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An experimental study of the dynamics of saltation within a three-dimensional framework

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ABSTRACT

Our understanding of aeolian sand transport via saltation lacks an experimental determination of the particle borne kinetic energy partitioned into 3 dimensions relative to the mean flow direction. This in turn creates a disconnect between global wind erosion estimates and particle scale processes. The present study seeks to address this deficiency through an extended analysis of data obtained from a series of particle tracking velocimetry experiments conducted in a boundary layer wind tunnel under transport limited conditions. Particle image diameter, as it appeared within each camera frame, was extensively calibrated against that obtained by sieving, and the ballistic trajectories detected were disassembled into discrete particle image pairs whose distribution and dynamics were then examined in vertical profile with sub-millimeter resolution.

The vertical profile of the wind aligned particle transport rate was found to follow a power relation within 10 mm of the bed surface. The exponent of this power function changes with increasing spanwise angle (θ) to produce a family of curves representing particle diffusion in 3 dimensions. Particle mass was found to increase with θ, and the distribution of the total particle kinetic energy was found to be very similar to that for the particle concentration. The spanwise component of the kinetic energy of a saltating particle peaks at $\theta = 45°$, with the stream-aligned component an order of magnitude higher in value. Low energy, splashed particles near the bed account for a majority of the kinetic energy distributed throughout the particle cloud, regardless of their orientation.

List of Symbols

x	streamwise direction
y	spanwise direction
z	vertical direction (elevation)
d	particle diameter, where subscripts “p” and “s” denote the diameter measured on camera and from sieving, respectively
ζ	diameter correction factor
j	vertical segmentation counter, where $j = 1$ is the nearest segment to the bed.
θ	spanwise angle of the particle trajectory within the xy plane, i.e. at 0° particles are travelling parallel to the airflow.
$n_{j,\theta}$	total number of particle pairs identified in the *j*th segment bin for a spanwise angle of θ
N_{θ}	total number of particle pairs identified for a spanwise angle of θ
ρ	particle density
$q(x)$	horizontal mass flux
$f_{j,\theta}$	particle frequency in the *j*th segment bin for a spanwise angle of θ, also referred to as the normalized particle transport rate
m	particle mass, where subscript “p” denotes mass calculated from d_p and subscript “s” mass calculated from d_s
t	time
$u_{j,\theta}$	streamwise velocity component in the *j*th segment bin for a spanwise angle of θ
$v_{j,\theta}$	spanwise velocity component in the *j*th segment bin for a spanwise angle of θ
U	mean wind velocity, with subscript ∞ denoting freestream flow
u_*	friction velocity
u_{*t}	aerodynamic threshold friction velocity
z_0	aerodynamic roughness length
i	particle image pair counter
E_i	kinetic energy of a given particle (i), with subscripts x and y referring to the streamwise and spanwise components of kinetic energy respectively
$KE_{i,\theta}$	total kinetic energy sampled within the *j*th segment bin for a spanwise angle of θ per second, with subscripts x and y referring to the streamwise and spanwise components of kinetic energy respectively

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Where specified, subscripts 1 and 2 refer to ascending and descending particles, with ˜ and ¯ referring to median and mean values respectively.

1. Introduction

The ballistic trajectories of wind-blown particles, known as saltation, are associated with a wide range of features observed on planetary surfaces, both erosional (e.g. ornamentation on ventifacts, desert pavements and yardangs) and depositional (e.g. sand sheets, impact ripples and dunes) in nature. In this geophysical process, momentum is transferred from the airflow to the bed, initiating a cascade of particle ejections and ricochets such that the cloud of saltators rapidly expands in height and breadth along the path of the mean airflow. At some finite distance downwind, the particle concentration reaches saturation and the fluid momentum flux is suggested to drop below the threshold for aerodynamic entrainment of particles resting on the bed surface (Owen, 1964). Ballistic impacts during saltation are widely recognized to drive the emission of dust and thereby affect air quality and contaminant transport on a global scale. Hence, the physics of saltation has been a primary area of investigation for over 75 years since the early seminal work of Bagnold (1941).

A large number of studies have addressed the vertical distribution of the horizontal flux, $q(x)$, inclusive of Bagnold (1941), Sharp (1964), Williams (1964), Nickling (1978, 1983), Anderson and Hallet (1986), Nalpanis et al. (1993), Zou et al. (2001), and Wang et al. (2006). A consensus built upon empirically based wind tunnel and field studies, as well as computational models of the saltation cloud, suggests that a majority of particles travel within 1–2 cm of the bed surface, and that q decays exponentially with height (z) (Butterfield, 1999; Rasmussen and Sorensen, 2008). The full height of the saltation cloud observed in field settings generally exceeds that observed in the laboratory (Sharp, 1964).

Direct measurement of the vertical profile of the particle transport rate tends to be constrained by the dimensions of the instrumentation to a relatively coarse (cm) spatial resolution. Commonly used sensors include: i) either segmented or stacked sand traps (e.g. BSNE traps; Fryrear, 1986), ii) Peizoelectric sensors (Baas and Sherman, 2005; Sherman et al., 2011), iii) Sonic sensors (e.g. saltiphones; Cornelis et al., 2004), and particle counters (e.g. Wenglor gate sensors; Barchyn et al., 2014). None of these instruments provide information on the velocity components of the sampled particles to obtain the particle-borne momentum flux of the ascending and descending populations, although the amalgamated size distribution can be obtained by sieving the contents obtained from sediment traps. Such measurements are also lumped so that the departure of particle trajectories from the alignment of the mean wind is not isolated to provide information on the spanwise diffusion within the saltation cloud. As compared to the fetch effect associated with the particle cascade (Chepil, 1957; Gillette et al., 1996), the diffusion of particles moving normal to the mean airflow has received relatively little consideration except for only a few works involving high speed photography (Yang et al., 2009; O'Brien and McKenna Neuman, 2016), and a discrete particle 2.5D model (Kang, 2012). Indeed, O'Brien and McKenna Neuman (2016) were able to determine from their wind tunnel experiments that as little as 12% of all particles travel in ballistic trajectories that are strictly wind aligned, ± 1°.

More advanced, laser based methods of measuring the wind aligned particle transport rate have been employed in wind tunnel simulations, though these technologies are costly and fragile. They include Laser Doppler Anemometry (Li and McKenna Neuman, 2014), Particle Imaging Velocimetry (Yang et al., 2007) and finally, Particle Tracking Velocimetry (White and Shulz, 1977; Rice et al., 1995, 1996, Beladjine et al., 2007; Wang et al., 2008; Gordon and McKenna Neuman, 2009; Zhang et al., 2014; O'Brien and McKenna Neuman, 2016). Such instruments can provide a high resolution (i.e. sub-millimeter) description of the variation in saltation intensity along a vertical profile, and in the case of PTV, can track an individual particle throughout much of its lifecycle in saltation. However, considerable challenges remain with sampling large concentrations of particles within a saltation cloud that has reached saturation, and in particular, with accurate measurement of each particle diameter as required for assessment of the dynamics of the near bed transport phenomenon. This in turn limits the capability of geomorphologists to validate both large scale wind erosion models that require a thorough understanding of transport processes, as well as models of the development of small scale aeolian bedforms and their stratigraphy, as for example, impact ripples.

This paper builds upon recent PTV work by O'Brien and McKenna Neuman (2016) in which automated image processing that employs Expected Particle Area Searching (EPAS-PTV) was used to identify particle trajectories captured via high speed photography in the Trent Environmental Wind Tunnel (TEWT). The particle concentration was observed to decrease and the trajectory angle increase as the orientation of the vertical light sheet, in which the sampled particles were illuminated, increased in 5° increments from 0° (wind aligned) through to 60°. The results suggest that a large proportion of low velocity particles move at high spanwise angles relative to the mean airflow, likely as reptators. The vertical profile of the particle concentration was not considered at the time. The central objective of the present work aims to extend the analysis of the 1.5 Terabyte data set to obtain a high resolution, near-bed vertical profile of the particle dynamics captured in the original wind tunnel experiment over a range of spanwise angles. As described in the section to follow, the primary methodological advancement associated with the present paper concerns a calibration of the particle image size in pixels to determine the equivalent physical diameter (~ length of the intermediate axis, also known as width) of the saltating particle, as would be determined through conventional sieve analysis.

2. Methods

2.1. Wind tunnel facility and general experimental design

The data set required for the present analyses was captured during 39 particle tracking experiments carried out in the environmental wind tunnel at Trent University in 2015. A short synopsis of these experiments is outlined below, while further details can be found in O'Brien and McKenna Neuman (2016).

The TEWT is a low speed, boundary-layer wind tunnel with an open-loop, suction-type design (see http://people.trentu.ca/~cmckneuman/website/facilities.html). It is housed within a large environmental chamber with precise temperature (± 0.5 °C) and humidity control (± 2%). The working section of the tunnel is 77 cm high by 70 cm wide and extends over a distance of 13.5 m. The boundary layer flow within this section is created by sucking conditioned air from the external lab chamber through a honeycomb straw filter and compression bell before passing it over a trip plate of wooden dowels to hasten development of the shear layer.

In order to study a saltation cloud that was fully saturated with particles and transport limited, the entire bed of the tunnel was filled with well-sorted coarse quartz sand (d_{50} = 550 µm) and leveled to a depth of 2.54 cm. The freestream velocity (U_∞) was set to 8 m s^{-1} (± 0.02 m s^{-1}) and a vertical profile of the wind velocity (U_z) (Fig. 1) was measured using a pitot tube anemometer mounted on a vertical slide positioned by stepping motors. The friction velocity (u_*) was determined to be 0.40 m s^{-1} and the aerodynamic roughness length (z_0) 5.0 × 10^{-4} m. In comparison, the threshold friction velocity (u_{*t}) required for entrainment of the given sand particles by fluid drag was 0.30 m s^{-1}, as determined experimentally, so that u_*/u_{*t} was 1.33. The boundary-layer flow then was seeded with similar sized particles trickled into the working section from a feed apparatus positioned 0.5 m downwind of the inlet. This feed served to initiate the development of saltation within the upwind sections of the tunnel, and thereby extend the length of the test bed over which the flow was saturated with particles. The flux divergence ($q_{in} - q_{out}$) was assumed