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Effect of Saltation Bombardment on the Entrainment of Dust by Wind

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Saltation is the wind-driven, hopping motion of sand-sized particles across an erodible surface. This mode of motion not only transports sand and similar materials in its own right but can also initiate (through bombardment of the surface) the entrainment and subsequent transport by suspension of smaller dust particles. In this paper, we report a wind tunnel study of the effect of saltation bombardment on dust entrainment. The technique is to allow sand grains to saltate from an upwind sand source onto a bed of dust particles. The experiment confirms that the ejection of dust particles by saltation bombardment (as opposed to detachment of dust particles by aerodynamic forces) is the principal mechanism for the natural entrainment of dust by wind. The data are used to examine the dependence of the dust emission flux F_d (mass per unit ground area per unit time) upon the friction velocity u_*; it is found that F_d is closely proportional to the streamwise flux of saltating sand grains, which in turn is approximately proportional to u_*^3. At a given u_*, F_d increases as the size of the bombarding sand grains increases. On the basis of the hypothesis that F_d is proportional to the kinetic energy flux of the saltating sand grains, we derive theoretically the result that F_d scales with the streamwise saltating sand grain flux and thence approximately with u_*^3, as observed in this experiment.

1. Introduction

Bagnold [1941] identified three particle transport modes contributing to wind erosion: suspension, saltation, and creep. Suspension, the natural transport mode for the smallest soil particles (diameter less than about 50 μm), leads to transport of fine soil constituents over large distances (kilometers to thousands of kilometers) from their point of origin. Because these fine constituents contain a disproportionate share of soil nutrient [*Gupta et al.*, 1981; *Zobeck and Fryrear*, 1986], this transport is a potential source of significant long-term land degradation.

In principle, the movement of dust particles can be initiated either by aerodynamic forces or by the impact of saltating sand grains, a process known as bombardment. However, the part played by aerodynamic lift on dust entrainment is insignificant under realistic wind conditions, because of the strong cohesive forces associated with small particle size [*Greeley and Iversen*, 1985]. The interparticle bonds maintained by these cohesive forces are not readily broken by the typical aerodynamic forces acting on dust particles resting on the surface; however, they are easily disrupted by the impacts of saltating sand grains. Thus, bombardment is the most important mechanism responsible for eolian dust entrainment [*Gillette*, 1981].

The dependence of bombardment-induced dust entrainment upon wind velocity is rather indirect, as it involves the relationship between wind and saltation as an intermediate process. Despite this indirect connection, a simple expression describing the dependence of dust entrainment rate on wind speed is a practical necessity, both for models of local wind erosion and for estimating large-scale dust movement. *Gillette and Passi* [1988] suggested (on the basis of a personal communication from P. R. Owen) that the upward dust flux at the surface, F_d, can be approximated by

$$F_d = \alpha_0 u_*^4 (1 - u_{*t}/u_*) \qquad (u_{*t} \le u_*) \tag{1}$$

where u_* is the friction velocity, u_{*t} is the threshold velocity of saltation, and α_0 is a dimensional constant. Owen's unpublished derivation of (1) (which was kindly communicated to us by D. A. Gillette) is based on aerodynamic considerations of the vortex field generated by a saltating sand grain suddenly brought to rest by impaction on the surface. *Gillette and Passi* [1988] presented empirical evidence showing that (1) reasonably well describes dust flux measurements, including those obtained by *Gillette* [1977, 1981] for eroding fields, and the results of wind tunnel experiments by *Fairchild and Tillery* [1982] and *Borrmann and Jaenicke* [1987]. However, as discussed later, the scatter in this comparison was very large.

Our purpose here is to present, and explain theoretically, results obtained in a wind tunnel investigation of dust emission by saltation bombardment. The experimental data suggest that dust flux, F_d, is approximately proportional to the vertically integrated streamwise flux of saltating particles, Q_s, and therefore scales approximately with u_*^3, the classical result for the dependence of Q_s on u_* [*Bagnold*, 1941; *Owen*, 1964]. Therefore, (1) is not supported by this study. In the following, we first describe the experiment and next present the observational results. We then outline a possible theoretical explanation for the observed proportionality of F_d to u_*^3 and finally discuss our findings in the context of previous work, especially the field observations of *Gillette* [1977, 1981].

2. Description of Experiment

The experiment was carried out in the portable wind tunnel of the Department of Conservation and Land Management (formerly the Soil Conservation Service) of New South Wales. The construction and aerodynamic properties of the tunnel are described by *Raupach and Leys* [1990]. The maximum operational wind speed is 15 m s^{-1} in a rectangular working section 1.15 m wide and 0.9 m high. *Owen and Gillette* [1985] considered the constraints on the development of saltation

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imposed by the wind tunnel dimensions and concluded that the tunnel Froude number U^2/gH (where U is wind speed, g is the acceleration due to gravity, and H is the height of tunnel), should be less than 20. The dimensions of the tunnel are sufficiently large that this requirement is satisfied for normal operational wind speeds, so our results should be free of any serious effects caused by tunnel constraints. In the first 2 m of the working section, the development of a deep turbulent boundary layer is initiated by a tripping fence (40 mm high) mounted on a roughened, nonerodible baseboard. The wind tunnel length (excluding the initial 2-m flow development section) can be extended to 17 m, but for the purpose of this experiment, a short tunnel (6 m) was found to be sufficient and easy to operate. The principal experimental configuration, here called the "bombardment" configuration, is illustrated in Figure 1. Two beds of material were placed in the tunnel: an upstream bed of saltation material of streamwise length 1 m, which produced a supply of saltating grains, followed immediately by a bed of dust of length 2 m, which was subjected to saltation bombardment.

The saltation material was prepared from an eolian red sand obtained from a site near Balranald, New South Wales, Australia; the particle size distribution of the natural sand (median diameter, 200 μm) is given by *Shao and Raupach* [1993]. The sand was oven dried at 70°C and sieved into three size classes, with sieve diameters 100 to 210, 210 to 530, and 530 to 1000 μm. The first 1 m of the tunnel floor in the working section (downstream of the 2-m flow development section) was covered with sieved red sand to a depth of 20 mm. Saltation from this sand bed occurred when the local u_* exceeded a threshold friction velocity u_{*t}, varying from about 0.2 m s^{-1} for the 100 to 210-μm size class to 0.4 m s^{-1} for the 530 to 1000-μm size class [*Greeley and Iversen*, 1985]. Thus, the saltation material was produced by natural wind erosion from a mobile sand surface rather than by artificial injection as in the experiments of *Fairchild and Tillery* [1982] and *Borrmann and Jaenicke* [1987].

The dust bed, of length 2 m and immediately downwind of the sand bed, consisted of fine, loose kaolin clay. Kaolin particles have a typical diameter of about 2 μm. Interparticle cohesive forces cause these primary particles to form aggregates, even in a non-compacted bed. However, for loose clay material, the aggregates are easily broken by external forces, including saltation bombardment, so that the dust particles entering the flow are likely to be almost completely disaggregated.

Vertically integrated streamwise fluxes of both sand and dust were measured with a modified Bagnold sampler, placed 6 m downstream from the leading edge of the sand surface. The 3 m of surface between the downwind edge of the dust bed and the sampler consisted of smooth wood, upon which both sand and dust deposition was negligible. The sampler, identical to the one used by *Leys and Raupach* [1991], was a vertically integrating, active trap of height 500 mm and slit width 5 mm. (This height can be shown to be adequate to catch essentially all of the dust plume, as follows. Suppose that dust particles diffuse as rapidly as fluid elements in the wind tunnel; then the characteristic depth of the dust plume, $\bar{h}$, can be estimated by $\bar{h}=xu_*/U$, with x being the distance between the dust surface and sampler. Since u_*/U is around 1/25 and the maximum value of x is 5 m, $\bar{h}$ is typically 200 mm, which is less than half the trap height.) The trap was connected to a pair of interchangeable filter collectors (only one of which was used at any one time), and air was drawn through the trap and one collector by a high-volume pump. Rapid sequential measurements of particle fluxes, integrated over short time periods, could be made by interchanging the collectors to permit replacement of the filter in the off-line collector. Careful calibration showed that the modified Bagnold sampler slightly oversampled the vertically integrated flux but that the oversampling error was less than 10% [*Shao et al.*, in press]. The sand and dust components of the material caught in the filters were separated by sieving through a 75-μm sieve, with mechanical agitation to eliminate any aggregation of dust particles. The sand and dust components were then weighed individually. Great care was taken to avoid losses during the sieving and weighing process.

Wind speeds were measured with three Pitot tubes at 30, 130, and 280 mm above the soil surface, at the same streamwise location as used for the modified Bagnold sampler. However, despite considerable efforts, the Pitot tubes at the two lower levels were often blocked by dust particles. The placement of the measurement location 3 m downwind of the dust bed represented our attempt to overcome the problem but was not entirely successful. The wind velocity profile measurements are not sufficiently reliable to derive estimates of friction velocity. Therefore, throughout the paper, we use the measured mean wind speed at height 280 mm, U_R, as a reference. Where friction velocities are required, they are inferred from U_R by using the surface drag coefficient, $C_d = u_*^2/U_R^2 \approx 0.042^2$, obtained from measurements over red sand surfaces in the same tunnel [*Shao and Raupach*, 1993].

Observations were made under four different wind conditions with nominal reference wind speeds, U_R, of 8.0, 9.5, 11.0, and 12.5 m s^{-1}. Each run lasted 9 min, starting at time t = 0 with the wind speed being brought from zero to a steady value as rapidly as possible (less than 5 s). During the run, the two collectors connected to the modified Bagnold sampler were interchanged at times t = 15 and 60 s and then at intervals of 60 s.

Besides the principal "bombardment" configuration (Figure 1), experiments were done with two additional configurations: "pure dust" and "mixture." In the "pure dust" configuration, no

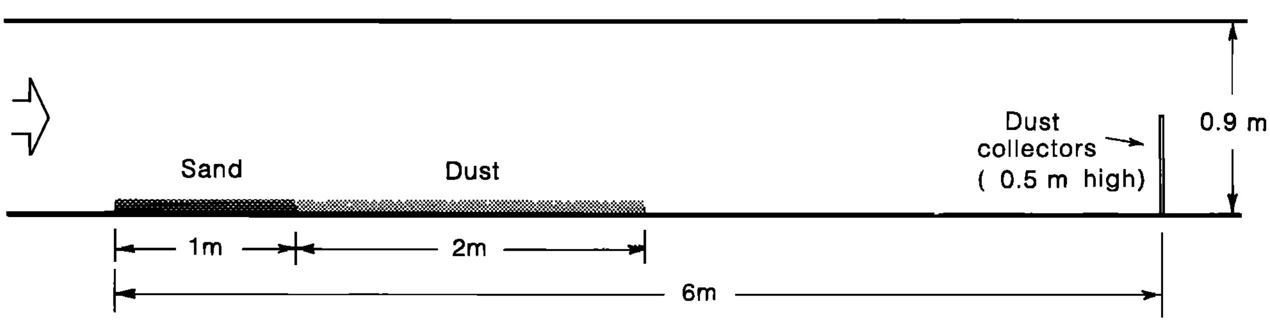

Fig. 1. Schematic illustration of the principal experimental ("bombardment") configuration.

saltating material was used and the dust bed extended for 3 m in the streamwise direction (encompassing the section otherwise occupied by the sand bed). The purpose of this test was to determine the entrainment rate of dust by aerodynamic lift alone, without saltation bombardment. The test was carried out at the four standard wind speeds but without replication. In the "mixture" configuration, dried but unsieved sand was mixed uniformly with dust in the ratio 1:2 (sand:dust) by volume; this mixture was then spread over the tunnel floor for a length of 3 m. The complete course of the experiment is summarized in, Table 1.

The streamwise flux measurements were interpreted as follows. The vertically integrated streamwise particle mass flux, Q, with dimension g m^{-1} s^{-1}, is defined as

$$Q = \int_0^\infty q\,dz \tag{2}$$

where q is the streamwise mass flux density (dimension g m^{-2} s^{-1}) and z is the height. Conservation of particle mass implies that, in steady conditions, Q is related to the upward mass flux density at the surface, F, by

$$F = dQ/dx \tag{3}$$

where x is the streamwise distance coordinate. If particle entrainment is occurring from a bed of streamwise length L into a particle-free incident airflow (so that $Q = 0$ at the upwind edge of the bed), then the upward mass flux density of particles from the bed surface (averaged over the streamwise length of the bed) is $F = Q/L$, where Q is measured at the downwind edge of the bed. This argument applies to both the sand and dust constituents in the present experiment; hence, the bed-average surface upward mass flux densities of sand (F_s) and dust (F_d) are given by

$$F_s = Q_s/L_s\,, \qquad F_d = Q_d/L_d \tag{4}$$

where the vertically integrated streamwise sand and dust fluxes, Q_s and Q_d, are values at the downstream edges of the sand and dust beds, respectively, and L_s and L_d are the streamwise lengths of the sand and dust beds.

3. RESULTS

3.1. *Dust Entrainment by Saltation Bombardment*

We first consider the "pure dust" configuration (runs 1 to 4 in Table 1). Figure 2 shows that the streamwise dust flux, Q_d (and thus the surface flux density, F_d, or dust entrainment rate), decays rapidly with time, becoming negligible less than 200 s after the onset of the wind. The initial dust fluxes (which are small in comparison with the fluxes induced by saltation bombardment, as shown later) are caused by the removal of extremely loose dust particles from the newly prepared bed; once these particles are removed, the dust bed stabilizes and is not subject to further erosion. This is a well-known phenomenon, observed by *Bagnold* [1941] in experiments with cement particles. Bagnold ascribed the stability of the dust bed to the aerodynamic behavior of particles at very small Reynolds numbers. However, a substantial body of later work, reviewed by *Greeley and Iversen* [1985, p. 80], has shown that the bed stability is actually caused by the cohesive forces between particles: the ratio of cohesive to aerodynamic forces acting on a particle on the surface increases rapidly as particle size decreases. In summary, aerodynamic lift alone induces negligible eolian dust entrainment under normal wind conditions.

The "bombardment" configuration examined the effect of saltation bombardment on dust fluxes (runs 5 to 26 in Table 1). Figure 3 shows the time evolution of the streamwise sand and dust fluxes, Q_s and Q_d, in the presence of saltation bombardment, for the 210 to 530-μm sand particle size range at four wind speeds. The dust flux, Q_d, is substantially larger than even the maximum value produced by aerodynamic forces alone at a corresponding wind speed and is sustained for far longer times, essentially for as long as there is a supply of both sand and dust. In the two lower-wind-speed cases (Figures 3*a* and *b*), both Q_d and Q_s remained constant with time for the 9-min run duration, following a short initial period of less than 60 s during which fluxes were abnormally high as very loose material was blown off the newly prepared bed (as in Figure 2). The higher-wind-speed cases (Figures 3*c* and *d*) behaved similarly, except

TABLE 1. Runs in Saltation Bombardment Experiment

Run	U_R, m s^{-1}	Sand Size, μm	Configuration
1, 2, 3, 4	8.3, 9.8, 11.1, 12.9	----	pure dust
5, 6, 7	8.4, 8.1, 8.1	210-530	bombardment
8, 9, 10	9.7, 9.7, 9.7	210-530	bombardment
11, 12, 13	10.9, 11.4, 11.2	210-530	bombardment
14, 15, 16	12.9, 12.3, 12.6	210-530	bombardment
17, 18, 19, 20	8.3, 9.7, 11.0, 12.4	530-1000	bombardment
21, 22, 23, 24	8.0, 9.5, 11.0, 12.5	100-210	bombardment
25, 26	8.2, 8.2	unsieved	mixture
27, 28	9.6, 9.6	unsieved	mixture
29	11.0	unsieved	mixture
30	12.5 (estimate)	unsieved	mixture

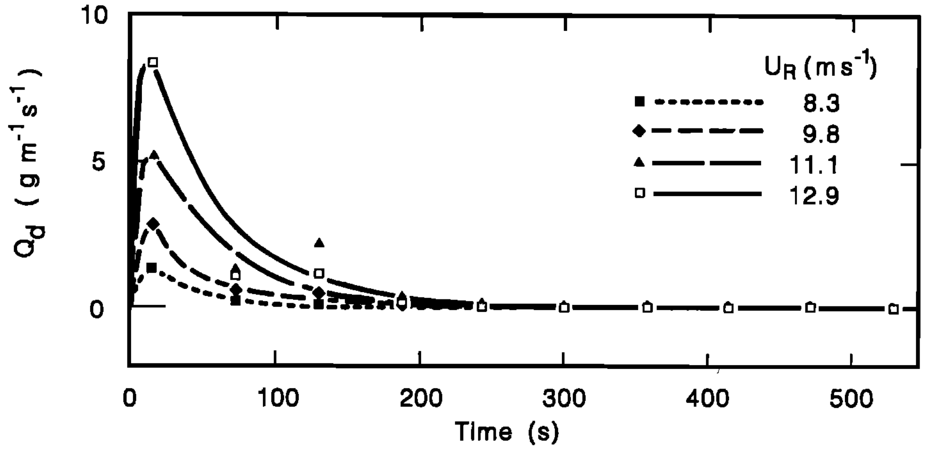

Fig. 2. Decay of streamwise dust flux, Q_d, with time for four reference wind speeds, U_R, in the "pure dust" configuration.

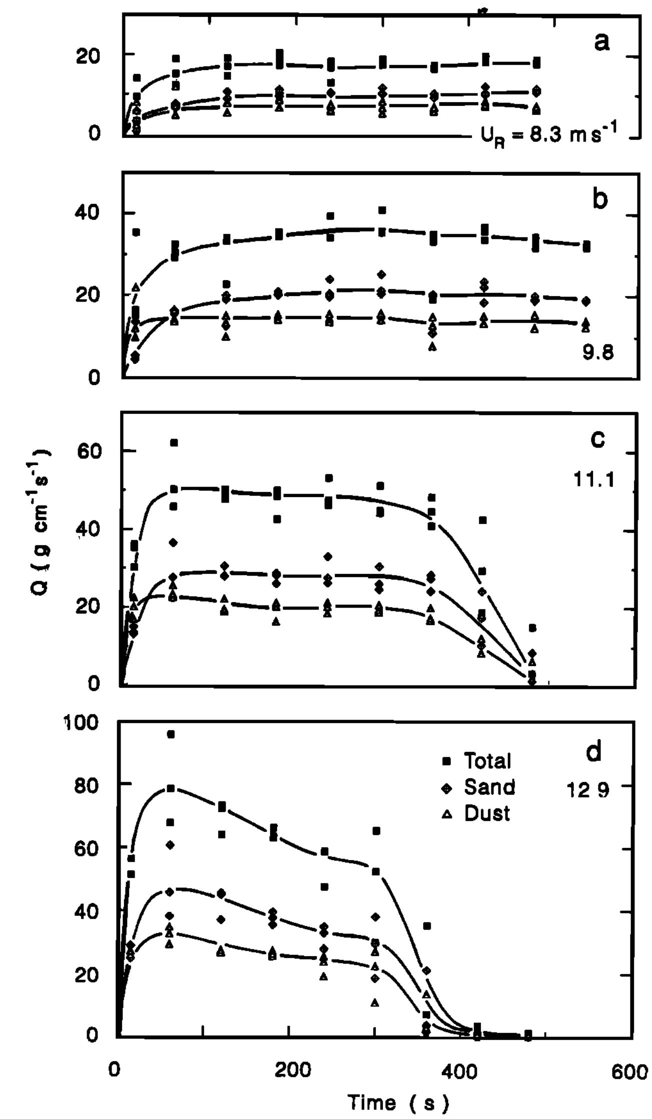

Fig. 3. Time evolution of streamwise fluxes of sand, Q_s, dust, Q_d, and total mass, Q_t, for four reference wind speeds, in the "bombardment" configuration. Saltation size class is 210 to 530 μm.

for rapid decreases at the end of each run as a result of exhaustion of the supply of source material (either sand or dust); in other words, the process became "supply-limited" rather than "transport-limited." Taken together, Figures 2 and 3 confirm that bombardment is the principal mechanism responsible for eolian dust entrainment, while aerodynamic forces play a negligible role under normal wind conditions.

In the "mixture" configuration, the bed consisted of a mixture of one third unsieved sand and two thirds dust. Somewhat surprisingly, the result was very similar to the "pure dust" configuration (Figure 2): after a short period of about 100 s, the streamwise fluxes of both sand and dust were negligible. An explanation is that as the sand particles are coated by dust particles, the cohesive forces between grains are greatly enhanced and the "coefficient of restitution" (crudely, the elasticity) of the bed is greatly reduced. Both effects cause the saltation process to be inefficient [*Anderson and Haff*, 1991, p. 28]. The same experiment was done with a mixture of half sand and half dust and produced essentially the same result. It appears that a much higher proportion of sand is required to generate a significant amount of dust from intimate mixtures of sand and dust, at least with the present materials.

3.2. *Dust Emission Flux is Proportional to* u_*^3

To examine experimentally the relationship between the surface dust flux, F_d, and the friction velocity, u_*, we use the direct measurements of the streamwise flux, Q_d, which is related to the bed-average value of F_d (over a streamwise length L_d) by (4). As mentioned earlier, the measurements of u_* are unreliable; hence, instead of using u_*, we study the relationship between the streamwise fluxes and the reference wind speed, U_R.

Figure 4 shows the vertically integrated streamwise fluxes of sand, dust, and total mass ($Q_t = Q_s + Q_d$) for the 210 to 530-μm saltation size fraction, plotted against U_R in logarithmic coordinates. The measurements of Q_s are in good agreement with those obtained in another experiment [*Shao and Raupach*, 1993] using different traps in the same wind tunnel. The logarithmic plots of each of Q_s, Q_d, and Q_t against U_R are linear, with slopes close to 3; least-square fits show that

$$\ln Q_s = 3.026 \ln U_R - 4.00 \quad (5)$$

$$\ln Q_d = 2.832 \ln U_R - 3.88 \quad (6)$$

$$\ln Q_t = 2.926 \ln U_R - 3.23 \quad (7)$$

Thus, the saltation flux, Q_s, is proportional to U_R^3 and thence to u_*^3, consistent with the classical theoretical predictions of *Bagnold* [1941] and *Owen* [1964]. *Greeley and Iversen* [1985, p. 100] review numerous subsequent predictions for the

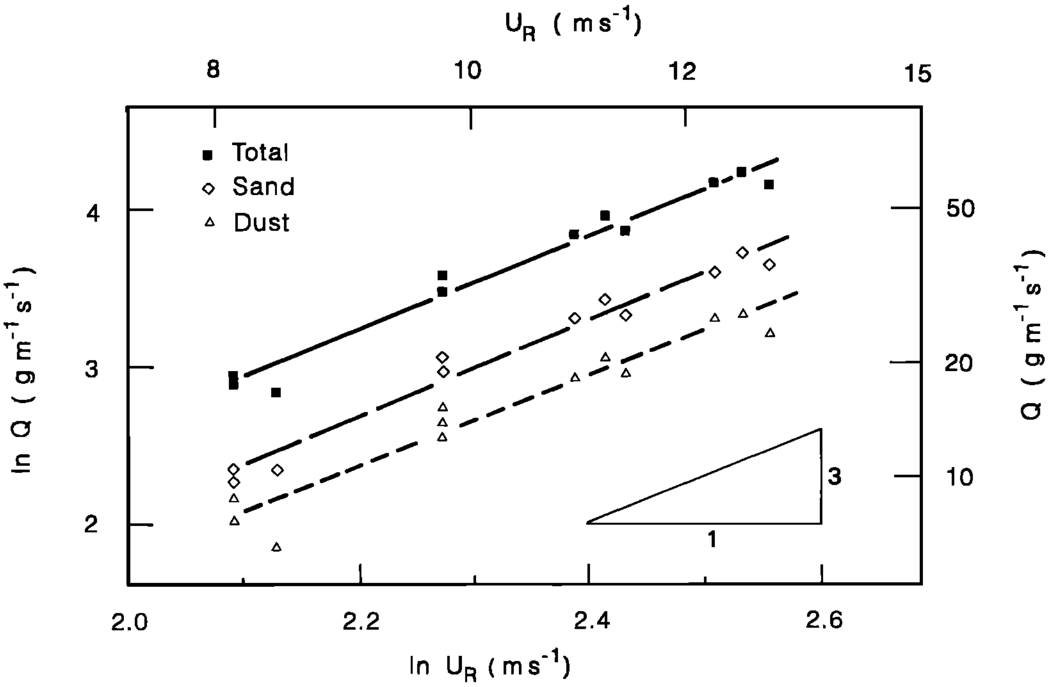

Fig. 4. Streamwise fluxes of sand, Q_s, dust, Q_d, and total mass, Q_t, for the 210 to 530-μm saltation size class, plotted against reference wind speed, U_R, in logarithmic coordinates.

dependence of Q_s on u_*, which all tend to proportionality with u_*^3 well above saltation threshold. For the dust flux. however, Figure 4 shows that Q_d is proportional to U_R^3 and thence that F_d is proportional to u_*^3. This result is in contradiction with the only hypothesis about the wind speed dependence of F_d known to us, equation (1), which suggests a u_*^4 dependence well above saltation threshold. The implication of Figure 4 is that there is no fundamental difference between the wind speed dependencies of Q_s and Q_d; rather, the streamwise flux of dust, the entrainment of which is caused almost entirely by saltation bombardment, is proportional to the streamwise flux of the bombarding material.

3.3. *Bombardment Efficiency*

Figure 5 shows the time evolution of the sand and dust streamwise fluxes, Q_s and Q_d, together with their ratio, Q_d/Q_s, at the four reference wind speeds for all three saltation particle size ranges. Both Q_s (Figure 5*a*) and Q_d (Figure 5*b*) show the expected increase with wind speed, apart from some supply limitation at the later stages of runs at the two higher wind speeds, which caused the fluxes to decay toward zero. The trend with saltation particle size class is for Q_s to decrease with increasing particle size (at a given wind speed), mainly because of the increase in threshold friction velocity with increasing particle size above 100 μm [*Greeley and Iversen*, 1985]. For the largest size class (530 to 1000 μm), Q_s is negligible at the lowest wind speed (U_R = 8 m s^{-1}, u_* = 0.34 m s^{-1}) because the wind speed is below (or just at) the entrainment threshold.

We have argued that the dust flux, Q_d, is closely linked to the sand flux, Q_s, by the bombardment mechanism, so similar patterns of evolution are expected in both fluxes; this is what is observed (Figures 5*a* and *b*). In particular, the dust flux is negligible for the largest saltation particle size class at the lowest wind speed, which was below saltation threshold. Also, limitation of sand supply at the two higher wind speeds produced not only declines in Q_s but also declines in Q_d at corresponding times.

The close relationship of Q_d to Q_s is verified in Figure 5*c*, which shows the ratio Q_d/Q_s, which can be regarded as a measure of the efficiency of the bombardment process. This ratio is approximately constant (independent of wind speed) for a specified saltation particle size class; the values of Q_d/Q_s are about 0.25, 0.7, and 0.8 for the 100 to 210-, 210 to 530-, and 530 to 1000-μm size classes, respectively. These constant values are observed throughout, apart from short initial periods during which extremely loose material is blown off the freshly prepared beds, as in Figure 1, and periods of acute supply limitation late in the higher wind speed runs, when the ratio becomes undefined.

In summary, Figure 5 shows that the efficiency ratio, Q_d/Q_s, is independent of wind speed for a given saltation particle size class and increases with saltation particle size at a given wind speed.

4. THEORY FOR THE DUST EMISSION FLUX

The following theory for dust emission by saltation bombardment is formed from two components: a theory for the dependence of saltation on friction velocity (following well-established lines), and a hypothesis about the energetics of dust emission.

Saltation: In general terms, the theory of saltation is well established, following *Bagnold* [1941] and the detailed analysis of *Owen* [1964]. The purpose of this section is to draw a few results from this theory by outlining a simplified summary. We consider the saltation of identical particles (saltators) of mass m_s. The vertically integrated streamwise saltation flux, Q_s, is given by

$$Q_s = m_s n X_s \tag{8}$$

where n is the ejection rate or dislodgment rate (the flux density of saltators at the surface, either up or down, in particles per unit area per second) and X_s is the mean saltation jump length in the streamwise (x) direction. The total momentum flux to the ground surface, ($\tau = \rho u_*^2$, where ρ is air density), can be written as the sum $\tau_p + \tau_a$ of contributions from the saltator motion (τ_p) and turbulent and viscous transfer through the air (τ_a). The particle contribution at the surface is $\tau_p = n m_s(U_1 - U_0)$, where U_0 and U_1 are the streamwise velocity components of the saltator at ejection from the surface and on impact, respectively. The air contribution can be taken to be $\tau_a = \rho u_{*t}^2$, where u_{*t} is the threshold friction velocity for saltation, as stated by *Owen* [1964]. It follows that n is given by

$$n = \frac{\rho u_*^2(1 - u_{*t}^2/u_*^2)}{m_s(U_1 - U_0)} \tag{9}$$

[see *Raupach*, 1991, equations (3) and (11)]. A form for Q_s follows by noting that the jump length, X_s, in equation (8) is $U_{av}t_s$, where U_{av} is the average particle velocity during a jump and t_s is the average saltation jump time. Approximating t_s with the ballistic time, $2W_0/g$, where W_0 is the initial (ejection) vertical velocity of the saltating particle, (8) and (9) give

$$Q_s = \rho u_*^2 \left(1 - \frac{u_{*t}^2}{u_*^2}\right)\left(\frac{U_{av}}{U_1 - U_0}\right)\left(\frac{2W_0}{g}\right) \tag{10}$$

If we take $U_{av}/(U_1 - U_0)$ and W_0/u_* as constants of order 1 [*Anderson and Hallet*, 1986], then (10) becomes

$$Q_s = \frac{c\rho u_*^3}{g}(1 - u_{*t}^2/u_*^2) \tag{11}$$

where c is a dimensionless O(1) constant. This is the saltation equation of *Owen* [1964, equation (41c)], though Owen's form includes a small additional u_* dependence in c.

Dust emission: The emission of dust under saltation bombardment is caused by the rupturing of interparticle bonds between dust grains by the impact of a saltator. Let ψ be the typical binding potential energy of a dust particle on the surface, equal to the energy required to dislodge the particle from the "potential well" induced by the binding forces. The energy supplied to the surface by a saltation impact is $E_1 - E_2$, where E_1 is the kinetic energy of an impacting saltator and E_2 is the total kinetic energy of the saltators ejected by the impact, which may cause both ricochet of the original saltator and ejection of others. (The subscripts 0, 1, and 2 denote an ejection, impact, and subsequent ejection sequence.) Letting N be the typical number of dust particles ejected by a saltation impact, we suppose that N satisfies

$$N\psi = c_N(E_1 - E_2) \tag{12}$$

where c_N is a constant of proportionality, which must be less than 1, to satisfy the energetic requirement that $E_1 - E_2$ exceeds

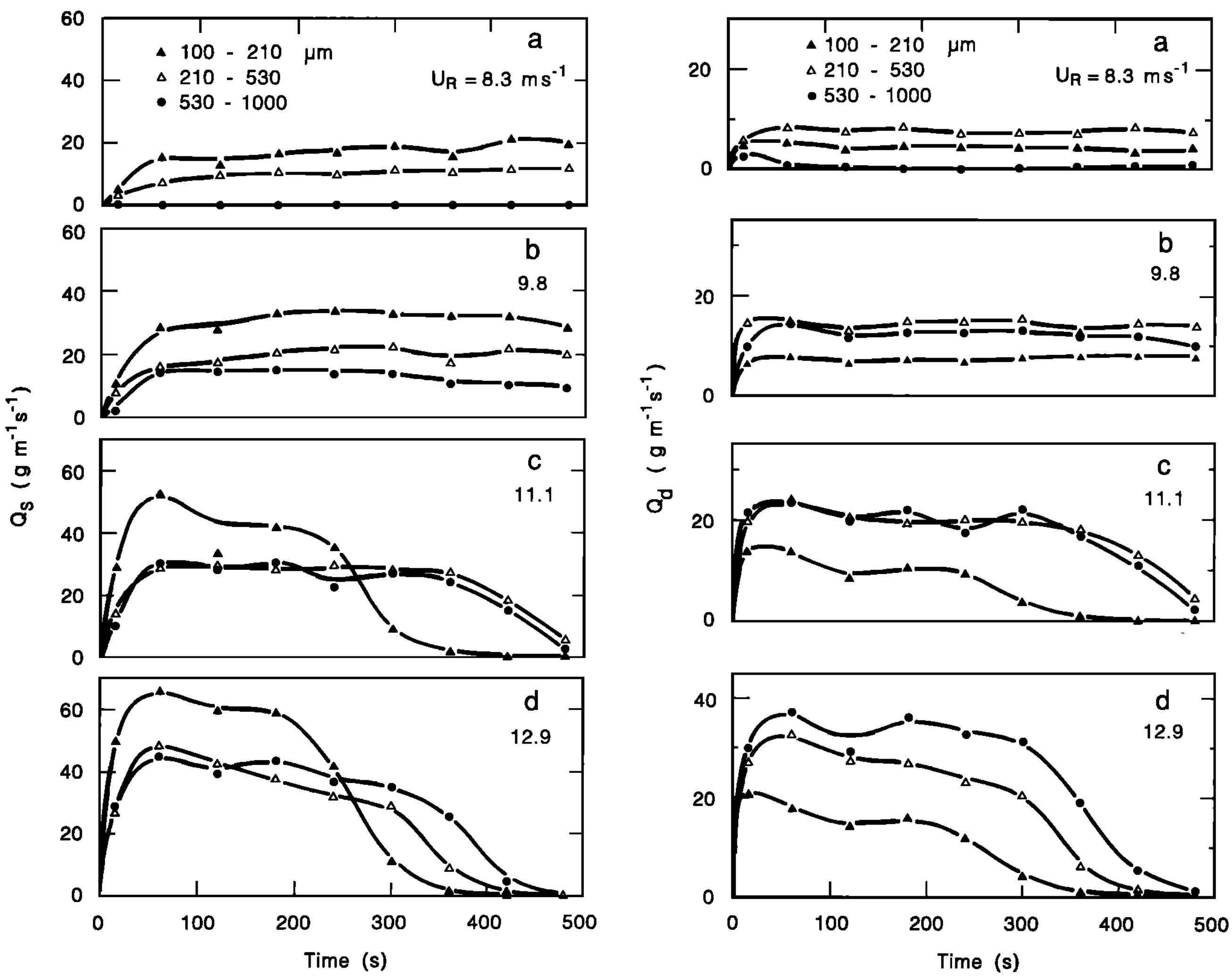

Fig. 5. Time evolution of (*a*) streamwise sand flux, Q_s, (*b*) streamwise dust flux, Q_d, and (*c*) the ratio Q_d/Q_s for three saltation size classes at four reference wind speeds, U_R.

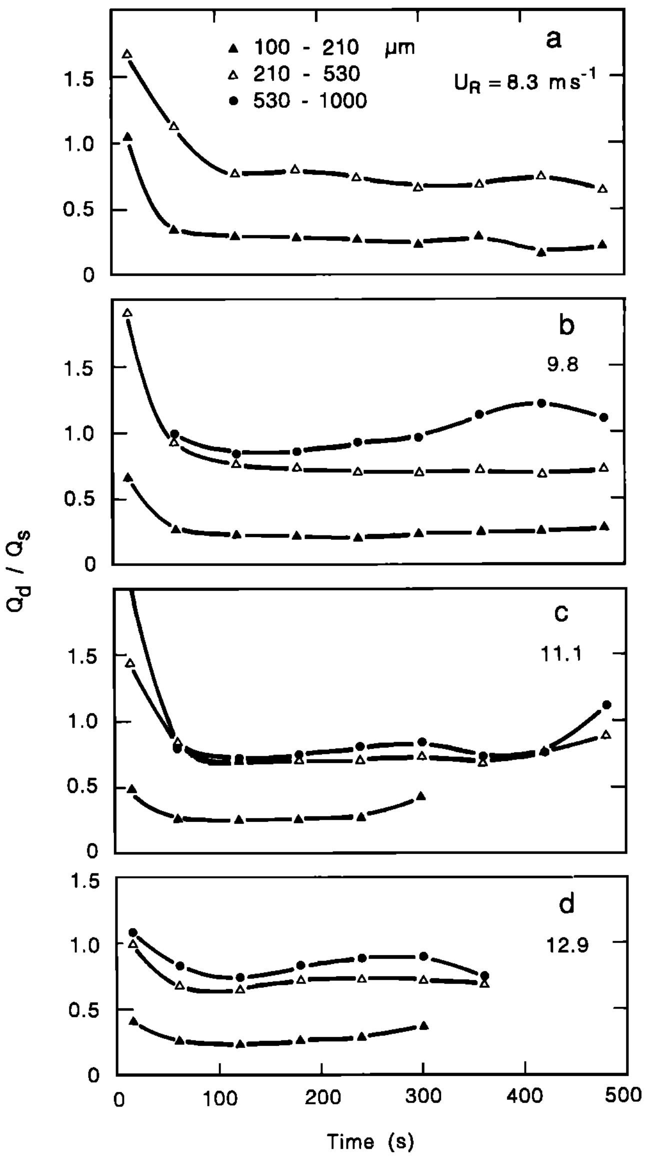

Fig. 5. (continued)

the sum of the binding energies of all dislodged dust particles. On the right hand side of (12) we have excluded the initial kinetic energy of dust particles obtained from the impact by assuming that this energy is either much smaller than or proportional to ψ. The emission dust flux across the surface is $F_d = m_d n N$, where m_d is the mass of a dust particle and n is the number of saltation impacts per unit area per second. We use (9) and (12) for n and N, respectively, and write $E_1 - E_2 = (m_s/2)(U_1^2 - U_0^2)$ to relate the kinetic energy difference, E_1 - E_2, to the ejection and impact velocities, U_0 and U_1 respectively, of a typical saltator (which is an approximation because of the possibility of multiple ejections from a single impact). It follows that

$$F_d = m_d \left(\frac{\rho u_*^2 (1 - u_{*t}^2/u_*^2)}{m_s(U_1 - U_0)} \right) \left(\frac{c_N m_s (U_1^2 - U_0^2)}{2\psi} \right) \quad (13)$$

which simplifies through the use of (11) to

$$F_d = \frac{m_d g Q_s}{\psi} \left(\frac{c_N}{2c} \right) \left(\frac{U_1 + U_0}{u_*} \right) \quad (14a)$$

$$= \alpha_1 u_*^3 (1 - u_{*t}^2/u_*^2) \quad (14b)$$

where α_1 is a dimensional parameter which determines the efficiency of the bombardment process.

Equation (14a) shows that the basic quantities governing the dust emission flux are embodied in the proportionality $F_d \sim m_d g Q_s/\psi$ (apart from the dimensionless factor $c_N/2c$ and the dimensionless wind parameter $(U_0 + U_1)/u_*$, which is typically of order 10; see *Owen* [1964]). In particular, F_d is predicted to be proportional to the streamwise saltation flux, Q_s, and thence proportional to u_*^3 (well above saltation threshold). This is the observed behavior in Figure 5. Also, for a given Q_s, the dust flux decreases as the binding energy, ψ, increases; that is, the bombardment efficiency decreases. Equation (14b) expresses our result in a form comparable to (1), where the dimensional parameter $\alpha_1 = (m_d\rho/\psi)(c_N/2)(U_1 + U_0)/u_*$, or $\alpha_1 \sim c_N m_d \rho/\psi$. Hence, α_1 depends on c_N proportionally and on ψ inversely, c_N reflecting the proportion of the incoming bombardment energy available for breaking bonds; and ψ reflecting the resistance of the surface to breakdown by this available energy.

One aspect of the experimental results not predicted by (14a and b) is the observed increase in the efficiency of the bombardment process, as measured by the ratio Q_d/Q_s, with saltation particle size. This indicates that (12) is an oversimplification and that the constant of proportionality, c_N, relating N to $(E_1 - E_2)/\psi$ is dependent on saltator diameter, d. However, the experimentally observed change in Q_d/Q_s with d is large only for the transition from the smallest to the middle d class (100-210 to 210-530 µm) and is quite small for the transition from the middle to the largest d class (210-530 to 530-1000 µm). It is therefore possible that (12) (with a constant c_N) is reasonable for saltators above a certain threshold size, perhaps of order 200-500 µm, given the dust material used in this experiment.

5. DISCUSSION

It is important to compare our findings with field data. *Gillette* [1977] presented field measurements of F_d and Q_s as functions of u_* for nine soils; Q_s was obtained from a modified Bagnold trap, and F_d from measurements of dust concentrations and wind speeds at heights 1.5 and 6.0 m, assuming similarity of turbulent transfer of dust and momentum. The Q_s data generally conform to (11). The F_d data show a strong increase with u_* but are so scattered that for most of the nine soils it is impossible to distinguish between a third- and a fourth-power dependence on u_*. However, the ratio F_d/Q_s (which Gillette plotted separately against u_*) does not depend systematically on u_*, in agreement with the experimental and theoretical conclusion of this paper. The only clear exception is Gillette's soil 3, "a loamy soil with very little surface coherence," for which F_d increased very rapidly with u_*, apparently to a power around 7 or more.

In this context, we must allow for two major differences between our idealized bombardment experiment and natural dust emission in the field. First, the fetch was extremely short in our experiment, so that deposition of dust (as opposed to emission) is greatly underestimated. This is unlikely to affect our basic finding about dust emission, which is externally driven by saltation bombardment and is therefore largely independent of dust concentration. In contrast, deposition is strongly dependent on dust concentration [*Chamberlain*, 1983], which in turn is controlled by the upwind emission flux and fetch.

The second main difference is that both the sand and dust particle characteristics were carefully controlled (idealized) in our experiment: both particle size distributions were sharply peaked, and the dust bed was loose, implying that the binding energies between dust particles were low and not broadly scattered. It is likely that this group of soil-dependent factors accounts for much of the difference between our results and those of *Gillette* [1977] and also for much of the large variability between field soils observed by Gillette. If there is a broad distribution of the binding energy, ψ (say over several orders of magnitude), then a progressively greater fraction of the bombarded surface will become amenable to dust emission as the wind speed (and saltator kinetic energy) increases, leading to $F_d \propto u_*^n$ with $n > 3$. In this view, both the $F_d(u_*)$ relationship and its variability in the field are controlled by a combination of saltation energetics and soil mechanics. This can be contrasted with the view that dust emission is dominated by aerodynamic processes, which underlies (1).

Finally, the present work on saltation bombardment can be compared with investigations of eolian abrasion as a weathering process [*Anderson*, 1986]. *Dietrich* [1977] concluded that the fundamental parameters which control eolian abrasion are the kinetic energy of the impacting grain and the bond strength of the abraded material. This was confirmed by *Greeley et al.* [1982], who investigated the susceptibility of surfaces to abrasion, S_a, defined as mass of material eroded per particle impact. They found that for a given size of impact particle, S_a is proportional to the square of the impacting-particle velocity, v^2, while for a given impact velocity, S_a is proportional to d^3, where d is the impacting-particle diameter. Hence, the combined relationship is that S_a is proportional to the kinetic energy of the impacting particle:

$$S_a \propto d^3 v^2 \propto mv^2/2 \quad (15)$$

where m is the impacting-particle mass. These findings are fully consistent with the basic assumption of our analysis, equation (12).

6. CONCLUSIONS

(1) The experiments confirm that under normal wind conditions, saltation bombardment (as opposed to direct aerodynamic lift) is the dominant mechanism maintaining dust emission fluxes from the surface.

(2) The streamwise dust flux, Q_d, which is related linearly to the surface dust emission flux, F_d, in our experiment, is observed to be proportional to the streamwise saltation flux, Q_s; both streamwise fluxes are proportional to the cube of the wind speed (U_R^3) or of friction velocity (u_*^3) in the velocity range of this experiment.

(3) To derive an expression for the wind speed dependence of the dust flux induced by saltation bombardment, we assumed that the number of dust particles dislodged from the surface per saltation impact is proportional to the ratio of the kinetic energy loss during a saltation impact to the typical binding potential energy holding a dust particle to the surface, ψ. This assumption leads to the prediction that dust flux, F_d, is proportional to $m_d g Q_s/\psi$ and in particular that F_d is proportional to Q_s, as observed in this experiment.

(4) The efficiency of bombardment (the ratio Q_d/Q_s) was observed to increase with the size of saltation particles: the efficiency was about 0.2 for 100 to 210-μm saltators, 0.7 for 210 to 530-μm saltators, and 0.8 for 530 to 1000-μm saltators.

(5) The scatter of field measurements of $F_d(u_*)$ is very large, but most data are consistent with a u_*^3 dependence of F_d. The large field variability is likely to be related to differences in the statistics of the binding potential energy, ψ, which must be exceeded to dislodge dust grains from the surface.

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