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Sand transportation and reverse patterns over leeward face of sand dune

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ABSTRACT

Sand saltation has complex interactions with turbulent flow and dune form. Most models of wind-blown sand consider ideal circumstances such as steady wind velocity and a flat surface, and the bulk of data on wind flow and sand transport over an individual dune has focused mostly on the influence of dune shape or inter-dune space on the wind flow, neglecting the effect of morphology on sand saltation, particularly airflow and sand transportation over the leeward slope. Wind flow structures over the leeward slope of sand dunes have a fundamental influence on the organization of sand dunes. In order to understand sand dune dynamics, lee face airflow and sediment transportation should be paid more attention. Previous field observations could not measure turbulent flow structure well because of the limited observation points and the influence of experiment structure on wind field. In addition, the reverse sand particles over leeward face could not be collected by sand trap in field. Numerous field observations could not measure turbulent flow structure because of the limited observation points and the influence of experimental structures on the wind field. In addition, the reverse transport of sand particles over leeward face could not be collected by sand traps in field. Therefore, this paper aims to investigate the turbulent flow structure and sand transport pattern over the leeward slope. A numerical model of sand saltation over slope terrain is constructed, which also considers the coupling effects between air flow and sand particles. The large eddy simulation method is used to model turbulent flow. Sand transport is simulated by tracking the trajectory of each sand particle. The results show that terrain significantly alters the turbulent air flow structure and wind-blown sand movement, especially over the leeward slope. Here, mass flux increases initially and then decreases with height in the reversed flow region in the direction of wind flow, and the mass flux decreases with height in the reversed direction. The height of 0.5 H is the height of vortex core in the reversed flow region. The vortex core is a critical point in the flow region where few particles are transited. In the reversed region, the reversed mass flux of sand particles is 25% of the mass flux in the flow direction. This research may contribute to scientific understanding of the mechanisms of sand motion and wind flow over leeward of dune and it is likely to be significant in desertification control.

1. Introduction

The interactions between dune morphology, wind flow, and sand transportation have received increasing attention (Livingstone et al., 2007), and the importance of wind-sand-dune interactions in the dynamics of dune system has been recognized. Researches on wind-blown sand over individual dunes (e.g. Hunter, 1985; Anderson, 1988; Hand and Bartberger, 1988; Lancaster et al., 1996; McKenna et al., 1997; Lancaster, 2006; Burkinshaw and Rust, 2009) focused on sand transportation and deposition and explicated the influences of sand dunes on the wind flow and sand transport: the presence of the dunes leads to secondary flow, which affects the wind flow profile and shear stress, thence influencing the flux of sand transport. Direct measurement of surface shear stress over dunes confirmed and supported existing theories of the sedimentological effect on secondary airflow patterns (Walker and Nickling, 2002).

Measurements of the wind flow and sand sediment transportation over dunes revealed that wind velocity profiles on windward slopes do not obey the logarithmic law of the wall (Lancaster, 1985; Frank and Kocurek, 1996a; Lancaster et al., 1996; Wiggs et al., 1996). An important study by Walker and Nickling (2002) proposed the conceptual model of lee-side wind speed profile over a dune, and a mixing layer and highly turbulent shear zone were identified which affected flow reattachment and subsequent sediment transport in the leeward region of dune (Frank and Kocurek, 1996b; Walker and Nickling, 2002). For instance, sand particles transport and surface shear stress are closely related to secondary flow patterns in lee-side (Walker and Nickling, 2003). However, in experimental observations, contact measurement equipment alters the real wind flow and non-contact equipment has limited measurement area (such as a Phase Doppler Particle Analyzer). The sand transport in the turbulent flow and reversed flow regions

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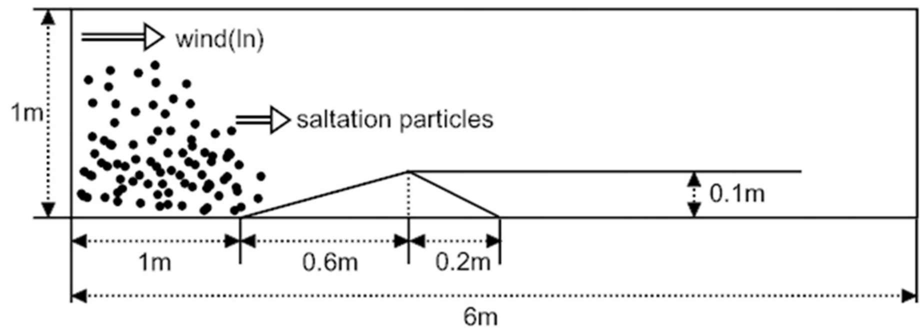

Fig. 1. Schematic of the computational area.

could not be measured accurately in wind tunnel experiments. Because of the complex flow structure and existence of reversed sand transport in the leeward region, it was generally neglected in previous experiments.

Recently many studies on the wind structure over dunes have been conducted using computational fluid dynamics (CFD) methods (Parsons et al., 2004a, 2004b; Herrmann et al., 2005; Shi and Huang, 2010; Wakes et al., 2010; Liu et al., 2011; Araújo et al., 2013). The reattachment distance and reverse wind flow region were quantitatively described from the lee-side of transverse dunes (Schatz and Herrmann, 2006; Araújo et al., 2013). Wind flow over the Barchan dunes was also simulated (Herrmann et al., 2005; Baddock et al., 2011; Palmer et al., 2012) and the length of the reverse region was found to depend strongly on the shape of dune; in particular, vertical flow and acceleration of horizontal flow occurred over the windward (stoss) slope. However, sand particles were not considered in these models. Some experiments have shown the relationship of flow separation and sand transport over dunes in the coastal zone (Lynch et al., 2009, 2010). Recent studies further examined the topographic forcing on wind flow and sand transport (Walker, 1999), and turbulence was found to exert a key control on sediment transport and morphodynamics. The effects of turbulence on sediment transport (Sterk et al., 1998; Schönfeldt and Von Löwis, 2003) and aeolian bedform development (Weaver and Wiggs, 2011) were also investigated. Compared with the correlation of sand flux and friction velocity, the sand flux and instantaneous velocity have better correlation in unsteady wind field (Spies, 1996; Sterk et al., 1998; Butterfield, 1998, 1999; Schönfeldt and Von Löwis, 2003; Leenders et al., 2004). Sand flux in the natural wind field may be greater than that in the steady wind field (Butterfield, 1998, 1999). The frequency of ejection and sweep increases in the turbulence burst process at windward toe, and analysis of the observation results reveals that the turbulent instantaneous velocity has a major influence on sand transport (Wiggs and Weaver, 2012). In addition, turbulence influences the trajectory of sand saltation, and the length and height of sand saltation are over-estimated if turbulence is neglected (Niño and García, 1998; Bialik et al., 2012). The intermittence of sand saltation is important to the instantaneous flow over the windward side of transverse dunes (McKenna et al., 2000). However, the Reynolds-averaged Navier-Stokes equations describe the mean-flow characteristics but cannot reflect the instantaneous flow over dunes in natural environments (Parsons et al., 2004a, 2004b; Herrmann et al., 2005).

Furthermore, most previous numerical simulation models focused on the effect of dune shape or inter-dune space on wind flow, and neglected the effect of morphology on sand saltation. To date, wind flow over individual dunes has been well investigated but mainly steady flow and windward slopes have been considered. However, in the lee-side, the sand transport pattern and sand particle reverse motion under the influence of turbulence have not been investigated sufficiently.

This research aims to investigate the turbulent flow structure, sand transport and sand particle reverse motion over the leeward slopes of dunes. In the present work, large eddy simulation (LES), which is a space-averaged hydrodynamic method, is used to calculate turbulence flow over slope terrain. The LES code used in this study is the “advanced regional prediction system (ARPS)” designed and developed by the Center for Analysis and Prediction of Storm (CAPS) of University of Oklahoma. Particle movement is calculated by tracking the particle trajectory, and the sand grain-bed collision process is simulated with the splash function. The wind-blown sand saltation system is also simulated, and then wind flow and sand transport over leeward slopes are discussed in detail, especially the reverse motion of sand particles.

2. Model and basic control

2.1. Equations of wind flow field

Equations of incompressible turbulence flow with constant viscosity coefficient under the influence of moving sand particles are (Shao and Li, 1999):

$$\frac{\partial}{\partial x_i}(V_f \rho u_i) = 0 \tag{1}$$

$$\frac{\partial (V_f u_i)}{\partial t} + \frac{\partial (V_f u_i u_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial (V_f p)}{\partial x_i} + \frac{\partial (\nu \times 2S_{ij})}{\partial x_j} + F_i \tag{2}$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{3}$$

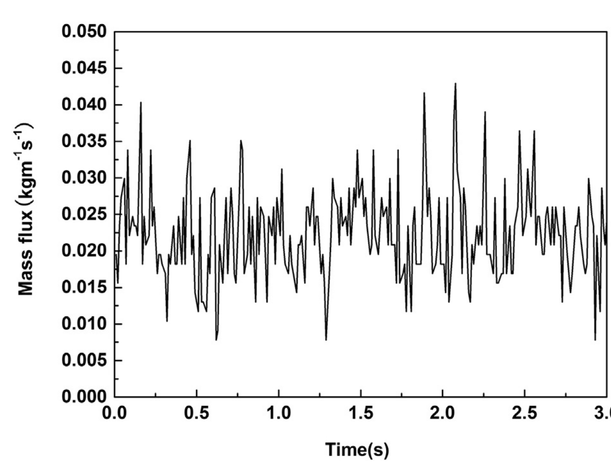

Fig. 2. Mass flux change with time at the inlet boundary.