Two modes for dune orientation

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ABSTRACT

Earth’s sand seas (dune fields) experience winds that blow with different strengths and from different directions in line with the seasons. In response, dune fields show a rich variety of shapes, from crescentic barchans to star and linear dunes. These dunes commonly exhibit complex and compound patterns with a range of length scales and various orientations, which up to now have remained difficult to relate to wind cycles. Here, we develop a model for dune orientation that explains the coexistence of bedforms with different alignments in multidirectional wind regimes. This model derives from subaqueous experiments, which show that a single bidirectional flow regime can lead to two different dune orientations depending on sediment availability, i.e., the erodibility of the bed. Sediment availability selects the overriding mechanism for the formation of dunes: increasing in height from the destabilization of a sand bed (with no restriction in sediment availability) or elongating in a finger on a non-erodible surface from a localized sand source. These mechanisms drive the dune orientation. Therefore, dune alignment maximizes dune orthogonality to sand fluxes in the bed instability mode, while dunes are aligned with the mean sand transport direction in the fingering mode. Applied to Earth’s deserts, the model quantitatively predicts the orientation of rectilinear dunes and their superimposed patterns. This field study suggests that many linear dunes on Earth elongate from sources, and are simply aligned with the mean sand transport direction.

INTRODUCTION

Dunes in arid sand seas are usually classified into three groups, distinguished by the directional variability of winds (Pye and Tsoar, 1990). Where winds are unidirectional and sand is scarce, crescentic barchan dunes migrate on a non-erodible floor; as the amount of sand increases, barchans link into barchanoid and then transverse ridges, perpendicularly to the mean wind direction (Figs. 1A and 1F). Sand seas exposed to a wide, multidirectional wind regime show star dunes, characterized by a massive pyramidal morphology with multiple radiating arms (Pye and Tsoar, 1990; Zhang et al., 2012). Finally, for a moderate wind direction variability, typically a bimodal wind regime with an obtuse divergence angle between winds, linear dunes are observed (Figs. 1B and 1C). Because of seasonal climatic variations, linear dunes are the most common dunes on Earth (Lancaster, 1982). They are long, relatively straight, parallel ridges that have been recognized to extend in the resultant wind direction (Tsoar, 1983; Livingstone, 1988) and to migrate laterally (Rubin and Hunter, 1985; Bristow et al., 2000; Rubin et al., 2008). Blown by winds from either side, their crests are reversing and can be sinuous but sharp in cross section, so that linear dunes are also referred to as seif (“sword” in Arabic) dunes. This stands for simple linear dunes but they can also be wide ridges, up to 200 m high, with superim-

Figure 1. Two modes of dune orientation in sand seas. A: Oblique barchanoid ridges in Mu Us Desert (China, 38.8°N, 107.7°E). B: Linear dune field (top) and superimposed bedform (bottom) in Rub’al Khali (Saudi Arabia, 19.3°N, 48.5°E). C: Linear (seif) dunes with superimposed bedform in Great Sand Sea (Egypt, 26.15°N, 26.9°E). D: Linear dune with superimposed bedform in Erg Chech-Adrar (Mali, 23.6°N, 5.1°W). Note that coexistence of small active dunes of similar size with two different orientations cannot be ascribed to a temporal change of wind regime. E: Spatial transition between two orientations for dunes in Taklamakan Desert (China, 38.3°N, 86.7°E). The transition from bed-instability mode (west) to fingering mode (east) corresponds to an abrupt decrease in sand availability in the inter-dune areas. F: Compound transverse dunes in Ubari Desert (Libya, 26.8°N, 12.6°E) with defects that align in fingering mode and extend from sand patches. Each panel shows sand flux rose, divergence angle ϕ, and predicted dune orientations, with blue arrows for bed-instability mode and green arrows for fingering mode. Low-contrast bedforms seen in inter-dune areas in panels B, C, and F appear to be sand sheets (Pye and Tsoar, 1990; see Fig. DR27 [see footnote 1]). Pictures are from Google Earth™. See the Data Repository (see footnote 1) for more comparisons and details.

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posed dunes on their surface, which are usually oblique or transverse to the primary trend (Lancaster, 1982) (Fig. 1B).

Experiments on the formation of aeolian ripples (Rubin and Hunter, 1987), underwater dunes (Rubin and Ikeda, 1990; Refet et al., 2010), and aeolian dunes in the field (Ping et al., 2014) within a bidirectional flow regime show that the bedform alignment maximizes the gross sand transport normal to the crest. Depending on the transport ratio and the divergence angle between winds, this leads to the formation of dunes that are transverse, oblique, or longitudinal with respect to the mean transport direction. Consequently, transverse dunes migrate, longitudinal dunes extend, and oblique dunes both migrate and extend. Using this concept, the orientation of dunes can be used as a proxy for wind regime (Lancaster et al., 2002; Bourke et al., 2010; Fenton et al., 2013; Telfer and Hesse, 2013). However, its application to aeolian dunes on Earth, using modern winds, reveals a clear mismatch for linear dunes (Lancaster et al., 2002; Lancaster, 2010). This discrepancy may be ascribed to the age of dunes that have been dated back to the Last Glacial Maximum (Lancaster et al., 2002). Wind regimes may have changed significantly since then. This seems to be supported by the difference observed between the primary (old) linear dune trend and the orientation of the smaller (modern) superimposed bedform.

Here we link all these observations with a model that explains the coexistence of different bedform orientations within a single wind regime. Thus, we predict the orientation of primary dunes and of their superimposed patterns using modern winds. The model derives from the experimental observation that a single flow regime can shape dunes with two distinct orientations, depending on the sand supply.

METHODS

We experimentally study the formation of dunes subjected to a bidirectional flow regime underwater, where the characteristic sizes (centimetric) and times are downscaled (Refet et al., 2010). The bedform, made of 90-μm-diameter ceramic beads, lies on a 70-cm-wide plate, which translates from one end to the other of a 2-m-long water tank. The translation is fast (30 cm/s) in order to generate transport in one direction, and slow (2 cm/s) to prevent grain motion in the other. This sequence, a blow, simulates a unidirectional flow over the bedform. The plate alternately rotates by an angle θ (≈θ) every 2 blows (N × 2 blows), to change the apparent direction of the flow. We vary the divergence angle θ and the transport ratio N (ratio between alternate numbers of blows) between the main and the second flow directions. We perform experiments with three different sand-supply conditions: (1) an initial flat sand bed with no additional sand supply, (2) an initial flat sand bed with systematic sand supply where the plate becomes visible, and (3) an initial 1 g conical pile at a point with periodic sand supply (typically 0.4 g every 20 blows) at the same point. The bedform evolution is followed through time with top-view images and three-dimensional profiles. Dune orientation is measured by autocorrelation.

In our model, the prevailing dune growth mechanism selects dune orientation. As a result, orientations maximize dune growth rate when dunes increase in height or correspond to the mean sand flux direction when dunes extend from a sediment source. These quantities are derived from sand fluxes over dunes.

To predict the orientation of dunes in the field, we collect wind velocities and direction from the ERA-Interim assimilation project (Dee et al., 2011). This general circulation model provides wind data at 10 m above ground since A.D. 1979, with a 0.75° horizontal resolution and a 6 h time resolution. We calculate the corresponding sand fluxes for sand grains of 180 μm using the model of Unger and Haff (1987). The resulting predicted orientations are not very sensitive to transport laws and parameters (Table DR1 in the GSA Data Repository1). Orientation of dunes is measured by autocorrelation from Google EarthTM images (Fig. DR15 in the Data Repository). See the Data Repository for full details.

UNDERWATER EXPERIMENTS

Figure 2 shows the morphodynamics of dunes for different sand supply conditions but within the same bidirectional flow regime, characterized by a divergence angle θ = 130° and a transport ratio N = 5.

Starting from a flat sand bed with a limited depth, a bedform instability develops roughly perpendicular to the dominant flow direction (Fig. 2A). This orientation is maintained while dunes increase in height and wavelength, until the non-erodible surface of the table is reached (Figs. 2D–2F). Without sand supply, the bed instability can no longer develop. As a result, these crest-reversing but migrating dunes become unstable and break. Instead of simply breaking into barchans, as observed when the flow is unidirectional (Refet et al., 2010; Parteli et al., 2011), they reconnect through extending fingers (Movie DR2 in the Data Repository). In response to this change in sand availability, the dune field switches orientation to a dune trend that is more parallel to the dominant flow direction. While

\[
\frac{\partial Q(t)}{\partial t} = \frac{H}{W} \sin(\psi(t) - \alpha) \left[ \cos(\psi(t) \bar{i} + \sin(\bar{i}) \bar{j} \right]
\]

where \(Q(t)\) is the value of the saturated sand flux over a flat sand bed, \(\beta\) is a dimensionless

GSA Data Repository item 2014273, description of the model for bidirectional flow regimes, full methods, additional results, and movies of experiments, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
As defined, the resulting dune orientation yields to the maximum gross transport normal to the bedform trend, as proposed by Rubin and Hunter (1987) with a wind velocity increase correction.

In contrast, when dunes form on a non-erodible floor from fixed sediment sources, they extend in the direction $\alpha_0$ of the mean sand flux $\nabla\mathcal{Q}$ (Equation 2), which is given by the integration of instantaneous fluxes over $t$ (Equation 1). Then, the finger dune orientation $\alpha_0$ is such that $\tan\alpha_0 = \left(\mathcal{Q}(i) \cdot j / \mathcal{Q}(j) \cdot i\right)$. The very existence of a finger dune aligned in the mean flux direction may be surprising. Indeed, such a dune cannot develop under a unidirectional wind. However, in a multimodal wind regime, the finger dune pointed in the mean flux direction is blown on either side by winds, which can build and sustain the dune (see the Data Repository).

In Earth sand seas, linear dunes are typically observed for a multidirectional wind regime with an obtuse divergence angle. For such a wind regime, the two predicted orientations $\alpha$ and $\alpha_0$ are equal when the wind regime is symmetric, e.g., a bidirectional wind regime with a transport ratio equal to 1. Dunes align along the bisector of the angle between the two flow directions. The two modes differ more and more as a wind direction prevails over the others: dunes in the bed-instability mode tend to be perpendicular to the prevailing wind, whereas dunes in the fingering mode tend to align with it. See the Data Repository for analytical solutions of $\alpha$ and $\alpha_0$ for bidirectional wind regimes and their comparison to experimental results.

FIELD STUDY

Figure 1 compares field observations in sand seas of the Northern Hemisphere to our model predictions. Predicted orientations are computed from sand flux distributions corresponding to wind data of the past 30 yr with a topography parameter $\beta H / W$ (Equation 1) set to 1, which is a typical reported value (Walker et al., 2009; see the Data Repository). As expected, where there is no sediment in the inter-dune areas, one observes linear dunes in the fingering mode (Figs. 1B–1D and 1E, right). In zones with no limitation in sand availability, dunes are in the bed-instability mode (Figs. 1A and 1E, left). This mode is observed for the main bedform structures on large linear-finger dunes (Figs. 1B–1D). Indeed, these giant dunes represent an erodible floor where the bed instability develops. The two modes of orientation are generic, and can coexist as superimposed patterns or where there is an abrupt spatial transition in sand availability (Fig. 1E). Although the coexistence of dunes with different orientations could result from a change in wind regimes, it finds here a simple and consistent explanation.
Our model is quantitatively compared to all field data in Figure 3. It accurately predicts dune orientation within 5°, not only for small dunes (~30 m wide) but also for larger and older dunes (~1 km wide). This suggests that the 30 yr data of modern winds used to predict dune orientation provide an accurate picture of the wind regimes that built these sand seas in the past.

Dunes on Earth sand seas are aligned with the mean sand transport direction (Figs. 1 and 3). Such longitudinal alignment could correspond to the bed-instability mode, but it would then result from symmetric wind regimes. This is not what is observed in the field. These dunes are in the fingering mode, which suggests that they extend away from geomorphologic sand sources (e.g., coastal or fluvial-alluvial systems). Indeed, the spreading nature of the fingering mode is likely to produce vast dune fields, with hundreds-of-kilometers-long and parallel linear dunes as observed on Earth sand seas.

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