Modeling the turbulent wind flow over transverse dunes

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Introduction—Transverse dunes (Fig. 1), which form under unidirectional winds and have fixed profile in the direction perpendicular to the wind, occur in almost all celestial objects of our solar system where dunes have been detected. Although the transverse dune is the most studied and simplest type of dune, the behavior of the wind flow over it is still poorly understood. In particular, the role of the wind speed for the size and the shape of the zone of recirculating flow at the dune lee (the "separation bubble") is still uncertain. Here we perform a numerical study of the average turbulent wind flow over a transverse dune by means of computational fluid dynamics (CFD).

Numerical simulations—The dune profile used in our simulations (Fig. 2) was generated using a morphodynamic model⁴. We employ the FLUENT Inc. commercial package (v. 6.1.25) in order to solve the Reynolds-averaged Navier-Stokes equations with the standard k-ε model, which is used to describe turbulence. At the upper wall, the shear stress is set equal to zero.

\[ u(z) = \frac{u_\tau}{K} \log \left( \frac{z}{z_0} \right) \]

where \( u_\tau \) is the wind shear velocity, \( K = 0.4 \) is the von Kármán constant and \( z_0 = 100\mu m \) is the surface roughness.

Moreover, a constant pressure is imposed at the outlet, while the no-slip boundary condition is imposed for the solid-fluid interface comprising the dune and the bottom wall⁵.

Results and discussion—The length (\( l \)) of the separation bubble depends on \( u_\tau \) (Figs. 3 and 4). \( l \) is nearly constant with \( u_\tau \) within region II (Fig. 5), which includes average values of Earth’s sand-moving winds, but increases with \( u_\tau \) for \( u_\tau > 0.8 \) m/s (region III) and for \( u_s < 0.2 \) m/s (region I). Moreover, the separation streamline has an angle \( \theta \) with the horizontal at the reattachment point \( x_r \) (insets of Figs. 4 and 5). We calculate the bed shear stress \( \tau_b = \tau_{Re} \), within the separation bubble as a function of the downwind distance from the brink position \( x_0 \) (upper inset of Fig. 6). We see that \( \tau_b \) has negative values and its minimal value \( \tau_{Re} \) occurs at position \( x_0 + l_{Re} \), whereas \( l_{Re} \) depends only weakly on \( u_\tau \) (lower inset of Fig. 6). The magnitude of the shear velocity \( u_{Re} = (\tau_{Re}/\rho_0)^{1/3} \) associated with \( \tau_{Re} \) increases with \( u_\tau \) (main plot of Fig. 6) and can exceed both threshold shear velocities for sand entrainment \( (u_e) \) and sustained saltation \( (u_s) \) for realistic values of average upwind shear velocity \( u_\tau \) (Fig. 6). Our results have implications for understanding the intermittent nature of the reverse transport of sand within the separation bubble of dunes⁶.

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