to three and, in some cases, reached values of six and seven in the presence of saltating grains.

Two recent models describing the bombardment process have been developed by Owen (Gillette & Passi, 1988) and Shao *et al.* (1993). Shao *et al.* (1993) argued that the aerodynamic lift component identified in the Owen model (Gillette & Passi, 1988) is insignificant relative to interparticle cohesion, and the ejection of dust-sized sediment is solely dependent on the rupturing of interparticle bonds. Shao *et al.* (1993) presented evidence that the emission of dust particles, and therefore the vertical dust flux (F), is proportional to the shear velocity (u_*) to the third power:

$$F = \alpha u_*^3 \left(1 - \frac{u_{*t}^2}{u_*^2}\right) \qquad (1)$$

where u_t^* is the threshold shear velocity, and α is a dimensionless parameter. The α parameter describes the efficiency of the bombardment process:

$$\alpha \approx \frac{c_N m_d \rho}{\psi} \qquad (2)$$

where c_N is the proportion of the incoming saltation energy available to disrupt the interparticle bonds (ψ), m_d is the mass of the dust material, and ρ is the air density. This model is based on the relationship between the saltation transport rate and shear velocity first identified by Bagnold (1941) and later by Owen (1964). The model also recognizes the importance of interparticle cohesion and the need for saltating grains to disrupt those bonds. Specifically, Eq. 2 indicates that the ability of sand to emit PM_{10} depends on the proportion of incoming bombardment energy available for breaking interparticle bonds and is inversely related to the resistance of the interparticle bonds to rupture. Unlike transport models for cohesionless sand (Bagnold, 1941; Owen, 1964), the emission of PM_{10} is predicted based on the surface controls for particle release and not on the transport capacity of the wind.

The supply limitations induced by interparticle forces can be augmented on natural surfaces through crusting. Gillette *et al.* (1982) presented evidence that surface crusts formed through soil enrichment by clay, silt, microphytic organisms or natural salts can effectively protect a soil from erosion for all but extreme wind events. The emission of dust-sized sediment is, nonetheless, regularly observed from crusted surfaces. Similar to the unconsolidated material studied by Bagnold (1941), the emission of dust-sized sediment has been linked to the quantity of sand in transport (Gillette, 1977; Nickling, 1978; Nickling & Gillies, 1989; Gomes *et al.*, 1990; Gillette *et al.*, 1997; Nickling *et al.*, 1999). These studies have found that, as a result of repeated impacts, dust particles may be liberated from the surface and lifted up by turbulent diffusion processes. In studies by Greeley *et al.* (1982) and Suzuki & Takahashi (1981), it was found that the amount of material removed through the abrasion of rock material is proportional to the kinetic energy of the saltating grains and the strength of the abraded surface. The findings of this abrasion research are consistent with the energy balance approach used in the Shao *et al.* (1993) model, although particle energy was not expended in the rupturing of interparticle bonds in the latter study.

The semi-empirical nature of emission models (Eq. 1) requires that the models are verified and calibrated through observation and documentation of emission rates and vertical dust fluxes from natural surfaces. Although the emission and ultimate transport of dust have been linked to the abrasive action of sand, shear velocity is conventionally used for modelling out of practical necessity and not because that relationship is necessarily an accurate description of the emission process. Studies of dust emissions from crusted surfaces (Gillette, 1977; Nickling, 1978; Nickling & Gillies, 1989, 1993; White *et al.*, 1996;

Gillette *et al.*, 1997; Lopez, 1998) have clearly demonstrated the range of variation that exists in the vertical dust flux for a given shear velocity. The exponent of this power relationship has been observed to vary considerably from 6·54 (Table 1; White *et al.*, 1996) to 1·89 (Nickling & Gillies, 1989). In these studies, the observed variations have been variously attributed to interparticle bond strength (ψ) and the structural and textural characteristics of the crust at each location, relative to the quantity and energy of the sand abrading the surface. Rice *et al.* (1997) argued that the amount of dust released from a surface depended on the extent of the overlap between the distributions of crust strength and the kinetic energy of the saltating grains. Larger quantities of dust are released from a surface when there are greater overlaps between these distributions.

Despite these studies, the role of saltation abrasion on crusted surfaces is poorly understood and, consequently, there is a need to observe and document further the emission and vertical fluxes from natural surfaces. As traditional modelling has focused on the relationship between vertical dust flux and shear velocity, it is also important to verify whether shear velocity alone is an appropriate basis for modelling the emission of PM_{10}. In this paper, the results of a series of wind tunnel tests are presented, investigating the emission and vertical dust flux of PM_{10} from a crusted surface. The experiments were developed to compare the emission of PM_{10} from a crusted surface with and without abrasion by saltating grains. The dependence of the emission rate and vertical dust flux on the shear velocity and saltation transport rate is also examined, and the implications for modelling are discussed.

STUDY SITE

The wind tunnel tests were conducted on a series of clay-crusted playas along the Bouse Wash, near Desert Wells, Arizona (Fig. 1). Bouse Wash is the major drainage channel through the valley and is the primary source of sediment for the playa. According to McCauley (1981), the Bouse Wash and surrounding floodplain are inundated by floods every few years, resulting in the deposition of new material and redistribution of the existing surface material. The resulting texture of the crust material ranged from 73% to 100% silt/clay, with crust strengths ranging from 0·94 kg cm^{-2} to 4·5 kg cm^{-2} (Houser, 1999).

The playa system and surrounding land is actively used for cattle grazing, and it was estimated that there were approximately 10 000 head of cattle in this area. The cattle were observed to follow a daily migration between two watering holes situated on either side of the playa system. Consequently, the crust on and immediately surrounding the playas has been disturbed by the cattle, creating small reservoirs of unconsolidated material. Based on photographs taken of the surface at each of the 45 test sites, it was found that the amount of surface disturbance varied widely from a maximum of 71% coverage of the wind tunnel test area (12 m^2) to a minimum of 5% coverage of the test area. The average level of surface disturbance was found to be 31% of the test area.

Table 1. Comparison of exponent values (x) of the relationship between the vertical dust flux and the shear velocity ($F \propto u_*^x$) obtained from past studies.

Study	Exponent (x)	Sediment collected	Methodology
Nickling *et al.* (1999)	4·94	PM_{10}	Tower array
Lopez (1998)	5·67*	PM_{10}	Tower array
White *et al.* (1996)	6·54*	PM_{10}	Wind tunnel
Nickling *et al.* (1997)	3·64	PM_{10}	Wind tunnel
Nickling & Gillies (1989)	1·89 (all sites)	TSP‡	Wind tunnel
Nickling & Gillies (1989)	4·27 (sites > 25% clay/silt)	TSP‡	Wind tunnel
Nickling & Gillies (1989)	3·02 (sites < 15% clay/silt)	TSP‡	Wind tunnel
Nickling (1978)	3·55	TSP‡	Tower array
Gillette (1978)	3·00†	TSP‡	Tower array

* Calculated from data for the purposes of this study.
† Regression exponent forced by original author.
‡ Total suspended particulate concentration measured.

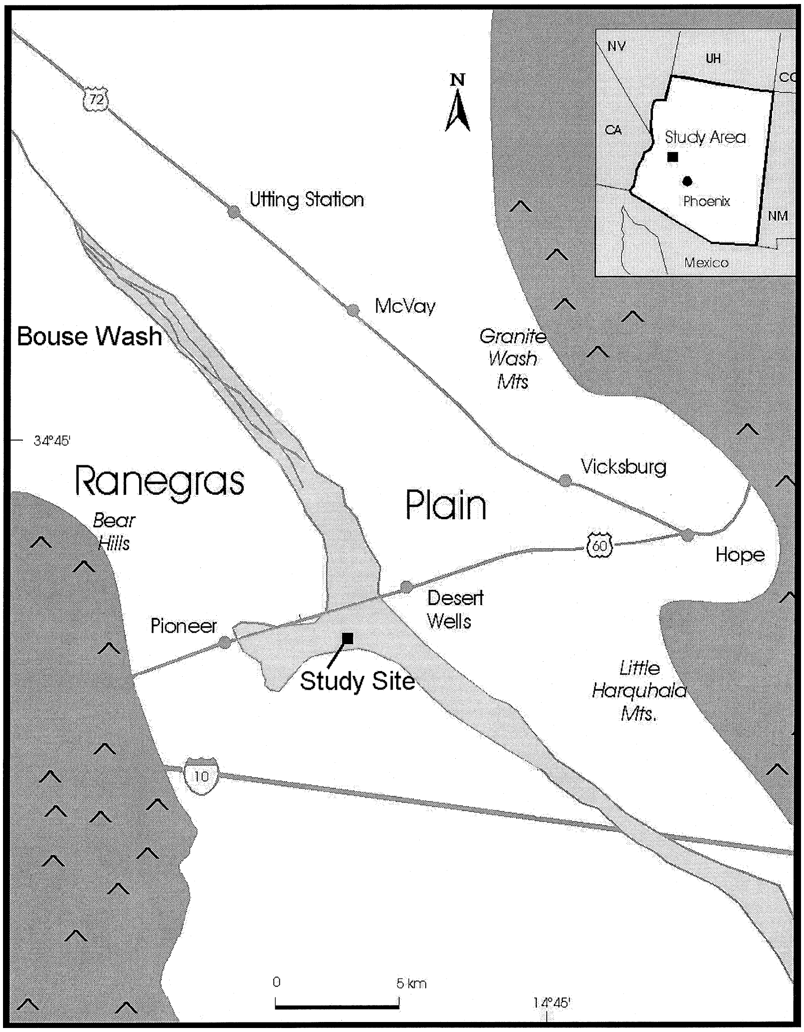

Fig. 1. Location of the study site along the Bouse Wash near Desert Wells, Arizona (adapted from Wolfe, 1993).

EXPERIMENTAL METHODS

Tests were conducted using a portable field wind tunnel, which has a 1·0 × 12-m open-floored working section with a height of 0·75 m. Flow is generated by a 96-cm centrifugal fan powered by a 45-hp diesel engine. A total of 45 tests was conducted corresponding to five fan speed settings of three replicates, at three locations within the playa system that visually exhibited low (<33%), moderate (33–66%) and high (>66%) levels of surface disturbance. These sites were classified based on the analysis of surface photos at each wind tunnel site in order to ensure that the full range of surface disturbance was sampled. To compare the emission and vertical dust flux of PM_{10} between an unabraded and an abraded surface, each test consisted of two wind tunnel runs: one over the bare surface without abrading material; and the second with saltating grains to abrade the surface. In order to fulfil the objectives of the study, the wind velocity, PM_{10} concentration and saltation transport rate were monitored simultaneously.

Wind velocity

The wind velocity profile was measured by a pitot tube rake consisting of six tubes covering the thickness of the boundary layer (≈30 cm). The pitot tubes were connected to a multiport scanning valve (Scannivalve model WS5-24), which sequentially directs the velocity pressure to a differential pressure transducer (Viatran model 219). The six pitot tubes were logarithmically spaced to cover the boundary layer at heights of 2, 4, 8, 12, 17 and 30 cm above the surface (Fig. 2). The pitot tubes were connected by 6·35-mm (quarter-inch) Tygon tubing to the pressure transducer. The dynamic pressure on each port was measured sequentially for a 5-s period so that a complete profile was completed every 30 s. The profiles were averaged to remove any effects of unsteady flow in the tunnel, which are apparent in a single profile. From the velocity profiles, the shear velocity (u_*) was calculated using the 'law-of-the-wall':

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

where u is the velocity at height z, z_o is the roughness length for the surface, and k is von Karman's constant (0·4). Velocity measurements used in Eq. 3 were averaged over the 10-min sampling period.

PM_{10} concentration and flux

Calculating the emission rate and the vertical flux of PM_{10} requires knowledge of the flow conditions that transport the particles and the particle concentration at two or more heights. Dust concentrations were measured using Dusttraks (model 8520) at three heights (8, 17 and 30 cm) offset from the centre line of the tunnel (Fig. 2). These heights correspond to the heights of three pitot tubes, allowing simultaneous measurement of wind velocity and PM_{10} concentration. The Dusttraks use the principle of backscattering from a laser diode to calculate the concentration of sediment <10 μm in diameter. An aerosol sample is drawn into the sampling chamber in a continuous stream and illuminated by laser light at 90° to the aerosol stream. The sampling inlets of the Dusttraks were connected by 6·35-mm (quarter-inch) Tygon tubing to aluminium nozzles within the tunnel.

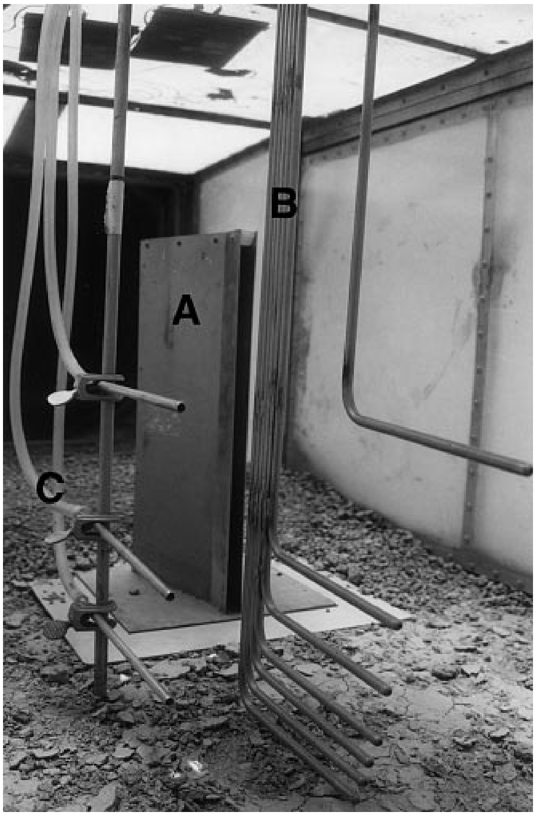

Fig. 2. Instrument array in wind tunnel to measure saltation transport rate (A), wind velocity (B) and PM_{10} concentration (C). The saltation transport rate was measured using a vertically integrating passive Guelph-Trent sediment trap. A pitot tube array was used to measure wind velocity at six heights within the boundary layer (2, 4, 8, 12, 17 and 30 cm above the surface). The PM_{10} concentrations at three heights (8, 17 and 30 cm) were measured using Dusttraks connected to aluminium nozzles within the tunnel.

The flow rate into the Dusttrak was maintained at 1·7 L min^{-1} throughout the study. This particular flow rate, which is equivalent to an intake nozzle velocity of 0·88 m s^{-1}, was largely a pragmatic choice. Although an intake velocity that equalled the wind velocity at each sampling height would be desirable to ensure efficient sampling, this was not possible as the wind velocities were greater than the range of intake velocities available for the Dusttraks. Consequently, a single intake velocity at the upper end of the available range was used for each test. Because the intake velocity of the sampler is less than the wind velocity (subisokinetic), the sediment collected will tend to be coarser, as small particles will follow the fluid streamlines that are bent around the sampling nozzle. The actual concentration of PM_{10} will therefore be underestimated. Based on recent laboratory tests conducted by the manufacturer, the efficiency of the Dusttraks used in this study is estimated to vary from 95% at the lowest fan setting to 60% at the highest fan setting (TSI Instruments, 2000).

Before each wind tunnel test, an ambient background concentration was taken at 1-s intervals for 2 min and subtracted from the dust concentrations measured during the test. The background test was conducted at the upwind end of the tunnel oriented into the wind. The emission rate of PM_{10} from the surface (E, μg m^{-2} s^{-1}) was calculated, similar to the method of Shao *et al.* (1993), as the mass of PM_{10} emitted from a surface of given area per unit time:

$$E = \frac{1}{L}\int_0^z Cu\,dz \tag{4}$$

where L is the tunnel length over which dust is being emitted, C is the dust concentration and u is the wind velocity at each height (z) within the boundary layer. The vertical flux of PM_{10} (F, μg m^{-2} s^{-1}) was calculated from:

$$F = -u_* \kappa \rho \frac{dC_z}{dz} \tag{5}$$

where C_z is the PM_{10} concentration at height z (Gillette, 1977). The log-linear concentration gradient (dC/dz) was calculated through non-linear regression analysis using the three measured concentration values with height. The vertical PM_{10} flux represents the proportion of the total PM_{10} emitted from the surface (calculated by the emission rate, E) that is transported vertically. Based on Eq. 5, the vertical dust flux and the emission rate should be related through the shear velocity.

Saltation transport rate

Sand-sized sediment was used to abrade the surface and was introduced into the tunnel through a hopper system at the upstream end of the tunnel. Sand was collected from a relict dunefield within the Bouse valley and had a mean grain size of 1·86 ϕ (275 μm) and a standard deviation of 0·66 ϕ (633 μm). Before the tests, the sand was passed through a 1·0-mm mesh screen to remove large particles and then winnowed to remove dust-sized sediment (<10 μm). The winnowed sand was placed into the hopper system, which introduces the sand to a screw feed that continuously transfers the sand to two tubes extending 0·5 m into the tunnel. The sediment feed rates varied from 2·64 g s^{-1} at the lowest fan setting to 23·80 g s^{-1} at the highest fan setting. These feed rates coincide with the transport capacity of the wind at the upwind end of the tunnel, which was estimated visually (before the wind tunnel tests) as the feed rate at which there was a balance between the amount of sediment deposited below the feeder tubes and the amount of sediment that is transported down the tunnel from that point.

The transport rate of the sand was measured using a vertically integrating, passive sediment trap, which was described by Nickling & McKenna Neuman (1997). The trap has a 20 × 300-mm rectangular sampling orifice that extends 40 mm from the main trap body. The back of the trap is covered by a stainless steel wire mesh with a 62·5-μm grid (60% porosity) to ensure that there is a low impedance of the airflow, while ensuring that all fine silt and clay material is collected. The wedge shape of the trap displaces turbulence generated at the orifice downwind of the trap entrance in order to inhibit scouring at the trap entrance and ensure that the flow is not impeded. Laboratory testing by Nickling & McKenna Neuman (1997) found that the trap is efficient (>90%) over a wide range of wind speeds. Only at shear velocities (u_*) within 1 m s^{-1} of the entrainment threshold was the saltation transport rate found to be underestimated. Nickling & McKenna Neuman (1997) attributed this inefficiency to the temporal and spatial variability of the entrainment/transport processes across the bed and to the higher humidity conditions experienced during the laboratory tests. As the present study was conducted in a semi-arid environment with wind speeds well above the threshold of motion, these efficiency problems were not experienced during this study.

The trap was placed along the centre line of the tunnel in the working section (Fig. 2). The cumulative weight of sediment falling onto an electronic balance beneath the trap was recorded by a microcomputer every 5 s. Before each run, the area underneath the trap was excavated for the electronic balance and its housing unit. The surface around the trap, disturbed while digging the trap hole, was wetted before each run to inhibit scouring. As a result, there was no evidence of any surface level changes around the sediment trap during the study.

RESULTS

Under non-abrading conditions, the PM_{10} concentration increased rapidly upon start up of the wind tunnel (Fig. 3). However, the initial peak in concentration was followed by a rapid decay, towards the background concentration, over a period of 6–200 s. In contrast, PM_{10} was emitted continuously from the surface in the presence of saltating grains (Fig. 3). Through visual observation, it was found that fracturing of the surface and the removal of larger crust fragments was minor and concentrated along the weak and thin edges of the crust. Striations, similar to those documented by McKenna Neuman *et al.* (1996) and Rice *et al.* (1996), were observed in the disturbed patches. As evidenced by these striations, a greater amount of material was emitted from the disturbed patches, which were com-

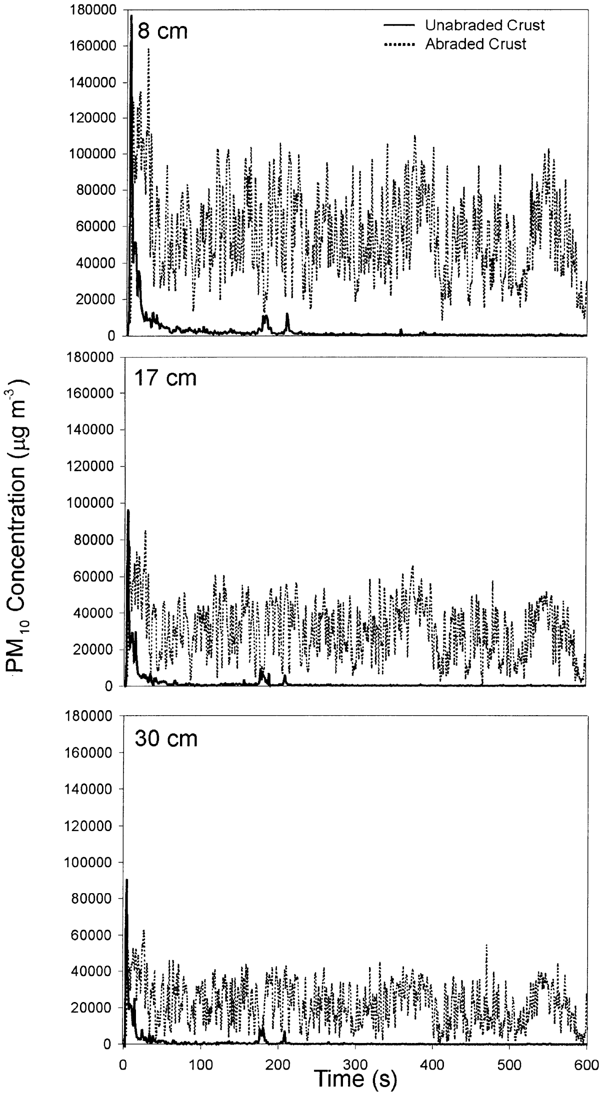

Fig. 3. Representative time series of PM_{10} concentration emitted from the surface with and without abrasion at the 8, 17 and 30 cm sampling heights.

posed of unconsolidated material, relative to the intact crust.

The emission rate of the PM_{10} (the total amount of sediment released from the surface) was found to vary linearly, at the 95% confidence level, with the saltation transport rate (q):

$$E = 0.013\,\mathrm{m}^{-1} q\left(r^2 = 0.50\right) \tag{6}$$

As the emission of PM_{10} quickly reaches the background concentration on the bare surface, the relationship has been forced through zero. Figure 4 illustrates that there is considerable variation in the emission rate (E) for a given saltation transport rate (q), by several orders of magnitude in some cases. The wide data scatter for a given saltation transport rate is most likely related to textural and structural characteristics of the surface, which are not accounted for in this simple bivariate relationship.

Although the emission of PM_{10} from the surface is dependent on the abrasive action of the sand, traditional modelling of dust emissions has focused on the relationship between the amount of dust transported vertically and the shear velocity. The vertical dust flux is a proportion of the total amount of dust emitted. The relationship between the vertical dust flux (F) and the emission rate (E) is statistically significant at the 95% confidence level (Fig. 5) and can be described by:

$$F = 0.55\,E\left(r^2 = 0.91\right) \tag{7}$$

This suggests that approximately 55% of the total amount of dust emitted from the surface is transported vertically. The observed variability in this relationship was found to vary with the drag coefficient ($u_*^2\ u_{0.3}^{-2}$), with 75% of the variation in this transport ratio attributable to the drag coefficient (Fig. 6). This suggests, as would be expected, that the primary difference between the vertical PM_{10} flux and the emission rate is the shear velocity (Eq. 5).

The shear velocities associated with the vertical dust fluxes and emission rates ranged from 0·16 to 1·29 m s^{-1}. In general, vertical dust fluxes increased as a power function of shear velocity (Fig. 7). Although considerable data scatter is evident, by an order of magnitude in some cases, the statistically significant relationship at the 95% confidence level can be described by:

$$F = 9836\,u_*^{2{\cdot}14}\left(r^2 = 0.38\right) \tag{8}$$

The exponent of 2·14 is at the lower end of the range reported in the literature (1·89–6·54). Comparison of the data with the models of Shao *et al.* (1993) and Gillette & Passi (1988) shows that neither model provides a good fit to the data (Fig. 7).

Although a relationship was observed between the vertical PM_{10} flux and the shear velocity, no statistically significant relationship was found between the emission rate of PM_{10} (the total amount of PM_{10} emitted from the surface) and the shear velocity (Fig. 8). The lack of a statistically significant relationship therefore reflects the statistical independence of the saltation transport rate from the shear velocity (Fig. 9), as the saltation transport rate on this site is limited by

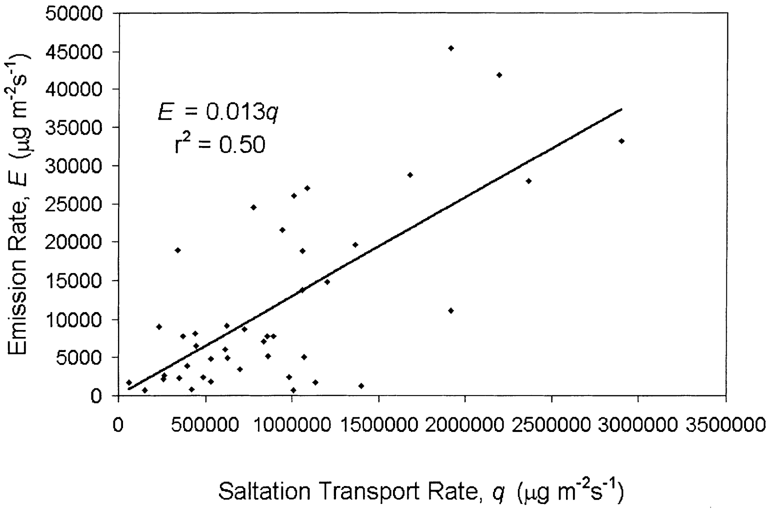

Fig. 4. Comparison of emission rate (E) with the saltation transport rate (q) for the abraded surface. The identified relationship has been forced through the origin (0,0).

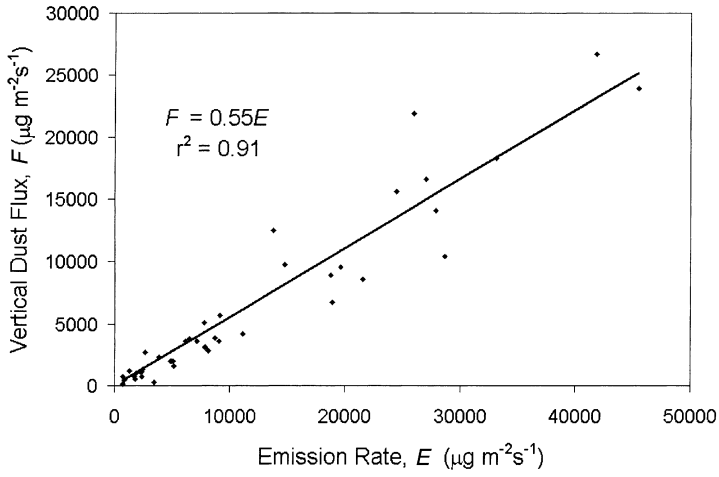

Fig. 5. Comparison of vertical PM$_{10}$ flux (F) with the emission rate (E) for the abraded surface.

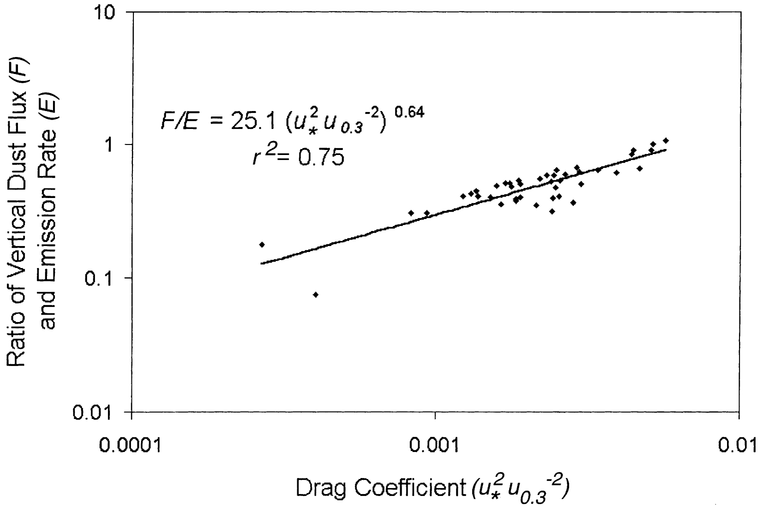

Fig. 6. Relationship between the drag coefficient of the flow ($u_*^2\ u_{0\cdot3}^{-2}$) and the ratio of the emission rate to the vertical flux of PM$_{10}$.

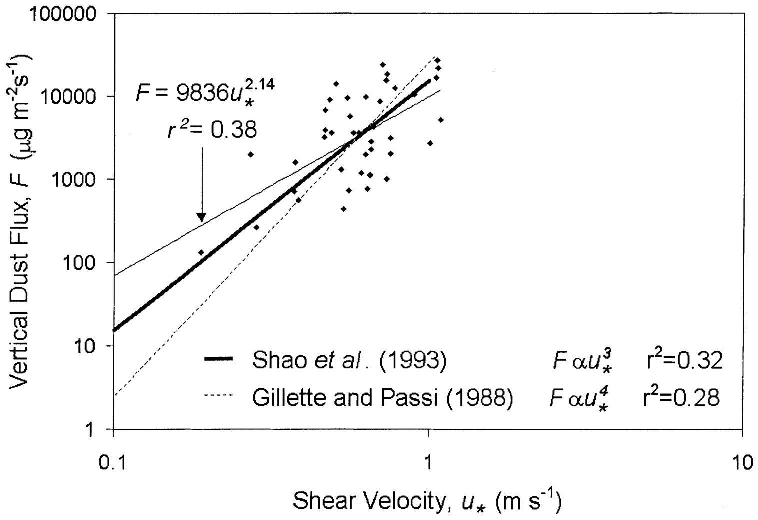

Fig. 7. Comparison of vertical PM_{10} flux (F) with the shear velocity (u_*) over the abraded surface showing the model predictions of Shao *et al.* (1993) and Owen (Gillette & Passi, 1988). Although the data are better fitted by the Shao *et al.* (1993) model, relative to the Owen model, the degree of data scatter makes it difficult to distinguish conclusively which model describes the data best.

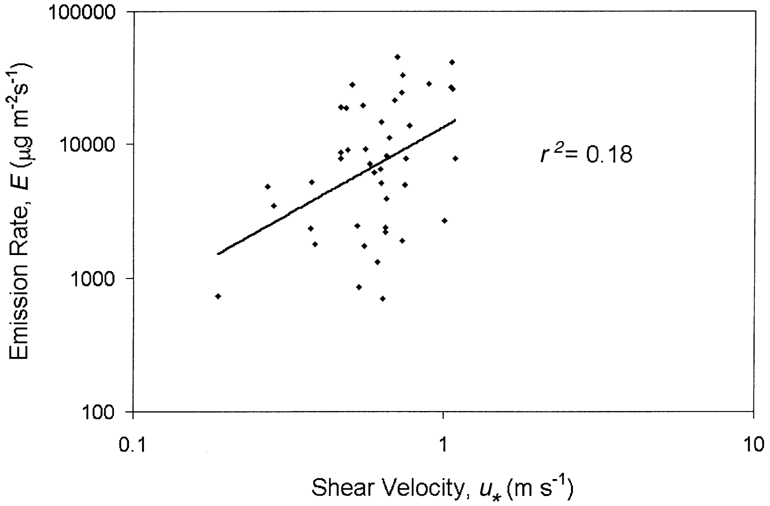

Fig. 8. Comparison of emission rate (E) with the shear velocity (u_*) for the abraded surface.

the sand supply and not by the shear velocity. This suggests that the statistically significant relationship between the vertical PM_{10} flux and the shear velocity is not based on a physical relationship, but reflects the use of shear velocity to calculate the vertical dust flux. As shown previously, the emission rate is better described by the saltation transport rate and the variables controlling the abrasion process.

DISCUSSION

The results of this study indicate that the supply of PM_{10} on this surface is limited under typical wind regimes. As the limited amount of surface material is entrained, the supply of PM_{10} is progressively exhausted, causing the airborne concentration in the tunnel to decay towards the background concentration. It is interesting to note that disturbance to this surface did not lead to the sustained emission of PM_{10}. This is in contrast to the sand-dominated environments studied by Belnap & Gillette (1998), in which the transport rate increased rapidly with disturbance. The unconsolidated material in the disturbed patches is difficult to entrain under normal wind conditions because of the cohesive forces associated with dust-sized sediment (Greeley & Iversen, 1985). Although the passage of turbulent structures such as dust devils may create the required stresses to entrain this sediment, they pass over the surface quickly. Crusted surfaces are only significant continuous sources of PM_{10} when the interparticle bonds of the crust and the unconsolidated material within the disturbed patches are broken. As found in the

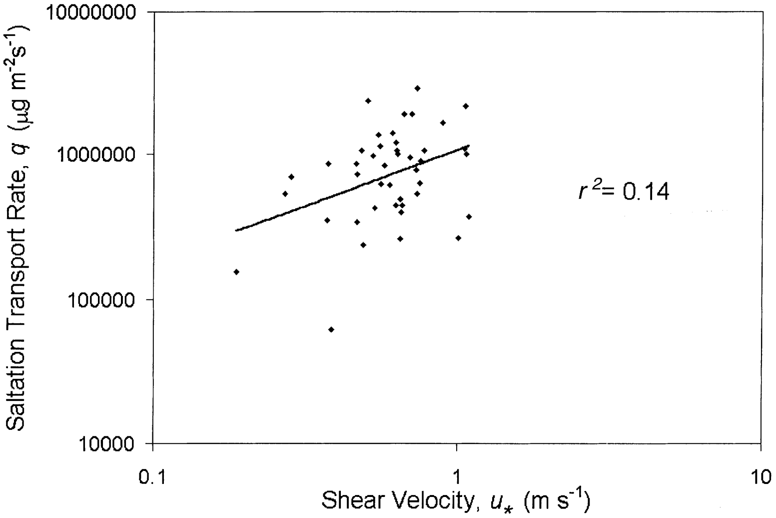

Fig. 9. Relationship between the saltation transport rate (q) and the shear velocity (u_*).

present study, the abrasive action of saltating grains is an effective mechanism through which these bonds are broken, permitting PM_{10} to be liberated from the surface continuously.

The amount of PM_{10} emitted from the surface was found to be linearly related to the saltation transport rate (Eq. 6). A linear relationship between the saltation transport rate and the emission of dust-sized sediment forms the basis of the bombardment model developed by Shao *et al.* (1993) for loose sediments. Rice *et al.* (1997) proposed that saltating grains are unable to liberate individual particles within a crusted sediment. Rice *et al.* (1997) suggested that the interparticle bonds of the crust can only be broken through repeated impacts with the surface. However, if the abrasion of a crusted surface depends on the cumulative effect of saltating grains, then the relationship would be best described by a non-linear function (McKenna Neuman, 1989). As a linear relationship was observed between the emission rate of PM_{10} and the saltation transport rate, it is likely that every impact liberated crust particles and that the interparticle bond strengths (ψ) of the crust and disturbed patches are within the range of impact energies afforded by the sand (Eq. 2).

Although the results indicate that the emission of PM_{10} from a crusted surface is proportional to the transport rate of saltating grains, traditional modelling has focused on the relationship between the vertical dust flux and shear velocity. As stressed by Shao *et al.* (1993), a simple expression describing the dependence of dust transport on flow characteristics is a practical necessity, both for local wind erosion and for estimating large-scale dust movement. In this study, the estimated vertical dust flux was observed to increase with shear velocity raised to the power of 2·14. This exponent falls at the lowest end of the range of values reported in or calculated from previous studies (Table 1).

Although a statistically significant relationship ($r^2 = 0{\cdot}38$) was observed between the vertical dust flux and the shear velocity (Fig. 7), the emission rate (the total amount of dust coming off the surface) was only weakly related to the shear velocity (Fig. 8). This result suggests that shear velocity does not provide any information on the abrasion mechanism controlling the emission of PM_{10}. As the vertical dust flux was found to be a proportion of the emission rate defined by the drag coefficient ($u_*^2\ u_{0.3}^{-2}$), the moderately strong relationship between the vertical dust flux and the shear velocity simply reflects the inclusion of shear velocity within the calculation of the vertical dust flux. In this regard, the relationship is a spurious correlation. This finding is contrary to the model of Shao *et al.* (1993), which assumes a physical relationship between shear velocity and the emission rate.

The use of the shear velocity for emission modelling is rather indirect, as it depends on the relationship between the wind velocity and the saltation transport rate (Shao *et al.*, 1993). In order for shear velocity to be related to the emission of $PM_{10,}$ it should be related to the quantity of sand abrading the surface. In this study, no relationship was found between the saltation transport rate and the shear velocity, as the supply of sand was limited. Although higher feed rates were used at the higher fan settings, it could not be ensured that a consistent relationship could be created between the flow and the amount of sand in transport. The independence of the saltation transport rate on the shear velocity is therefore only an artifact of the methodology used. However, similar degrees of variation in this relationship can be found in the data sets of Gillette (1977), Gillette *et al.* (1997) and Nickling *et al.* (1999). In these studies, the variability in the relationship reflects a limited supply of sand or flow conditions near the threshold of motion (u_{*t}).

Contrary to the findings of this study, Shao *et al.* (1993) found a strong statistical relationship between the emission rate and shear velocity. This relationship was developed in a transport-limited system, in which the saltation transport rate was found to be proportional to the cube of the shear velocity ($q \propto u_*^3$). This relationship follows the well-established dependence of the saltation transport rate on the cube of shear velocity developed by Bagnold (1941) and later revised by Owen (1964):

$$q = \frac{c\rho u_*^3}{g}\left(\frac{u_t^2}{u_*^2}\right)$$

where c is a dimensionless constant, and g is the acceleration resulting from gravity. Bagnold (1941) developed this relationship by assuming that the total wind stress at the surface was carried by the saltating grains. It is thus assumed that the shear velocity limits the saltation transport rate, not the supply of sand, restricting the Shao *et al.* (1993) model to transport-limited environments. In supply-limited systems, which characterize many of the surfaces contributing to the atmospheric loading of PM_{10}, saltation transport is dominated by aerodynamic forces and not impact forces. It therefore follows that the saltation transport rate will not relate consistently to the shear velocity as a result of variations in the empirical coefficient (c) of the relationship.

Gillette *et al.* (1997) found that the transport rate of a limited quantity of sand varies with the cube of shear velocity and that the different quantities of sand in transport reflect different values for the coefficient. As the coefficient of this relationship depends on the availability of sediment and the nature of the bed impact processes, the resulting dust flux models based on shear velocity will be site specific and potentially variable through time. Inconsistencies in the relationship will lead to a varied array of exponents. Even if a reliable relationship could be found between the saltation transport rate and shear velocity, the ability of that sand to abrade the surface remains quite variable (Fig. 5), depending on the structural and textural characteristics of the surface relative to the energy of the abrading sand (Eq. 2). Limitations in the sand supply and variability in the abrasion efficiency are difficult to model statistically through the bivariate relationships used to date and are therefore important considerations for future modelling.

CONCLUSIONS

The continuous emission of PM_{10} from a crusted surface requires that saltating grains abrade the surface. Although dust is emitted from the surface without abrasion, the available supply of PM_{10} on the crust is limited. As this material is entrained, it is quickly depleted, resulting in a non-emissive surface. Crusted surfaces can only contribute significantly to atmospheric loading of PM_{10} where there is a supply of abrading material. Although disturbance to the surface was expected to result in sustained levels of emission without the presence of saltating grains (Wolfe, 1993), the fluid shear stress is unable to overcome the interparticle bonds associated with the small particles. Like the crusted surface, these unconsolidated patches of material also require saltating grains for PM_{10} to be emitted. Thus, it can be concluded that the bombardment and abrasion of the surface by saltating grains is the dominant mechanism through which dust-sized sediment is emitted from both unconsolidated and consolidated soils. The development of dust emission models for sediment budget or impingement models thus requires that the abrasion process is accurately described and understood.

Dust emission research has traditionally focused on the relationship of vertical dust flux to the shear velocity. However, the results of the current research have clearly indicated the emission of PM_{10} to be an independent function of the shear velocity. Only where the saltation transport rate is related to the shear velocity does the shear velocity have a statistical relationship to the emission of PM_{10}. This has important implications for predicting dust emission rates required for various sedimentary models that depend on shear velocity. In supply-limited environments, the relationship between the saltation transport rate and the shear velocity is not necessarily steady on account of variability in the coefficient *c*, which reflects the availability of sand material. Thus, it can be concluded that, in supply-limited environments, emission models should be directly related to the saltation transport rate and the factors that control its ability to abrade the surface, rather than to the shear velocity. This suggests that the development of predictive models for dust emissions has been constrained by the traditional dependence of models on shear velocity as the primary or sole variable.

The abrasion of crusted surfaces by saltating grains is the dominant mechanism by which PM_{10} sediment is liberated. The saltating grains abrade the surface through the removal of individual particles and disaggregation of the crust pieces along the weaker crust edges. As the interparticle bonds are broken, the dust-sized sediment is entrained into the flow. The quantity of PM_{10} emitted from the surface was found to vary linearly with the saltation transport rate. The linear nature of this relationship indicates that PM_{10} is removed with each impact, and is therefore not dependent on repeated impacts on the surface (McKenna Neuman, 1989), and that the ranges of bond strengths are smaller than the energy supplied by the saltating grains.

Although the emission of PM_{10} was found to increase with the saltation transport rate, there is a considerable amount of variation in this relationship. Based on the findings of previous studies, it is anticipated that the amount of dust emitted for a given saltation transport rate (E/q) reflects the susceptibility of the surface to abrasion in relation to the energy of the saltating grains available to abrade the surface. In order to improve current emission models, further research is needed to understand the complexities of the abrasion process.

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LIST OF SYMBOLS

α	dimensional constant
ϕ	phi grain size
ρ	air density (kg m^{-3})
ψ	energy required to disrupt interparticle bonds (kg m^2 s^{-2})
c_N	proportion of the incoming saltation energy available for abrasion
C	sediment concentration (kg m^{-3})
C_Z	PM_{10} concentration at height z
C_d	particle drag coefficient
d	particle diameter (m)
E	emission rate (μg m^{-2} s^{-1})
F	vertical dust flux (μg m^{-2} s^{-1})
g	acceleration due to gravity (9·81 m s^{-2})
k	von Karman's constant (0·4)
m_d	mass of dust particles (kg)
m_f	mass flux of dust particles (μg m^{-1} s^{-1})
q	saltation transport rate (kg m^{-1} s^{-1})
u	horizontal flow velocity (m s^{-1})
u_*	shear velocity (m s^{-1})
u_{*t}	threshold shear velocity (m s^{-1})
u_z	velocity at height z (m s^{-1})
$u_{0\cdot3}$	velocity at 0·3 m sampling height (m s^{-1})
z	height within boundary layer (m)
z_o	roughness length (m)

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