MIGRATION OF REVERSING DUNES AGAINST THE SAND fLOW PATH AS A SINGULAR EXPRESSION OF THE SPEED-UP EFFECT C. Narteau[1], X. Gao[2], Cyril Gadal[1]. [1]Université de Paris, Institut de Physique du Globe de Paris, CNRS (F-75005 Paris, France, narteau@ipgp.fr), [2]State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences (818 South Beijing Road, Urumqi, Xinjiang 830011, China, gaoxin@ms.xjb.ac.cn).

Introduction: Reversing dunes are recognized by their linear shape and transverse orientation in regions where two prevailing winds blow from opposite directions. As the wind blows alternately from both sides of their crest, they form from crest reversals that successively rework former lee slopes and generate new slip-faces on former stoss slopes. The dynamics of reversing dunes is therefore highly dependent on continuous changes in dune aspect-ratio experienced by the wind.

Despite the variety of possible multidirectional wind regimes, those characterized by two prevailing winds blowing from opposite directions are frequently observed due to the seasonality of near-surface atmospheric flows and/or the influence of local topography. Nevertheless, the morphodynamics of reversing dunes has not been the subject of extensive research and the impact of changes in wind directionality on the steepness of dune slopes remains so far poorly documented.

A positive topography deflects the air flow and the compression of streamlines causes the wind speed measured to be stronger on the stoss slope of an obstacle than on a flat bed away from any topography. Thus, there is a positive feedback between shear velocity and topography, so that the sand flux over a dune depends on its shape. Usually defined as the speed-up effect, the speed-up factor u_{crest}/u_{flat} is the ratio between the wind speeds measured at the same height at the dune crest and on a flat bed away from any topography. Following [1], it can be expressed as

$$u_{crest} = u_{flat}\,(1+\beta\, H/L),$$

where $\beta\, H/L$ is the fractional speed-up ratio, L and H the dune length and height experienced by the wind, and β a dimensionless coefficient that takes into account other physical ingredients (e.g., roughness) affecting surface wind speed. The positive dependence of the speed-up on dune aspect-ratio has been observed on reversing dunes by [2]. They report fractional speed-up ratio ranging from 0.5 to 2.5, in agreement with the values measured so far on different types of dunes around the world [3,4].

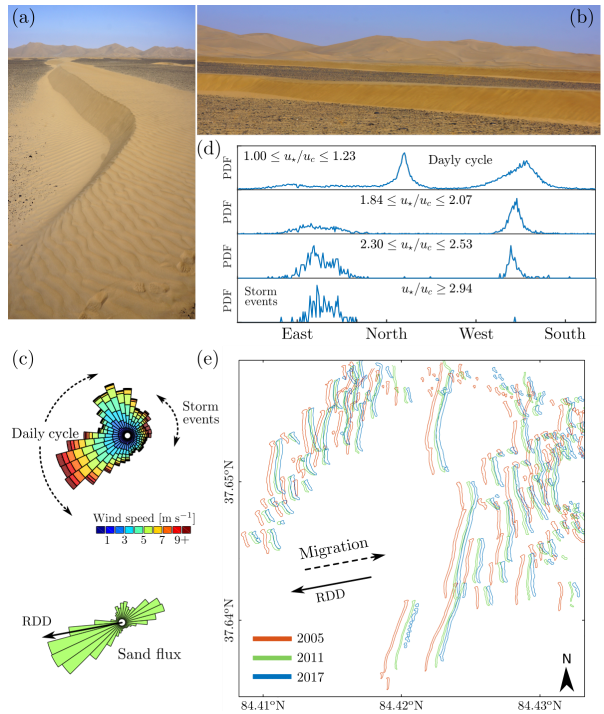

Figure 1: The dune migration paradox of reversing dunes. (a-b) Longitudinal and transverse views of the reversing dunes of metric height. (c) Local wind and sand flux roses. (d) Distribution of wind direction according to different ranges of wind speed ratio u_*/u_c, where u_* is the shear velocity and u_c the threshold shear velocity for particle entrainment. The prevailing wind comes from the east (diurnal phase of the daily cycle). Winds from the south are associated with weak transport (night phase of the daily cycle). Westerly winds are rare but associated with extreme transport events (i.e., storms). (e) Eastward migration of reversing dunes from (dashed arrow) against the direction of the resultant sand flux on a flat sand bed (solid arrows, RDD).

Method: The study area is located at the southern rim of the Taklamakan Desert on the large alluvial fan of the Molcha river flowing from the Altyn-Tagh mountains at the northern edge of the Tibetan Plateau. We focus on small dunes that form on the downstream border of the alluvial fan under conditions of limited sediment supply (Fig. 1a,b). Field sampling and measurements combined with ground-penetrating radar surveys are used to quantify the mean grain size, the shape and the internal structure of the dune. We analyze the wind data from a local wind tower and the ERA5 climate reanalysis (Fig. 1c,d). Sand flux and dune properties are derived from wind data according to the methods described in [5]. Three satellites images are used to estimate the migration of reversing dunes from 2005 to 2017 (Fig. 1e). Observations are compared to the predictions of numerical and analytical models that take into account the speed-up effect and the continuous change in dune shape after each wind reversal [6].

Results: Wind data reveal the presence of a regular daily cycle and the random occurrence of strong winds. They are associated with storm events that can last a couple of days. During these extreme events, sediment transport is continuous to the east-northeast, a direction of transport never experienced in days without storms. The regular daily cycle is characterized by diurnal sand-transporting winds and weaker winds at night. These nocturnal winds are to the north, while the stronger winds of the day are systematically to the west-southwest (Fig. 1d). The combined effect of the daily cycle and storms eventually explains the difference between the wind and sand flux roses (Fig. 1c). Finally, a resultant sand flux on a flat sand bed is oriented to the west [6].

Visual examination of a temporal sequence of satellite images is enough to conclude that dunes are migrating eastwards (Fig. 1e). Using the observed migration rate and the dune heigth measured in the field, we find an eastward sand flux Q_{crest}=14.6 m^2/yr at the crest of the dunes. There is therefore an apparent paradox between the eastward migration of the reversing dunes and the westward resultant transport on a flat bed.

Using the numerical dune model [7,8], we show that the sand flux at the reversing dune crest exposed to opposite winds of similar strength and duration varies a lot during a wind cycle. Due to the speed-up effect, the sand flux is high just after wind reversals and relaxes to a constant value over the characteristic time H^2/Q_{crest}. During this time interval, the crest is moving rapidly, the stoss slope flattens and the upwind and downwind boundaries of the dune move only over short distances [6]. Wind reversals are therefore associated with abrupt changes in the apparent dune aspect-ratio and non-linear variations in the sand flux at the crest, as predicted by the theory [1].

To account for crest reversals and transient changes in dune shape, we develop an iterative procedure that successively updates the apparent aspect-ratio of the dune with respect to wind strength and direction. This iterative procedure is implemented on a 2 m high and 28 m wide dune using the wind data. In agreement with field observations, the analytical model predicts a resultant sand flux at the crest which is against the direction of the resultant transport direction on a flat sand bed [6]. Thus, we show that the apparent dune migration paradox relies essentially on the asymmetry of the dune when storms occur and during the much longer period in which it is subjected to the daily wind cycle. In the study area, this translates into (strong) westerly winds blowing systematically on steeper dune slopes than those encountered by (weak) easterly winds.

Concluding remarks: The speed-up effect can cause the dunes to migrate against the transport direction of windblown sand particles. This apparent dune migration paradox requires specific conditions which are met in the study area. First, it is an area of low sand availability and the dunes that develop on the gravel deposits of the alluvial fan do not exceed a few meters in height. Second, this area is submitted to two opposite winds with different strengths. Westward winds are weak but occur daily, while eastward winds are associated with storm events. Since the infrequent storm winds always blow over a dune that is regularly smoothed by daily winds from the opposite direction, they produce much greater sand flux at the crest of the so-called reversing dunes, which can then migrate against the sand flow path. This singular behavior governed by the permanent feedback between airflow and dune topography illustrates the critical role of extreme events in sediment transport dynamics.

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References: [1] Jackson and Hunt (1975), Quart. J. Roy. Met. Soc., 101, 929–955. [2] Neuman et al. (1997), Sedimentology, 44, 1103–1113. [3] Wiggs et al. (1996), Geomorphology, 17, 29–46. [4] Walker and Nickling (2003), Earth Surf. Proc. Land., 28, 1111–1124. [5] Courrech du Pont et al. (2014) Geology, *42*, 743-746. [6] Gao et al. (2021) JGR-Earth Surface, 126, e2020JF005913. [7] Narteau et al. (2009), JGR-Earth Surface, 114, F03006. [8] Rozier and Narteau (2014) Earth Surf. Proc. Land., 39, 98-109.