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Interactions between turbulent wind flow and saltation sand transport

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Introduction

Aeolian transport of fine to medium sized sand particles is usually occurring as saltation, the jumping movement of grains over the surface. Saltating grains receive momentum from the near-surface wind, which causes particle lift, entrainment, acceleration, and when the particle rebounds with the surface, previously stationary particles will be splashed up (Rice et al., 1999). Saltation transport is highly intermittent under natural conditions (Bauer et al., 1998; Sterk et al., 1998). The gustiness of the natural, unsteady wind causes pulses of transport that are followed by relatively quiet periods without transport. Most predictive mass flux models relate saltation transport to the cube of shear velocity u_* without incorporating time-dependence (Bauer et al., 1998). Three recent papers (Bauer et al., 1998; Butterfield, 1998; Sterk et al., 1998) have raised some skepticism about the use of u_* or shear stress for modeling of saltation transport at time scales in the order of one second.

The aim of the present study was to determine the driving force of saltation transport. Specific objectives were: (i) to determine instantaneous wind speed and shear stress near the saltation layer, (ii) to relate saltation transport to fluctuations in wind speed and shear stress, (iii) to analyze the effects of turbulent flow structures on saltation transport.

Materials and methods

A field experiment was conducted during the months June and July of 2001. The location was the nature reserve Kootwijkerzand, a drift sand area in the central part of the Netherlands. Two 3-D sonic anemometers (R.M. Young Co., model 81000) were used to measure the three orthogonal components of the wind vector. The anemometers were mounted on a tower, with one anemometer fixed at 2.0 m height. The second anemometer was on an arm of 0.50 m and adjustable in height from 0 to 1.7 m. The sampling frequency of both sonics was 32 Hz. The output was low pass filtered with a 3.33 Hz first order filter and stored at 8 Hz in a CR10 (Campbell Scientific Ltd.) data logger.

Saltation transport was measured with two saltiphones, which is an acoustic sensor that records particle impacts with a microphone (Spaan and Van den Abeele, 1991).

During erosion, part of the saltating sand grains moving through the tube hit the microphone and create pulses. The centre of the microphones was positioned at 0.10 m height. The created pulses were sampled at 8 Hz and stored in the CR10 data logger at the same frequency.

The wind speed data from the sonic anemometers were used to determine shear stress and turbulent flow structures. Reynolds decomposition was applied to separate the instantaneous wind speed vectors into average and turbulent fluctuating parts: $u = \bar{u} + u'$,

$v = \bar{v} + v'$, and $w = \bar{w} + w'$, where overbars denote average values and primes denote the fluctuating turbulent part. The fluctuating velocity components u' (horizontal streamwise direction) and w' (vertical direction) were used for kinematic shear stress ($-u'w'$ [$m^2\ s^{-2}$]) calculations, and to determine the turbulent flow structures ejection (u'<0, w'>0), sweep (u'>0, w'<0), inward interaction (u'<0, w'<0), and outward interaction (u'>0, w'>0). Finally, saltation transport was correlated with 1) instantaneous horizontal streamwise and vertical wind speeds, 2) kinematic shear stress, and 3) turbulent flow structures.

Results and discussion

During the experiment five days with saltation transport occurred. Two events with a duration of 30 minutes and intense saltation transport were selected for further analysis. The events were almost similar in average wind speed conditions. During the first event, wind speed was measured at 2.0 and 0.4 m height. The average wind speeds at these two heights were 6.21 and 5.38 m s^{-1}, respectively. During the second event, the sonic anemometer at 2.0 m was not working, and wind speed was only measured at 0.3 m. The average wind speed was 5.55 m s^{-1}. Wind directions were exactly opposite, with a westerly wind during the first event and an easterly wind during the second event.

Instantaneous values of horizontal wind speed correlated much better with saltation flux than instantaneous shear stress. Correlation coefficients between u' and saltation for the first event were 0.54 at 0.4 m height and 0.51 at 2.0 m, and for the second event a correlation of 0.57 at 0.3 m height was obtained. The correlation coefficients between $-u'w'$ and saltation for the first event were 0.24 at 0.4 m height and 0.15 at 2.0 m, and for the second event a correlation of 0.22 at 0.3 m height was obtained. All correlation coefficients gradually improved when the wind speed data were averaged and the saltiphone data summed for time periods of 0.25, 0.50 and 1.0 sec. The correlation between u' and saltation improved to 0.69 for the second event (measurement height = 0.3 m), and the correlation between $-u'w'$ and saltation reached a maximum value of 0.47 for the first event (measurement height = 0.4 m). In short, the horizontal wind speed fluctuations have the greatest impact on saltation transport, while shear stress seems to play a less important but still significant role.

The analysis of turbulent flow structures showed that these structures occur only 16% (first event) to 20% (second event) of the time, but created 62% and 64%, respectively of the average shear stress. The main structures occurring in the flow were sweeps and outward interactions. These structures have a positive u' and result in opposite contributions to the average shear stress. However, they both result in significant saltation transport, while ejections (positive shear stress contribution) and inward interactions (negative shear stress contribution) did not result in saltation transport. This leads to the conclusion that fluctuations in horizontal streamwise wind speed (u') are of more importance for saltation transport than the instantaneous fluctuation in shear stress.

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