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Dune morphodynamics

Morphodynamique des dunes

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ABSTRACT

The physics of dunes relies on the interaction between a wind flow and an erodible topography. Thus, if strong enough to transport grains, the wind shapes sandy areas into dune fields. These dunes are reminiscent of a wavy sea so that sandy deserts are called sand seas. However, the comparison stops there. Contrary to water waves, dunes propagate only under wind action and when the wind stops, they do not vanish but stand. Consequently, dunes are not only the result of the present winds, but can integrate the wind regimes over long periods. Thus, they exhibit a range of shapes and sizes with superimposed patterns. They are witnesses of past wind regimes and their shape and orientation are used to constraint climatic models on other planetary bodies where they are observed as well (e.g., Mars, Titan and Venus). Here, we discuss the morphodynamics of dunes and endeavor to identify and to explain the physical mechanisms at play in the selection of their shape, size and orientation, whilst focusing on Earth desert sand dunes.

RÉSUMÉ

La physique des dunes repose sur l'interaction entre le vent et une topographie érodable. Quand le vent souffle au-dessus d'une surface de sable, des dunes se forment dès lors que des grains sont transportés. Ces dunes offrent un paysage qui ressemble à une mer mouvementée et les déserts sableux sont appelés des mers de sable. Cependant, l'analogie entre dunes et vagues s'arrête là. Contrairement aux vagues, les dunes ne se propagent que sous l'action du vent, et si le vent s'arrête de souffler, elle ne disparaissent pas, mais persistent. Ces tas de sable ne sont pas seulement le fruit des vents présents, mais peuvent intégrer l'histoire des vents sur de longues périodes. Cette propriété explique la richesse des formes et des échelles observées, et fait des dunes des témoins des vents passés. Ainsi, on utilise leur forme et surtout leur orientation pour contraindre les modèles climatiques des corps célestes comme Titan, Mars ou Vénus, où elles sont observées. Dans cet article, nous expliquons la forme, la taille et l'orientation des dunes en passant en revue la littérature récente et en nous attachant à identifier et à expliquer les mécanismes physiques mis en jeu.

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The physical study of dunes started with the seminal work of Ralph A. Bagnold [1], who found interest in the shape of dunes and in Aeolian sand transport, while stationed in Egypt and Libya as an officer of the British Army between World War I and World War II [2]. Since then, great progress has been achieved by the increasingly joint effort of a vast scientific community among Earth Sciences and Physics. Moreover, the abundance and free access to satellite images and meteorological data have allowed field remote studies, which is valuable to easily test models. The lushness of the physics of dunes stands in the permanent feed-back between the dunes topography, the air flow and the sediment transport. Carrying on the subject from start and at the light of recent studies, we aim to give a comprehensive and consistent picture of dune morphodynamics in Earth sandy deserts. In the first section, we present the main properties of turbulent wind flow and sand transport. In the second section we explain the genesis of dunes growing from the destabilization of a sand bed. In the third section, wind regimes in sandy deserts are quickly overviewed. In the fourth and main section we explain the shape, the orientation and the size of dunes. In the fifth section, we finally discuss the dynamics of a dune field.

1. Sand transport over a flat sand bed

1.1. Turbulent flow over a flat ground

For a steady unidirectional turbulent flow (high Reynolds numbers) over a flat bottom extending in the x direction at $z = 0$, the average fluid velocity component along x, u, increases with the logarithm of the distance z to the bottom [3]:

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \tag{1}$$

where $\kappa \simeq 0.4$ is the von Kármán constant, u_* the friction velocity and z_0 the roughness length. This equation, which is verified experimentally for a non-stratified fluid [4], arises from the different nature of the transport of momentum and from the lack of a characteristic length scale in turbulence. According to the Prandtl theory, the transport of momentum is not driven by the thermal agitation on a characteristic length set by the mean free path of gas molecules, but by the fluid velocity fluctuations on a mixing length of the order of the distance to the bottom. As in a laminar viscous simple shear flow, the shear stress or momentum flux τ_{xz} is constant and imposed by the bottom. Here τ_{xz} is equal to the friction stress: $\tau_{xz} = \rho_\mathrm{f} u_*^2$, where ρ_f is the volume mass of the fluid, and the friction velocity u_* relates to the root-mean-square of the velocity fluctuations along z [3]. Eq. (1) does hold very close to the ground. Just above the ground, where the velocity is zero, lies a viscous boundary layer where the velocity profile along the z-axis is linear. The viscous boundary layer extends to a height l_v where the two modes of momentum transport match, i.e. where $\rho_\mathrm{f} u_*^2 \sim \eta u_*/l_\mathrm{v}$. When the fluid is air ($\rho_\mathrm{f} \simeq 1.2\ \mathrm{kg\,m^{-3}}$, viscosity: $\eta \simeq 1.8 \cdot 10^{-5}\ \mathrm{Pa\,s}$), taking u_* equal to a typical value of transport threshold velocity of $0.2\ \mathrm{m\,s^{-1}}$ gives $l_\mathrm{v} \sim 75\ \mathrm{\mu m}$. Although l_v is not negligible compared to the diameter d of sand grains ($d \simeq 100$–$300\ \mathrm{\mu m}$), the transport does not take place in the viscous layer in the air. Nevertheless, when the surface is smooth, l_v sets the value of the aerodynamic roughness z_0. However, dunes are not smooth and z_0 is rather set by (equals a fraction of) the size of sand grains, the length of ripples or by the thickness of the transport layer [1].

1.2. Onset of transport

The fluid velocity has to overcome a critical value in order to set grains into motion. Before the transport onset, the forces acting on a sand grain trapped between its neighbors are the weight, the buoyancy, the Coulomb static friction, the bed reaction, possible cohesive forces (van der Waals or capillary forces) and the fluid drag and lift forces. A grain is set into motion when the equilibrium of forces (or torques) is broken. Assuming no cohesion and considering the granular sand bed as a continuous medium, the onset of transport can write as a balance between the bottom fluid shear stress τ and a solid Coulomb friction force per unit of area. This latter is proportional to the apparent weight of a grain-diameter-thick sand layer per unit of area, multiplied by a macroscopic friction coefficient μ. μ relates to the granular packing geometry (traps) and the granular angle of movement rather than to the grain–grain friction coefficient. Assuming that neither μ nor the packing fraction of the granular layer depends on the fluid, the grains' properties or the flow regime, the transport onset corresponds to a critical value of a dimensionless ratio Sh called the Shields number:

$$Sh = \frac{\tau}{(\rho_\mathrm{s} - \rho_\mathrm{f}) g\, d} \tag{2}$$

where ρ_s is the sand volumic mass and g the gravity acceleration. For a turbulent flow in the air, a constant Shields number with $\tau = \rho_\mathrm{f} u_*^2$ fairly describes the experimental measurements of transport onsets [5] provided that grains are large enough not to lie in the viscous sublayer of the flow ($d \gg l_\mathrm{v}$). When the wind speed further increases, the number of grains into motion increases. The transported grains impact the static bed and share a part of their momentum, which helps to untrap static grains. Thus, there is a dynamic threshold fluid velocity u_d, which is smaller than the static one and is relevant to describe the sand flux. If impacts play a bigger role than the fluid flow, one can argue that the threshold impacting grain velocity, which is proportional to the fluid velocity u_d, is the typical velocity to dislodge a grain from its trap. Then, u_d scales with the grain size, so that $u_\mathrm{d} \propto \sqrt{gd}$ [6–8] and the corresponding dynamic onset Shields number Sh_d depends on