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).

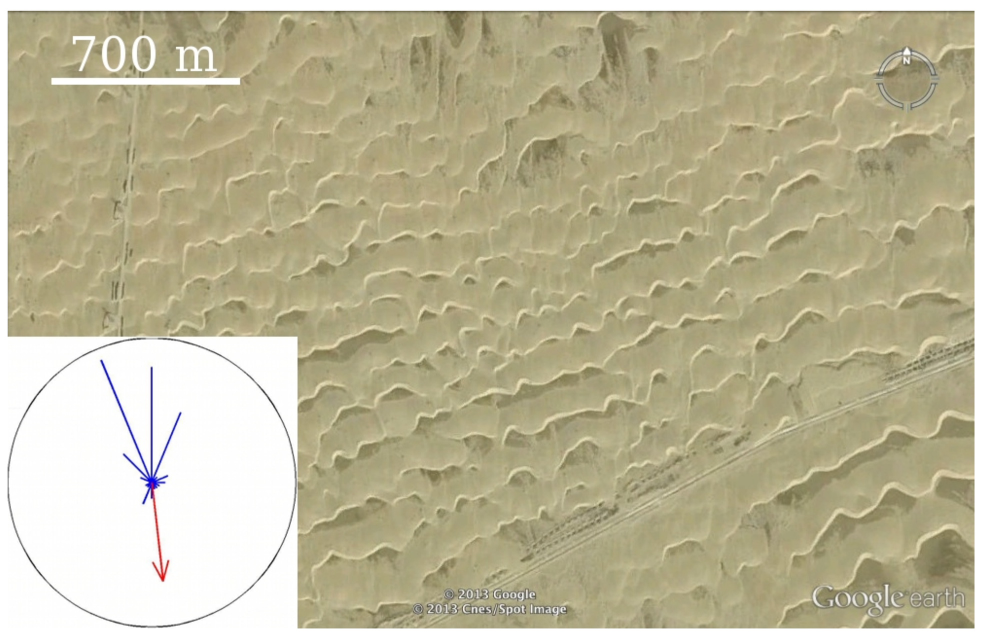

Fig. 1 – Transverse dunes in Bahrain, near 25°49 N, 49°55 E (credit: Google Earth). The inset shows the sand rose indicating the dominant sand-moving winds (blue lines) and the resultant transport direction (red arrow).

Numerical simulations – The dune profile used in our simulations (Fig. 2) was generated using a morphodynamic model[1]. We employ the FLUENT Inc. commercial package (v. 6.1.25) in order to solve the Reynolds-averaged Navier-Stokes equations with the standard κ-ε model, which is used to describe turbulence. At the upper wall, the shear stress is set equal to zero. At the inlet, the wind velocity u increases with the height z as,

$$u(z) = \frac{u_*}{\kappa} \log \frac{z}{z_0},$$

where u_* is the wind shear velocity, $\kappa = 0.4$ is the von Kármán constant and $z_0 = 100\mu$m is the surface roughness[2].

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 wall[3].

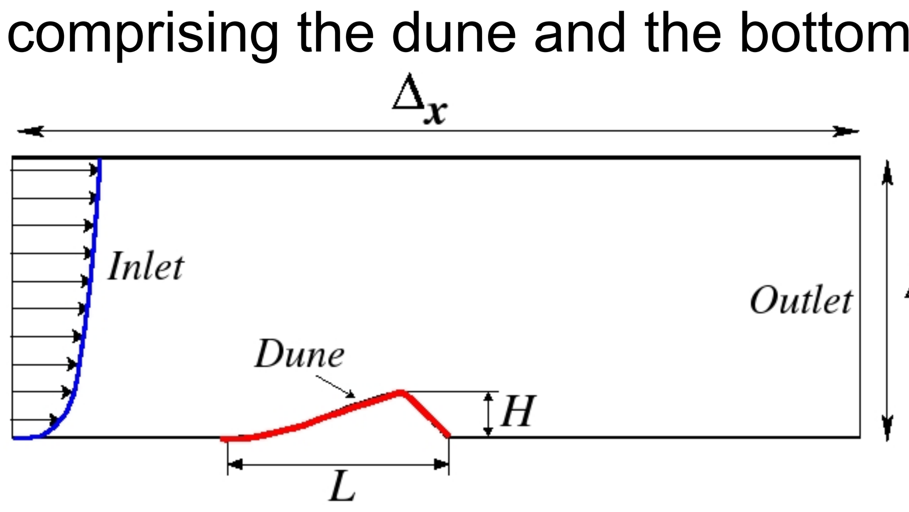

Fig. 2 – Schematic diagram showing the setup using in our simulations. The two-dimensional channel has width $\Delta_x = 100$ m and height $\Delta_z = 20$ m. The transverse dune has height $H = 3.26$ m and width $L = 26.2$ m.

Results and dicussion – The length (l) of the separation bubble depends on u_* (Figs. 3 and 4). l is nearly constant with u_* within region II (Fig. 5), which includes average values of Earth's sand-moving winds, but increases with u_* for $u_* > 0.8$ m/s (region III) and for $u_* < 0.2$ m/s (region I). Moreover, the separation streamline has an angle θ_r with the horizontal at the reattachment point x_r (insets of Figs. 4 and 5). We calculate the bed shear stress $\boldsymbol{\tau} = \tau_x \mathbf{e}_x$ within the separation bubble as a function of the downwind distance from the brink position x_b (upper inset of Fig. 6). We see that τ_x has negative values and its minimal value τ_{rev} occurs at position $x_b + l_{rev}$, whereas l_{rev} depends only weakly on u_* (lower inset of Fig. 6). The magnitude of the shear velocity $u_{*rev} = (|\tau_{rev}|/\rho_a)^{0.5}$ associated with τ_{rev} increases with u_* (main plot of Fig. 6) and can exceed both threshold shear velocities for sand entrainment (u_{ft}) and sustained saltation (u_t) for realistic values of average upwind shear velocity u_* (Fig. 6). Our results have implications for understanding the intermittent nature of the reverse transport of sand within the separation bubble of dunes[3].

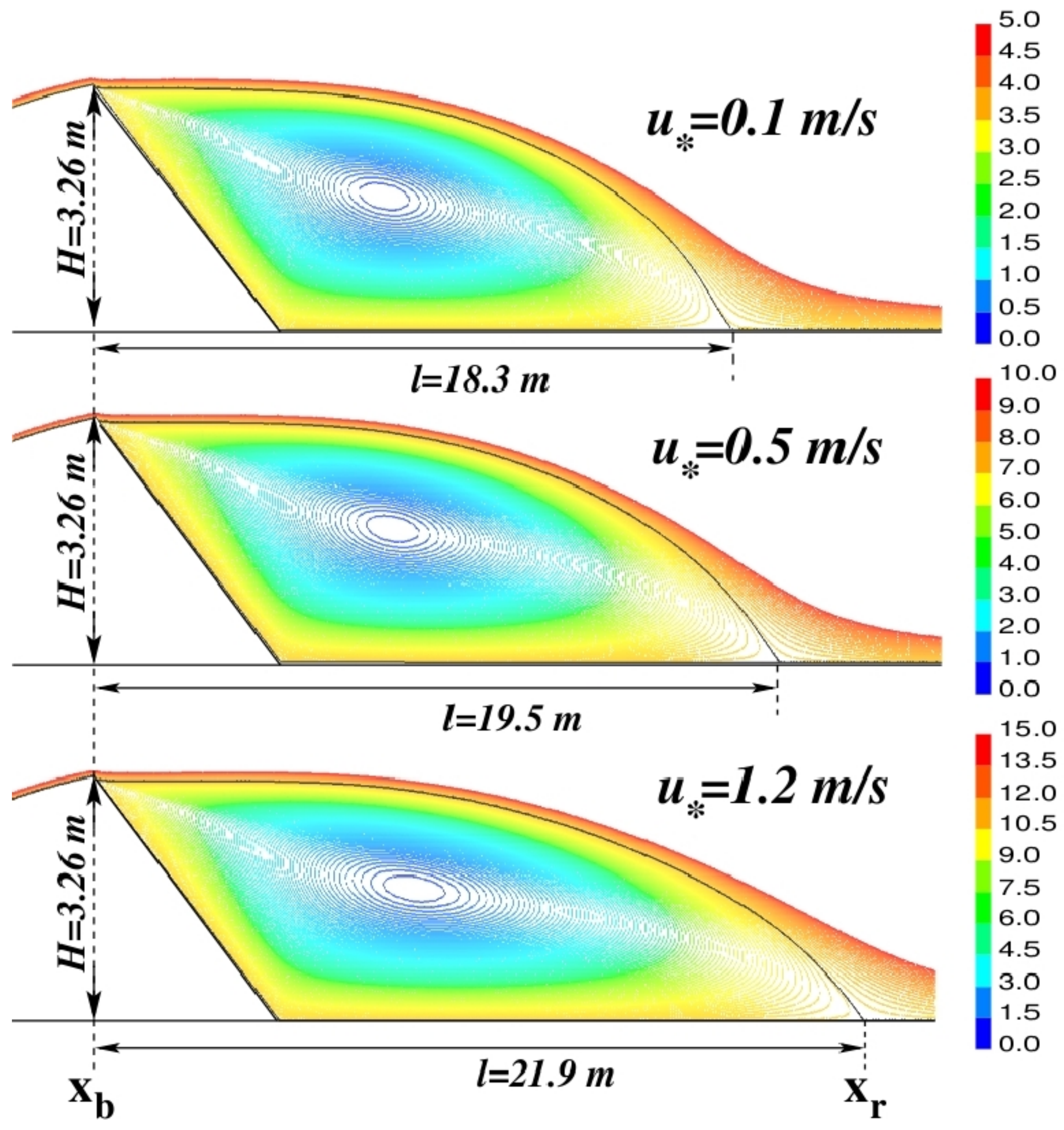

Fig. 3 – Calculation of the average turbulent wind flow over the longitudinal slice of the transverse dune for different values of u_*. Wind blows from left to right. The magnitude of the mass flux per unit time (q) associated with each streamline is plotted in units of kg/s, whereas the value of q increases from blue to red. The separating streamline is denoted by the black line connecting the brink to ground at position x_r (the flow reattachment point). The horizontal distance from the dune's brink (which is at position x_b) to x_r gives the reattachment length (l) associated with the given value of u_*.

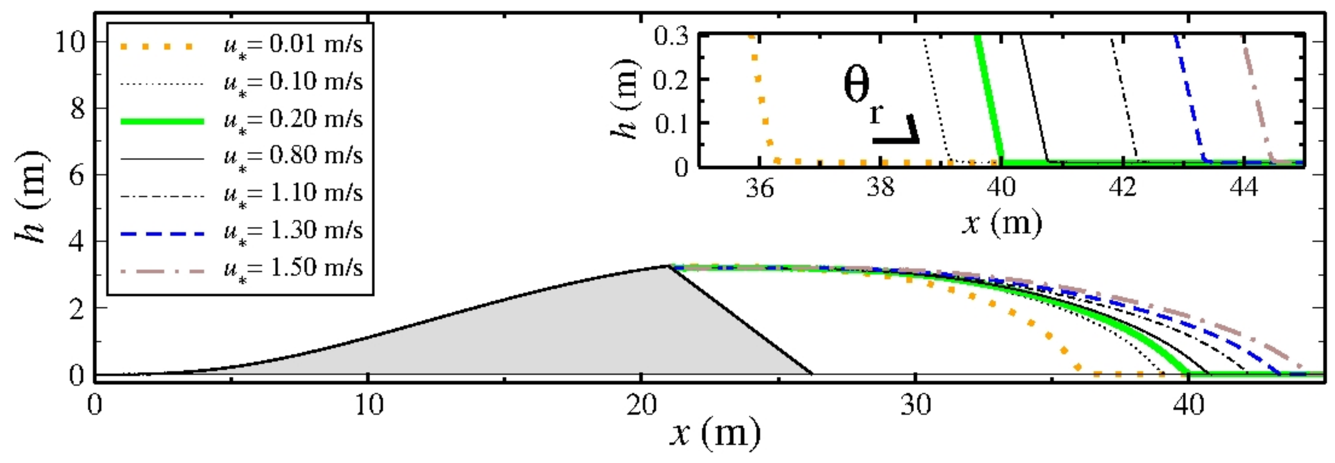

Fig. 4 – Main plot: Separation streamlines for different values u_*. Inset: The streamlines have an angle θ_r with the horizontal at the reattachment point.

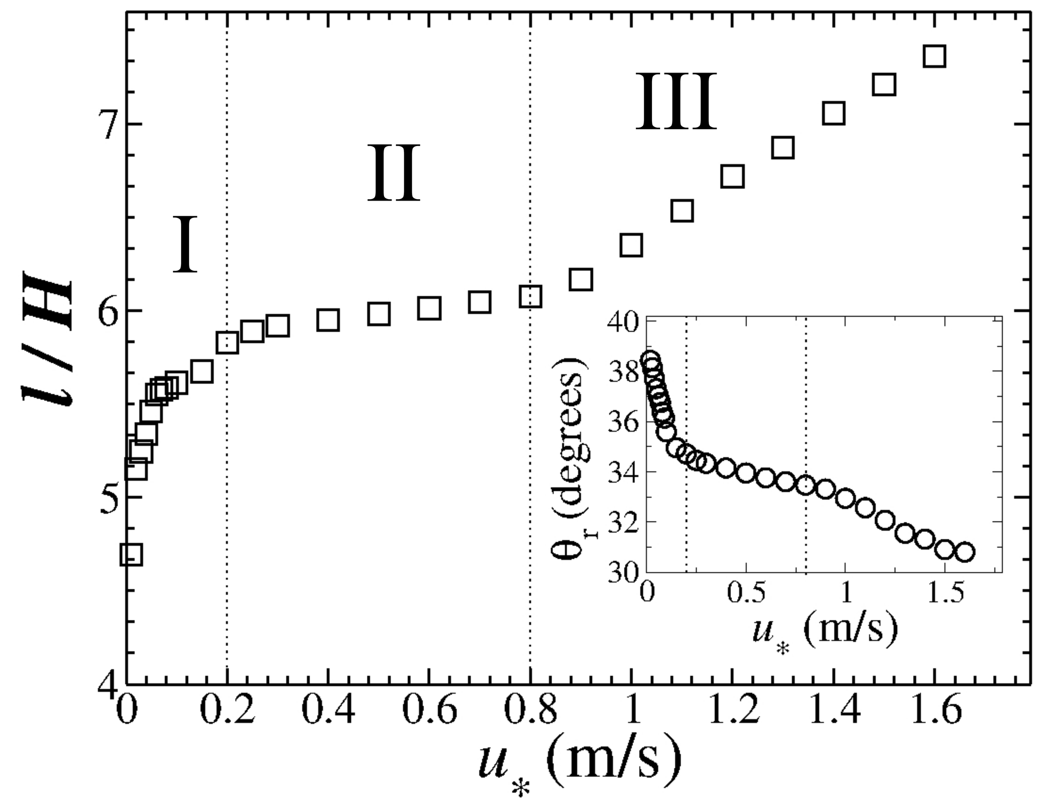

Fig. 5 – The main plot shows the dimensionless reattachment length l rescaled with the dune height H (where H ≈3.26 m) as a function of u_*. The region between the vertical dashed lines denotes the range of u_* within which l ≈ 6H. The inset shows the angle θ_r (defined in Fig. 4) which the streamlines associated with different values of u_* make with the horizontal at the reattachment point.

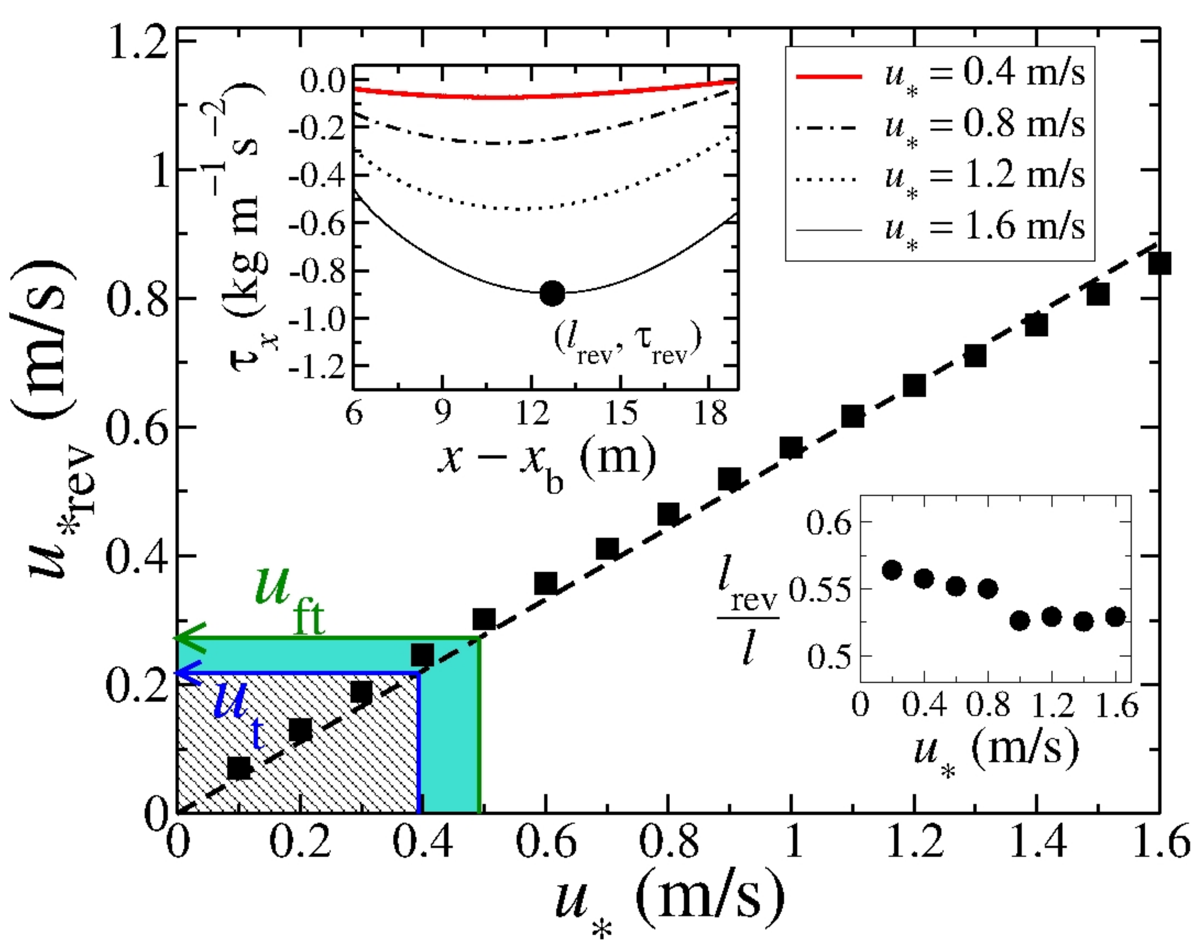

Fig. 6 – Upper inset: shear stress τ_x as a function of $x - x_b$, where x_b is the brink position. The minimum of τ_x is denoted by τ_{rev} and occurs at a horizontal distance l_{rev} downwind of the brink. The filled circle identifies the point $\{l_{rev}, \tau_{rev}\}$ associated with u_* = 1.6 m/s. Lower inset: l_{rev}/l as a function of u_*. Main plot: Magnitude of the maximal shear velocity at the ground, $u_{*rev} = (|\tau_{rev}|/\rho_a)^{0.5}$, as a function of u_*. The best fit using the equation $u_{*rev} = ku_*$ (dashed line) gives $k \approx 0.55$. The dashed area indicates the range of u_* for which no transport occurs ($u_{*rev} < u_t$), while the regime of u_* where u_{*rev} is smaller than the threshold for direct entrainment (u_{ft}) is denoted by the filled area.

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