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Study of Aerodynamic Grain Entrainment in Aeolian Transport

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Abstract Aeolian transport controls landform formations on Earth and other planets and crucially affects the atmospheric system. With elaborate wind tunnel measurements, we find that the aerodynamic entrainment rate follows a yet unreported exponential increase in the intermittent regime and only complies with the expected linear law for the condition of continuous entrainment. Subsequently, we propose a model accounting for the effects of turbulence on aerodynamic entrainment based on the distribution of local shear stress to describe the experimental results. We also provide evidence that aerodynamic entrainment can be an efficient way to directly induce a horizontal grain transport comparable to the steady and saturated saltation in unsaturated conditions and should not be ignored. Our findings substantially modify the present interpretation of surface erosion and bear thus important consequences on future soil protection techniques.

Plain Language Summary It has been recognized that grains can be lifted from the surface through two mechanisms, either ejection due to the impact of grains in saltation or the pull-out of grains due to aerodynamic entrainment. However, saltation has always been believed to be the dominant mechanism of aeolian sand transport. With elaborate wind tunnel measurements, we find that the aerodynamic entrainment rate follows a yet unreported exponential increase in the intermittent regime and only complies with the expected linear law above the threshold to continuous flow. We also present the first evidence that in fact turbulent grain entrainment contributes as least as much to or even more than the particle flux in the continuous flow regime. Our discovery will open a new avenue of research focusing on aerodynamic grain entrainment and thus significantly influence the research of others. It also represents an essential step toward mastering soil erosion.

1. Introduction

Aeolian transport is common on several planetary bodies in the Solar System, such as Earth, Venus, Mars, and Titan (Lorenz & Zimbelman, 2014), inducing a large shape variety of planetary landforms. It has great influence on the atmospheric system through the emission of airborne dust grains (Kok et al., 2012). It is also responsible for desertification and dune formation and thus of considerable importance to environmental studies (Shao, 2008).

It has been recognized that grains can be lifted from the surface through two mechanisms, either ejection due to the impact of grains in saltation or the pull-out of grains due to aerodynamic entrainment (Bagnold, 1941). Saltation impact is widely recognized as the mechanism sustaining wind-blown grain transport and has been extensively investigated in the past decades (Anderson & Haff, 1988; Bagnold, 1941; Kok et al., 2012; Owen, 1964; Shao & Li, 1999). However, only a few studies (Anderson & Haff, 1988; Doorschot & Lehning, 2002; Shao & Li, 1999; Williams et al., 1990, 1994) have tried to quantify aerodynamic entrainment which is normally considered as an inception of saltation and to be negligible in the stationary state of saltation (Bagnold, 1941; Kok et al., 2012), although some new evidences (Baker et al., 2018; Klose et al., 2015; Pähitz et al., 2018; Sullivan & Kok, 2017; Zhang et al., 2016) show that aerodynamic entrainment is important and can even play a dominant role in some places where saltation is limited or special atmospheric conditions are encountered, as is the case on Mars.
The amount of particles entrained directly by wind can be physically described by horizontal momentum conservation as

\[ \Delta m \cdot u_p = (\tau_s - \tau_t) \cdot \Delta t \cdot A \]

(1)

where \(\Delta m\) is the mass of particles emitted from the surface with a typical horizontal escape velocity \(u_p\), \(\tau_s\) is the wind shear stress exerted on the surface and \(\tau_t\) the critical shear stress to initiate particle motion (i.e., aerodynamic threshold, which is dependent on the constraining force of exposed particles). \(\Delta t\) and \(A\) are, respectively, the duration and surface area of the measurement.

The following law can be derived from equation 1:

\[ F = \alpha (\tau_s - \tau_t) \]

(2)

where \(F = \Delta m / (\Delta t \cdot A)\) is defined as aerodynamic entrainment rate and \(\alpha = 1 / u_p\) is normally treated as an empirical coefficient assumed to be dependent either on grain size \(d\) (Anderson & Haff, 1988; Doorschot & Lehning, 2002) or on friction velocity \(u_* = \sqrt{\tau_s / \rho_a}\) (where \(\rho_a\) is the air density) (Shao & Li, 1999). Actually, equation 2 is widely accepted and applied in aeolian research, but the variable \(\tau_t\) is generally considered as time-averaged value (Anderson & Haff, 1988; Bagnold, 1941; Shao, 2008).

It is noteworthy that equations 1 and 2 are only tenable when \(\tau_s > \tau_t\) (elsewise, \(F = 0\)). But the surface shear stress in the turbulent boundary layer is always fluctuating (Örlü & Schlatter, 2011) and instantaneous values below the threshold \(\tau_s\) commonly exist, which requires a strict premise for the application of time-averaged values in equation 2 (i.e., all instantaneous shear stresses are required to be larger than \(\tau_t\)). On the other side, it is really hard to confirm the aerodynamic threshold \(\tau_t\) in an experiment, due to the difficulty to simultaneously measure the instantaneous surface shear stress and aerodynamic entrainment. Over the last decades, the incipient motion of surface particles has been extensively studied (Lu et al., 2005) and the mean surface shear stress corresponding to the minimal amount of particle entrainment causing a general particle motion in an experiment is treated as threshold (Bagnold, 1941, for distinction, labeled incipient threshold). This incipient threshold only requires that the maximal instantaneous shear stress overcomes the critical value (aerodynamic threshold, \(\tau_t\)) but is not exactly equivalent to \(\tau_t\) as defined in equation 2. Moreover, some recent studies suggest that, in the stationary state of saltation, the mean surface shear stress is lower than the aerodynamic threshold (Kok et al., 2012; Walter et al., 2014). This is considered to be the main evidence for the assumption that aerodynamic entrainment is negligible in the stationary state of saltation. The effect of surface shear stress fluctuations stemming from turbulence and the complexity of the granular surface have been neglected in theories for wind-blown sand, although they are considered in numerous studies on sediment transport (Diplas et al., 2008; Parker et al., 2003; Seminara et al., 2002; Valyrakis et al., 2010, 2013). For a full understanding of aeolian grain transport it seems therefore necessary to explore turbulent aerodynamic entrainment in more detail.

2. Materials and Methods

2.1. Experimental Setup

The experiments were carried out in the wind tunnel of Lanzhou University. The wind tunnel has a work section of 1.4 m in width, 1.3 m in height, and 20 m in length, and the nominal air velocity can be varied between 3 and 40 m s\(^{-1}\).

Wedges and roughness elements are arranged in the front of the work section to generate a turbulent boundary layer (Figure 1). Then sandpaper is placed on the bed surface behind the roughness elements to mimic the characteristics of desert surface, as well as avoid occasional saltation due to detached grains. A metallic tray, filled with grains, is mounted flush with the ground downstream of the sandpaper to estimate the entrainment rate \(F\). To estimate \(F\) as accurately as possible, the length of the tray in wind direction should be short enough to avoid saltation impact but long enough to neglect influences from the tray's wall. We made several tests and found that a tray of width = 285 mm and length = 150 mm satisfies both requirements above.
According to the definition of entrainment rate \( F \) in equation 2, \( \Delta m \) is measured as the mass loss of the tray filled with grains, \( A \) the area of the tray, and \( \Delta t \) the run time of each test. An electronic balance with 0.01 g accuracy serves to measure \( \Delta m \). All of the tests were repeated at least three times.

By considering that the lost particles must escape through the downwind edge of the tray to yield horizontal transport, we have

\[
Q = F \cdot L
\]

where \( Q \) is the integrated horizontal transport flux (kg \( \cdot \) m\(^{-1} \cdot \) s\(^{-1} \)) and \( L \) is the streamwise length of the tray (as illustrated in the dashed box in Figure 1).

For the surface shear stress measurements, Irwin sensors (Irwin, 1981) were used to measure high-frequency signals of the surface shear stress on the sandpaper bed in our wind tunnel experiment. The sensors were validated on a smooth flat bed in several papers (Walter et al., 2014; Wu & Stathopoulos, 1994), confirming to be capable of providing a flat frequency response up to 100 Hz. In this work, a Pitot tube (and hot wire as a standby) was used to calibrate the relation between mean pressure difference \( \delta p \) measured by an Irwin sensor and mean surface shear stress \( \tau_s \) obtained by wind profiles (Figure S1 in the supporting information). Since a linear calibration relation is found between mean surface shear stress and mean pressure difference (Figure S2) and we apply it for short times of 0.01 s, a time series of surface shear stress of 100 Hz is obtained.

2.2. Materials

We employ spherical alumina grains with three different mean diameters \( (d = 40, 70, 120 \, \mu m) \) (Figure S3) to reduce the effect of irregular shape. Their density \( \rho_p = 3,900 \, kg \cdot m^{-3} \). More than five different wind velocities are imposed for each grain size.

3. Results

3.1. Dependence of Aerodynamic Entrainment Rate on Mean Surface Shear Stress

Well-controlled wind tunnel experiments were carried out to measure the average aerodynamic entrainment rate and the time series of surface shear stress on a rough bed. The results of the aerodynamic entrainment rate \( F \) and the time-averaged surface shear stress \( \tau_s \) are illustrated in Figure 2. It is clearly seen that a linear law is satisfied when the mean surface shear stress is large (Figure 2a), while it is not valid when \( \tau_s \) goes to smaller values, in which case \( F(\tau_s) \) deviates very strongly from the linear law and an exponential law is found (Figure 2b). By considering the essential mechanism of aerodynamic entrainment as discussed in equations 1 and 2, we deduce the reason for this observation as: If all (at least most) instantaneous surface stresses exceed the aerodynamic threshold \( \tau_t \) to satisfy the requirement of equation 2, the linear law is tenable; else if a considerable amount of instantaneous surface stress below \( \tau_t \), whether the mean surface shear stress \( \tau_s \) is bigger or smaller than \( \tau_t \), the linear law fails and an exponential law works.

We therefore fit equation 2 to the data of the first case (shown as the solid lines in Figure 2a) and the values of \( \alpha \) and \( \tau_t \) are obtained. Meanwhile, an empirical exponential law is employed to describe the remaining data (shown as the dashed lines in Figure 2b),
F = F_0 e^{\gamma (\tau_s - \tau_t)}

where \(\tau_t\) has been determined by the linear law. \(F_0\) and \(\gamma\) are empirical coefficients. \(F = F_0\) when \(\tau_s = \tau_t\), so \(F_0\) should be a function of the standard deviation of surface shear stress when \(\tau_s = \tau_t\). By fitting the data, we found \(F_0 \sim d^3\), \(\gamma \sim \alpha^2 d^3\), which indicate these coefficients depend on grain shape and turbulent flow properties.

### 3.2. Turbulent Effects Lead to Different Aerodynamic Entrainment Regimes

To deeply explore the behavior of aerodynamic entrainment effected by fluctuating surface shear stress caused by wind turbulence, the data of the time series of surface shear stress and the instantaneous entrainment rate calculated by equation 1 (only for \(\tau_s > \tau_t\), and \(F = 0\) for \(\tau_s \leq \tau_t\), \(\alpha\) and \(\tau_t\) are same to Figure 2) are analyzed.

For instance, the results of particles with diameter of 120 \(\mu\)m are shown in Figure 3 and three typical wind conditions are considered. As shown, the fluctuations always dominate the entrainment. For the case of...
Figure 3a, the mean surface shear stress $\tau_s$ is much smaller than $\tau_t$, and the instantaneous $\tau_s$ occasionally exceeds $\tau_t$ to produce sporadic and weak entrainment (shown as Figure 3d). When the mean surface shear stress gets larger (Figure 3b), both frequency and intensity of aerodynamic entrainment events will increase (Figure 3e), until a value of mean surface shear stress is reached (Figure 3c), above which grains are emitted all the time (Figure 3f). Under this condition, continuous aerodynamic entrainment happens, and the linear relation is satisfied all the time, which means that the instantaneous surface shear stress can be replaced by the time averaged surface shear stress to appear in equation 2. Based on the time series of $F$, the time-averaged aerodynamic entrainment rate $\bar{F}$ is also calculated and the results are consistent with the measured mean entrainment rate as shown in Figure 2, which indicates that the predicted instantaneous entrainment rates shown in Figure 3 are acceptable and the deduction of the reason behind Figure 2 is reasonable.

According to our understanding of aerodynamic entrainment, several regimes can be distinguished as shown in Figure 4a. The incipient threshold $\tau_i$, a minimal mean shear stress corresponding to detectable aerodynamic entrainment, could be defined to divide aerodynamic entrainment into undetectable entrainment and detectable entrainment. The continuous threshold $\tau_c$ could be defined as the minimal mean surface stress to satisfy the requirement of equation 2, and the aerodynamic entrainment is consequently split into the intermittent entrainment and the continuous entrainment. The former is affected by plenty of instantaneous surface shear stresses lower than the aerodynamic threshold and the exponential law works. The regime above the continuous threshold satisfies the linear law of equation 2 and all (at least most) of instantaneous surface shear stresses are above the aerodynamic threshold.

The incipient threshold is important to judge the initial particle motion which may trigger fully developed saltation transport, and the continuous threshold is pivotal to distinguish the data satisfying the linear law to estimate the aerodynamic threshold. One must, however, note that, $\tau_i$ and $\tau_c$ are both influenced not only by the surface particles but also the fluctuations of surface shear caused by wind turbulence, and therefore cannot be replaced by the aerodynamic threshold to be applied in equation 2. The comparison of measured thresholds obtained from different experiments (Figure S4) indicates that different definitions for the threshold adopted in influential papers may be a potential reason to cause the divergence between aeolian transport and fluvial transport (the threshold of aeolian transport normally corresponds to sporadic initial motion, i.e., $\tau_i$; but the one in fluvial work considers a $\tau_c$ corresponding to general motion of surface particles).

To take the effect from surface shear fluctuations caused by wind turbulence into account, equation 2 could be rewritten as

$$ F = \int_{\tau_i}^{\tau_c} \alpha (\tau_s - \tau_t) p(\tau_s) d\tau_s $$

(5)
where \( p(\tau_s) \) is the probability distribution of surface shear stress \( \tau_s \). We found that \( p(\tau_s) \) follows a Gaussian distribution (Figure S5). Figure 4b (solid lines) shows the predictions using equation 5 and \( \alpha \) and \( \tau_t \) are same as in Figure 2a. The predictions agree quite well with the experimental data in both the intermittent and continuous regimes. We also notice some deviations, especially for small grains at low shear stress. The deviation could be caused by the implicit assumptions of equation 5, that \( \alpha \) and \( \tau_t \) are considered as constants that only depend on particle size. By considering that the linear law has been validated for continuous entrainment and the value of \( \alpha \) is weakly dependent on wind condition, we prefer to ascribe the deviation to the incomplete treatment of \( \tau_t \). Based on the research of Shao who proposed approximate log-normal distributions for the threshold friction velocity (Shao, 2008), we keep the mean value unchanged and introduce the log-normal distribution of the threshold (see Figure S6), the predictions exhibit better agreement with the measurements, as shown in Figure 4b (dashed lines). This implies that the threshold distribution may be another factor influencing the entrainment of grains, especially the smaller ones.

### 3.3. Comparison of Horizontal Transport

Clearly, the grains entrained from the surface substantially contribute to the horizontal grain transport. The streamwise grain flux due to aerodynamic entrainment is calculated by equation 3, and the results are comparable to that measured in previous work (Bagnold, 1937) in stationary state saltation (Figure 5). Previously, people believed that impact entrainment dominates and that the contribution of aerodynamic entrainment can be ignored in stationary state saltation. It is generally accepted that for the case of saturated saltation in which the wind is weakened by airborne particles and the surface shear stress shifts approximately to 0.64\( \tau_t \) (Bagnold, 1937), so that the contribution of aerodynamic entrainment may be limited at a very low level, referring to the green box in Figure 5. However, we should also note that for the case of unsaturated saltation (wind is not weakened by airborne particles, such as at the onset of saltation), surface shear stress may reach a significant level and aerodynamic entrainment can be an efficient way to directly induce a horizontal grain transport comparable to the steady and saturated saltation (shown as the dashed red line in Figure 5). By considering that the sand stream in the field is never completely steady and saturated (Pähtz et al., 2020; Stout & Zobeck, 1997), the contribution of aerodynamic entrainment in natural horizontal grain transport should not be ignored.

### 4. Conclusions

Here a series of wind tunnel experiments were executed to deepen our understanding of aerodynamic entrainment in turbulence. The experimental data show that the prevalent model cannot even qualitatively predict the aerodynamic entrainment rate. The conventional linear relationship between entrainment rate \( F \) and excess shear stress \((\tau - \tau_s)\) is only confirmed for continuous flux for sufficiently large surface shear stresses. Additionally, intermittent
entainment, which is sensitively affected by wind turbulence, exists and follows an exponential law. A model including the effects of surface shear fluctuations [represented by a distribution p(τs)] is proposed and validated by the experiment. Additionally, the shape of the probability distribution of the threshold [p(τs)] is found to significantly influence the entainment of small grains.

We have shown that fluctuations in surface shear caused by turbulence and the variation of the entainment threshold caused by the spatially varying surface condition can both be represented by distribution functions that should be introduced into the theoretical modeling to fully describe aerodynamic grain entainment. The picture that emerged here about the spatiotemporal variability of the grain entainment process and its consequences on the macroscopic entainment rate is essential if one wants to improve the precision of wind-blown dust/snow/sand transport prediction and develop more efficient future soil preservation techniques.

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