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The Overshoot and Equilibration of Saltation

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Downwind of the leading edge of a saltating surface, the saltation process develops toward an eventual streamwise equilibrium. The nature of this development is investigated in a portable wind tunnel by measuring the vertically integrated streamwise flux Q of saltating sand grains as a function of distance x from the leading edge of the erodible surface, at wind speeds between 8 and 13 m s^{-1}. It is found that $Q(x)$ increases from zero at $x = 0$ to a maximum value at x around 7 m, before decreasing toward an eventual equilibrium value (about half the maximum value) when x is greater than about 15 m. These results are in qualitative agreement with two recent numerical simulations of the approach of saltation to equilibrium. The experiment indicates the minimum length of wind tunnel required for studying the saltation process in its equilibrium state, and the order of magnitude of the measurement errors if shorter tunnels must be used.

1. INTRODUCTION

Saltation, the bouncing motion of windblown grains across an underlying granular surface, is a principal mechanism for aeolian sand and soil transport. It is the primary process responsible for the formation of sand dunes and fenceline drifts. Also, the bombarding action of saltating soil particles plays an important part in the release of fine, nutrient-rich dust particles into the atmosphere; these fine particles become suspended and can be transported over large (up to continental) distances, thereby depleting the source soil of nutrients.

The dynamics of saltation involves an interacting set of momentum transfer processes between the air, the saltating particles, and the soil surface. Basic aspects of saltation dynamics were established by the pioneering work of *Bagnold* [1941] and *Owen* [1964], but only recently have attempts been made to model numerically the complete set of feedbacks governing saltation [e.g., *Werner*, 1990; *Anderson and Haff*, 1991; *McEwan and Willetts*, 1991; *Sorensen*, 1991]. Four interacting components of the saltation process were identified by *Anderson and Haff* [1991]: particle lift-off by aerodynamic forces, particle aerodynamic response characteristics, particle ejection or "splash" by impact, and the modification of the wind profile by the saltation. Based on this simplified conceptual model, Anderson and Haff were able to simulate the development of saltation in time, or with distance downwind from the leading edge of a saltating surface. They obtained two significant conclusions: first, a considerable distance is required for the process of saltation to reach an equilibrium, when the vertically integrated streamwise flux Q (hereafter called the streamwise flux) becomes independent of streamwise distance x. Second, in the initial stage before equilibrium is reached, Q increases rapidly with x to a maximum value, before decreasing to its eventual equilibrium value; this is the "overshooting" of saltation. The overshoot occurs because the initially high wind speed (over the relatively smooth, nonsaltating surface) induces a rapid "saltation cascade," which is eventually moderated and brought to equilibrium by a reduction in the wind speed near the bed, caused by the increased bulk surface roughness associated with downward momentum transport by the particles themselves.

As pointed out by *Anderson and Haff* [1991], these predictions are not yet well tested or confirmed by experimental studies. *Bagnold* [1941, pp. 180–183] provided some early observations of the dependence of the streamwise flux Q on distance x, which indicated a smooth increase to an eventual equilibrium at about 7 m, without overshoot. A possible explanation for this result is that Bagnold used a relatively short tunnel which (in the light of the present results) was probably insufficiently long to observe the full development of saltation.

Experimental studies of the approach of saltation to equilibrium are important for both theoretical and practical reasons. From the theoretical point of view, observations of approach to equilibrium provide a sensitive test of the basic physics in models such as that of *Anderson and Haff* [1991] and *McEwan and Willetts* [1991]. In practical terms, it is important to ascertain the performance of portable wind tunnels, necessarily limited in length, which are now widely used in wind erosion studies [e.g., *Raupach and Leys*, 1990; *Leys and Raupach*, 1991]. It is suspected that the soil erodibility observed in these tunnels differs substantially from what actually occurs in nature under similar wind conditions, because the tunnel measurements are made under nonequilibrium conditions.

This paper reports initial experimental results from a study of saltation in a wind tunnel with a working section 17 m long, 1.15 m wide, and 0.9 m high. The results confirm the basic features of saltation as predicted by the numerical models of *Anderson and Haff* [1991] and *McEwan and Willetts* [1991], despite some quantitative disagreements.

2. EXPERIMENTAL DETAILS

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 characteristics of the tunnel are described in *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. In the first 2 m of the working section, the development of a deep turbulent boundary layer is initiated by a tripping fence

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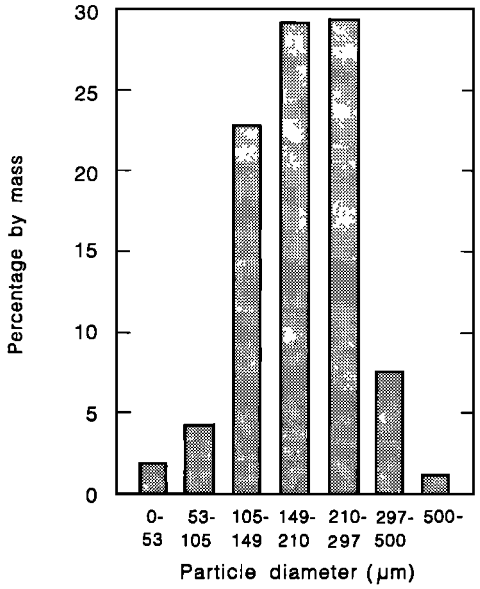

Fig. 1. Particle size distribution of the red sand used in the experiment, analyzed by sieving.

(40 mm high) mounted on a roughened nonerodible baseboard. Excluding this initial 2-m flow development section, the available length of the working section for the first part of the experiment was 10 m. The results with this length of tunnel indicated that a longer working section was required to observe the complete equilibration of the saltation layer, so the available length of working section (excluding the 2-m flow development section) was extended to 17 m for the second part of the experiment.

The dimensions of this tunnel are larger than most of the other wind tunnels used in saltation studies [e.g., *Williams*, 1964; *Butterfield*, 1991; *Rasmussen and Mikkelsen*, 1991]. *Owen and Gillette* [1985] investigated the constraint on the development of saltation imposed by a wind tunnel of limited height, and concluded that the tunnel Froude number $F = U^2/gH$ (where U is wind speed, g the acceleration due to gravity, and H the height of tunnel) should not be larger than 20. In our experiments, this requirement was fulfilled for all cases, so the results should be free from any serious effects caused by tunnel constraints.

The saltating material used in the experiment was red sand, obtained from a moving sand dune near Balranald, New South Wales. The particle size distribution (Figure 1) was determined by sieving. The red sand has very low clay content (less than 2%), a modal particle size near 200 μm, and 90% of the particle mass between 105 and 500 μm. Prior to use, the red sand was oven dried at a temperature of 70°C to eliminate the possible effects of moisture content, and sieved through a 530-μm sieve to eliminate traces of large organic particles.

The layout of the experiment is illustrated in Figure 2. The tunnel was placed on a concrete slab to provide a smooth, solid floor. This was covered with red sand to a depth of 20 mm and a width of 1 m, carefully screeded to a smooth surface before each run. The screeded surface defined the height origin, $z = 0$. The upwind edge of the soil surface, defined as the streamwise coordinate origin, $x = 0$, was located 1.5 m downstream of the tripping fence (which, in turn, was 0.5 m downstream of the honeycomb defining the start of the working section). For the first part of the experiment, the streamwise flux Q was measured at five stations located at $x = 1, 3, 6, 7.5$, and 9 m, while for the second part with the extended tunnel, Q was measured at $x = 1, 3, 6, 9, 12$, and 14.5 m. At the leading edge, the soil surface had a natural angle of repose of approximately 35°.

The mean wind speed U in the tunnel was measured with three Pitot tubes, which were placed at $x = 4.2$ m to record a mean wind profile at heights $z = 30$, 130, and 280 mm. Limitations of available equipment prevented measurement of the streamwise development of the wind profile in these preliminary experiments. Values of the friction velocity u_* (the square root of the bulk kinematic stress on the saltating surface) were obtained from the three-point wind profile using the standard stress-shear relationship for an equilibrium surface layer,

$$u_* = k \frac{dU}{d \ln (z)} \quad (1)$$

where $k = 0.40$ is the von Karman constant. The resulting u_* values are subject to at least two kinds of error: first, (1) is not valid in a saltation layer, where dU/d [ln (z)] is smaller than in the flow above because momentum is transferred from the air to the surface by grain motion as well as by turbulent transfer. This causes (1) to underestimate u_*. Second, the flow is subject to a change of aerodynamic roughness [*Bradley*, 1968; *Townsend*, 1976] because of the sudden increase in surface stress associated with the initial development of saltation. Therefore u_* evolves with x (first increasing very rapidly and then decreasing very slowly to a new equilibrium value far downstream), and (1) no longer describes the relationship between dU/d [ln (z)] and the local u_*. The data of *Bradley* [1968] show that in the transition layer (in which the flow is equilibrating to the new surface condition), (1) tends to overestimate u_* because of

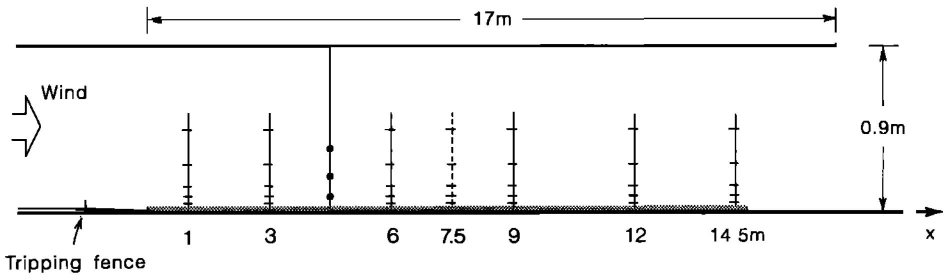

Fig. 2. Schematic view of the wind tunnel experiment. Streamwise flux density Q is measured at $x = 1, 3, 6, 7.5, 9, 12$, and 14.5 m. Short horizontal dashes indicate the position of traps, and dots indicate the position of Pitot tubes.

the nonequilibrium nature of the flow. The errors in u_* caused by these two effects are therefore opposite in sign, but even so, the values of u_* derived from the three-point wind profiles at $x = 4.2$ m cannot be taken as reliable. In the following, they are only used for semiqualitative comparisons.

The streamwise soil flux was measured with "Leach" traps, passive samplers with a frontal intake area of 10 mm wide and 20 mm high. These traps measure the streamwise particle flux density $q(x, z)$ at the point (x, z), averaged over the frontal intake area. The vertically integrated flux $Q(x)$ was then calculated using

$$Q(x) = \int_0^\infty q(x, z)\, dz \qquad (2)$$

Prior to the experiment, the efficiency of the Leach traps was determined by calibration against an accurate isokinetic sampler (work to be published separately). The efficiency was found to be 90% (with a standard deviation of 3%) for the present red sand, over the range of wind speeds used in the experiment. At each measurement station for streamwise flux, five traps were deployed logarithmically with height, with intakes centered vertically at z = 10, 50, 110, 220, and 410 mm. At successive stations, the traps were offset laterally in the tunnel to avoid interference at any one trap from others upstream.

The experiments were carried out at four reference wind speeds U_R (the wind speed measured at z = 280 mm, x = 4.2 m): 8.5, 10, 11.5, and 12.5 m s^{-1}. The corresponding values of the friction velocity u_* (determined from the measured wind profile at x = 4.2 m) were 0.34, 0.44, 0.50, and 0.60 m s^{-1}; all these u_* values are well above the threshold friction velocity for particles with the modal diameter of the red sand [*Pye*, 1987, p. 32]. For the first three wind speeds, six replicates were made, four in the 10-m tunnel and two in the 17-m tunnel. For the fourth (highest) wind speed only two replicates were made, both in the 17-m tunnel. Table 1 summarizes the experiments.

3. Results

An example of the basic data set from the experiment is shown in Figure 3, where the profiles of the direct measurements of $q(x, z)$ at x = 1, 6, and 14.5 m (averaged over the available runs for a given location) are shown for the four different wind speeds used. In all cases, q decreases rapidly with height. The maximum depth of the saltation layer is always lower than the maximum trap height (z = 410 mm). The dependence of q on z can be well described empirically by a function of the form

TABLE 1. List of Runs

Runs	U_R, m s^{-1}	u_*, m s^{-1}	Tunnel Length, m
A1, 2, 3, 4	8.5	0.34	10
A5, 6	8.5	0.34	17
B1, 2, 3, 4	10.0	0.44	10
B5, 6	10.0	0.44	17
C1, 2, 3, 4	11.5	0.50	10
C5, 6	11.5	0.50	17
D1, 2	12.5	0.60	17

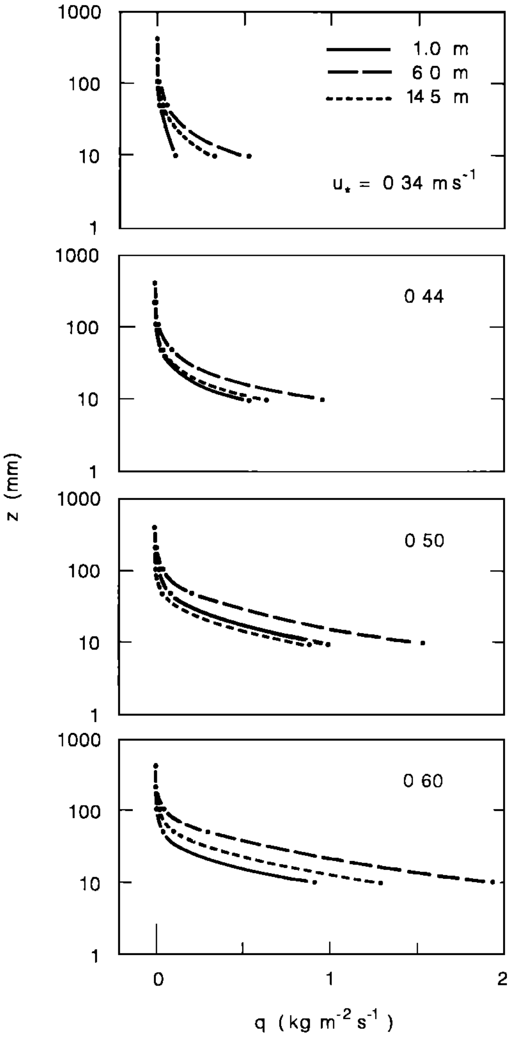

Fig. 3. Profile of streamwise flux density $q(x, z)$ of red sand at several locations of the tunnel, for four different wind speeds.

$$q(z) = C_0 \exp (C_1 z + C_2 z^2) \qquad (3)$$

where C_0, C_1, and C_2 are fitted parameters. This form was fitted to each of the profiles in Figure 3 by a least squares method, and then integrated vertically to calculate $Q(x)$.

The resulting values for the streamwise flux $Q(x)$ are shown in Figure 4. The qualitative evolution of Q is similar at all four wind speeds, and can be divided into three stages. The first few meters constitute a "growth" stage where Q increases rapidly with x, indicating a rapid cascade of particle mobilization and entrainment into the air flow. This is followed by an "overshooting" stage, where Q maintains high values for several meters. In the "equilibration" stage over the last few meters, Q gradually decreases with x toward a constant value with insignificant streamwise gradient dQ/dx. However, our extended tunnel (even at 17 m long) is not long enough to detect the final equilibrium state unambiguously.

As indicated earlier, the behavior of $Q(x)$ can be explained qualitatively in terms of the four components of the saltation process identified by *Anderson and Haff* [1991]. In the very early stage of saltation, aerodynamic entrainment of particles is the most important process. When these particles

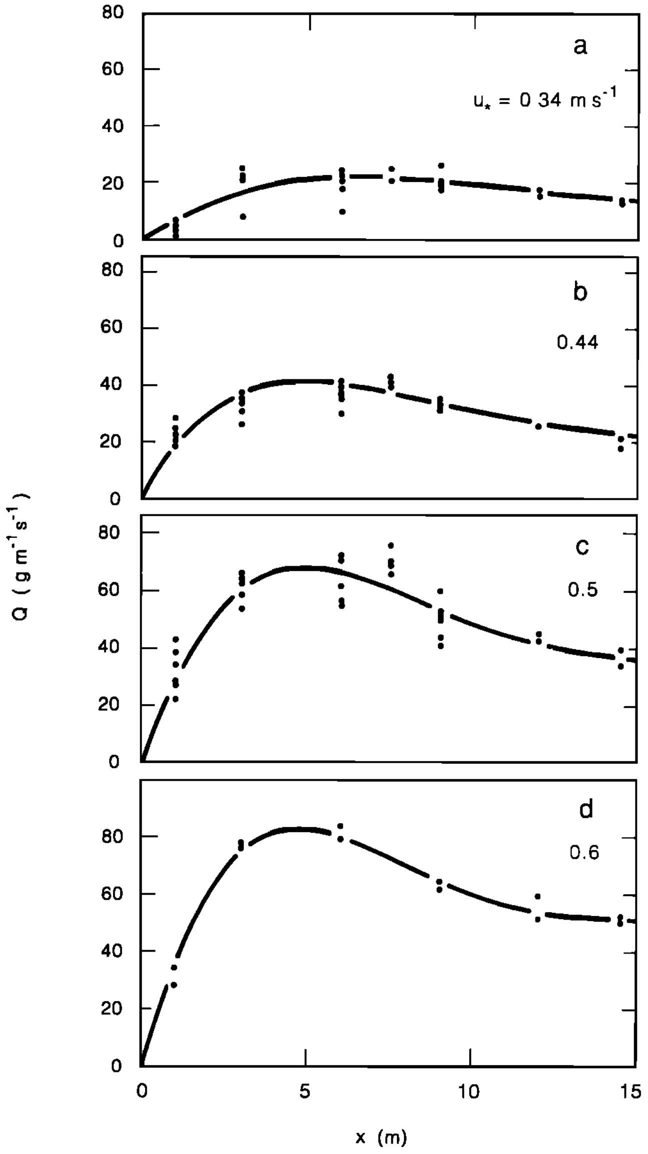

Fig. 4. Vertically integrated streamwise flux $Q(x)$ for four different wind speeds.

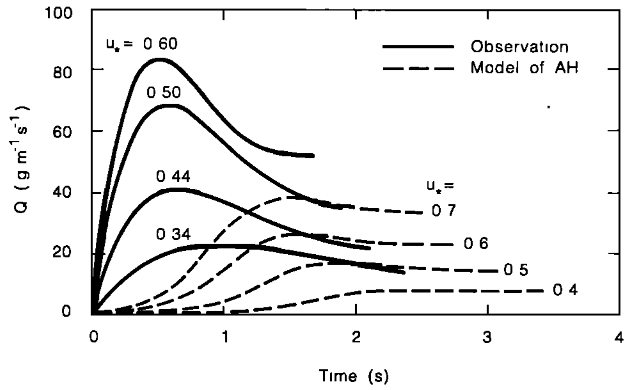

Fig. 5. A comparison of integrated streamwise flux $Q(x)$ as found by observation and predicted in the numerical simulation of *Anderson and Haff* [1991].

are mobilized and lifted a small distance above the surface, kinetic energy is transferred from air to the particles. At impact, these saltating particles of higher kinetic energy eject or "splash" more particles into the air. Entrainment by this particle bombardment process quickly dominates over aerodynamic entrainment, initiating a rapid growth in the number of airborne particles and in $Q(x)$. As more and more particles are entrained into the air, the air flow becomes significantly modified because of the additional transfer of momentum from the air to the surface by the particles themselves. Aerodynamically, the flow is undergoing a smooth-to-rough transition [*Bradley*, 1968; *Townsend*, 1976], which has several effects. There is an increase in the downward momentum flux above the saltation layer, and thence the friction velocity and the slope of the mean velocity profile above the saltation layer, from (1). Also, the mean wind speed near the bed is reduced; this decreases the particle ejection rate, leading eventually to an equilibrium state in which much of the enhanced downward momentum flux above the saltation layer is passed to the surface by grain motions rather than by the turbulent transfer [*Owen*, 1964; *Raupach*, 1991].

It is appropriate to compare our observations of the growth of saltation with results from the numerical models of *Anderson and Haff* [1991] and *McEwan and Willetts* [1991]. Both models give very similar results; here we concentrate on the predictions of *Anderson and Haff* [1991], for the saltation of 250-μm grains. Since the numerical simulations are made in the time domain, a direct comparison with the observations is difficult. However, qualitative agreement can be established between the simulation and the experiment by assuming that the time axis used in the simulation and the streamwise distance axis in the experiment can be related by $x = Ut$, where U is a typical wind speed in the saltation layer. Figure 5 compares the present observations with the numerical results of *Anderson and Haff* [1991], where distance is related to time by setting U equal to the mean wind speed measured at $x = 4.2$ m, $z = 30$ mm (well within the saltation cloud). The experimental data are represented by fourth-order polynomials fitted by a least squares regression technique. Although the experiments and the predictions are quantitatively different, both agree in two respects: the smaller the friction velocity, the larger the time or distance required for equilibrium, and small friction velocities correspond to relatively weaker overshooting, while large friction velocities give stronger overshooting.

There are two main quantitative disagreements between the observations and the simulations: the magnitude of the streamwise fluxes, and the location of the point of maximum overshoot. In magnitude, the simulated Q values are only about 50% of the observed values at similar friction velocities. This difference is observed consistently throughout the equilibration process, including both the point of maximum overshoot and the approach to final equilibrium. There are several possible explanations. First, the measurements of Q may be systematically in error. However, the magnitudes of the measured streamwise fluxes are in agreement with those reported by *Buckley* [1987], measured in similar wind conditions, and with measurements by *Leys and Raupach* [1991] made in the same tunnel as used here, but with different traps. A second and more likely source of measurement error is in u_*, as already discussed in section 2. Third, the simulations were for a sand of diameter 250 μm, for which

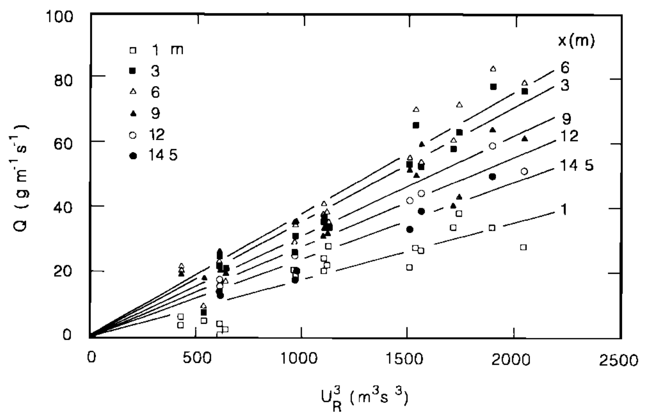

Fig. 6. Streamwise flux Q plotted against U_R^3, the cube of the reference wind speed, at different locations x.

the threshold friction velocity u_{*t} is about 0.3 m s^{-1}, whereas the modal diameter for the experimental red sand was about 200 μm (Figure 1) for which u_{*t} is a little less, about 0.25 m s^{-1}. A better comparison would result if the basis of velocity matching were $u_* - u_{*t}$ rather than u_* alone. Finally, it is possible that the difference between measured and simulated Q values is attributable to inappropriate choices for model parameters, most probably in the splash function.

The observations and the simulations also differ in the location of the point of maximum overshoot, provided that the distance and time coordinates can be correctly related by $x = Ut$ (where U has been set as the measured value at height z = 30 mm, well within the saltation cloud). The simulation overpredicts the time at which maximum overshooting occurs and, consequently, also the time at which the equilibrium is reached. For the case $u_* = 0.5$ m s^{-1}, for instance, the observed maximum streamwise flux occurred at about x = 6 m (t = 0.7 s), but around t = 1.5 s according to the numerical prediction. The equilibrium distance cannot be exactly determined from the observation, but the measurements suggest that equilibrium is reached around x = 15 m or slightly more. It appears that the model overpredicts distances for both maximum overshoot and final equilibrium by a factor of 1.5 to 2.

Finally, we test the relationship between streamwise flux Q and wind speed. It is generally accepted, following *Bagnold* [1941], that Q is approximately proportional to u_*^3 or U^3. *Greeley and Iversen* [1985, p. 100] summarize many suggested variations on this basic relationship, accounting for the threshold velocity for wind erosion and other factors. Figure 6 shows the relationship between the measured streamwise fluxes and the cube of the reference wind speed U_R (at x = 4.2 m, z = 280 mm). The reason for using U_R rather than u_* is simply that U_R is more accurately measured in this experiment than u_*, and is proportional to u_* at any given value of x. The choice of U_R^3 as an abscissa is to avoid (as far as possible) commitment to any particular form of the relationship between Q and wind speed. For any one value of x, a linear relationship between Q and U_R^3 is indeed a fair approximation; however, the coefficient of proportionality varies strongly with distance x. It is likely that a smaller streamwise variation of this relationship would occur if Q was plotted against a locally measured value of u_* at the location x (which we could not measure in this experiment), but strong variation is still expected, at least in the "growth" stage of the evolution of the saltation cloud.

4. CONCLUSIONS

The streamwise development of saltation has been investigated by measuring the vertically integrated streamwise sand flux Q in a wind tunnel. The working section of the tunnel was 17 m long, a sufficient length for studying the equilibration of the saltation process. It was found that the minimum distance for saltation to reach equilibrium is approximately 15 m, depending on wind speed. The observations confirmed the existence of an overshooting effect, an important characteristic of saltation predicted by the numerical models of *Anderson and Haff* [1991] and *McEwan and Willetts* [1991]. Although an exact comparison between the observations and the model results was difficult, the measurements indicate that the numerical model overpredicts the overshooting distance (the distance to maximum Q) and the distance required to establish an equilibrium Q, but underpredicts the streamwise flux Q itself, by a factor of about 2.

The overshooting of saltation was first proposed as a result of the modelling work of *Anderson and Haff* [1991], but has not hitherto been confirmed by observational studies. The importance of the present results lies in the fact that the measurements confirm the existence of overshooting, and thus qualitatively confirm the correctness of the physical basis of the model. The quantitative disagreement between the measurements and the model may also have useful implications for further understanding.

As overshooting is an important phenomenon in the development of saltation, a minimum tunnel length is required for wind tunnel measurements of Q to be comparable with measurements obtained by other methods, such as direct, undisturbed field measurements. In some previous wind tunnel studies [e.g., *Leys and Raupach*, 1991], short wind tunnels (of length about 6 m) were used. Therefore, there is a possibility that these studies overestimated the streamwise flux, because the measurements were made at a streamwise distance that coincidentally corresponds to the distance for maximum overshooting.

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