Aeolian Research 12 (2014) 121–133

Contents lists available at ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

Origins of barchan dune asymmetry: Insights from numerical simulations

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ARTICLE INFO

Article history:
Received 18 October 2012
Revised 29 November 2013
Accepted 2 December 2013
Available online 21 January 2014

Keywords:
Barchan dunes
Dune asymmetry
Wind erosion
Sand transport
Dune model

ABSTRACT

Barchan dunes — crescent-shaped dunes that form in areas of unidirectional winds and low sand availability — commonly display an asymmetric shape, with one limb extended downwind. Several factors have been identified as potential causes for barchan dune asymmetry on Earth and Mars: asymmetric bimodal wind regime, topography, influx asymmetry and dune collision. However, the dynamics and potential range of barchan morphologies emerging under each specific scenario that leads to dune asymmetry are far from being understood. In the present work, we use dune modeling in order to investigate the formation and evolution of asymmetric barchans. We find that a bimodal wind regime causes limb extension when the divergence angle between primary and secondary winds is larger than 90°, whereas the extended limb evolves into a seif dune if the ratio between secondary and primary transport rates is larger than 25%. Calculations of dune formation on an inclined surface under constant wind direction also lead to barchan asymmetry, however no seif dune is obtained from surface tilting alone. Asymmetric barchans migrating along a tilted surface move laterally, with transverse migration velocity proportional to the slope of the terrain. Limb elongation induced by topography can occur when a barchan crosses a topographic rise. Furthermore, transient asymmetric barchan shapes with extended limb also emerge during collisions between dunes or due to an asymmetric influx. Our findings can be useful for making quantitative inference on local wind regimes or spatial heterogeneities in transport conditions of planetary dune fields hosting asymmetric barchans.

1. Introduction

The classical symmetric shape of barchan dunes is far from being prevalent in nature. A wide variety of barchan morphologies on Earth and Mars are asymmetric, with one extended limb (cf. Fig. 1) (Tsoar, 1984; Bourke, 2010). Since the pioneering works by Bagnold (1941), various conceptual models have been proposed in order to explain the existing asymmetric dune morphologies. Dune asymmetry has been most predominantly attributed to asymmetric bimodal winds (Bagnold, 1941; Tsoar, 1984), topography (Finkel, 1959; Long and Sharp, 1964), dune collisions (Close-Arceduc, 1969; Hersen and Douady, 2005) or asymmetric sand influx (Rim, 1958). Indeed, understanding dune asymmetry constitutes an important issue in planetary science, as asymmetric dunes could potentially serve as a proxy for local wind regimes or variations in sand supply or topography. However, the significance of the different causes of barchan asymmetry is still poorly understood, whereas the potential range of dune morphologies resulting in each case remains unknown. Although some insights into the dynamics of asymmetric dunes could be gained from field monitoring within a time span of a few years (Bourke, 2010), assessment of dune shape evolution is a difficult task owing to the long timescales involved in dune processes. Moreover, diverse asymmetric dune morphologies (Bourke et al., 2004; Bourke and Goudie, 2009) might be the outcome of different factors in concurrent action, which poses a further challenge in the investigation of the developmental stages of asymmetric dunes through field observations.

Numerical modeling — which has become indispensable in the investigation of aeolian and dune processes on Earth and other

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1875-9637/$ - see front matter
http://dx.doi.org/10.1016/j.aeolia.2013.12.002

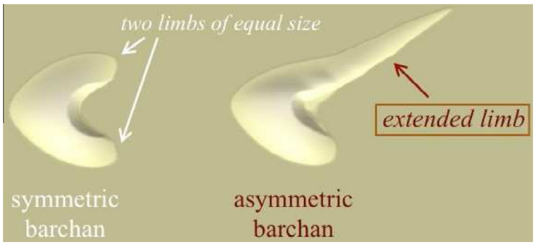

Fig. 1. Schematic diagram of a symmetric barchan with two limbs of equal size (left) and of an asymmetric barchan with an extended limb (right).

planetary bodies (Bourke et al., 2010; Kok et al., 2012) — could provide a helpful tool in the study of barchan dune asymmetry. In order to shed light on the factors competing for the appearance of various asymmetric dune shapes, a minimal model that accounts for a mathematical description of the wind over dunes, as well as for the equations for grain transport and landscape evolution is required. Such a model has been developed in the course of the last decade (Sauermann et al., 2001; Kroy et al., 2002; Durán and Herrmann, 2006a; Durán et al., 2010). This model combines an analytical model for the average turbulent flow over the sand landscape with a continuum model for sand transport. The model has proven to reproduce the shape of different types of dunes with good quantitative agreement with measurements (Sauermann et al., 2003; Durán and Herrmann, 2006a; Durán and Herrmann, 2006b; Parteli and Herrmann, 2007). The model has been further extended in order to model longitudinal seif dunes and diverse unusual Martian dune forms under bimodal wind regimes (Parteli et al., 2009).

In the present work, we use the dune model to investigate the role of different asymmetry causes for the diversity of asymmetric barchan shapes reported previously from observations of dune fields on Earth and Mars (Bourke, 2010). We calculate the evolution of a symmetric barchan dune under the separate action of the potential causes for dune asymmetry.

This paper is organized as follows. In Section 2 the dune model is described. In Sections 3–6 we present the results obtained from calculations of barchan dune asymmetry due to bimodal wind regimes, topography, asymmetric sand supply and dune collision, respectively. Moreover, in Section 7 we compare the results of our simulations with the shapes of real asymmetric barchans and discuss on the application of the model outcomes to the research of extraterrestrial dunes. Finally, conclusions are presented in Section 8.

2. Model description

The model used in the calculations of the present work consists of a set of mathematical equations that compute: the average turbulent wind field (the surface shear stress ($\boldsymbol{\tau}$) over the topography; the mass flux ($\boldsymbol{q}$) of saltating particles due to the shear stress, and the time evolution of the surface resulting from particle transport (Sauermann et al., 2001; Kroy et al., 2002; Durán and Herrmann, 2006a). In this Section, we present a brief description of the model equations and of the calculation procedure.

2.1. Wind field

The first step of the model calculations consists of describing quantitatively the average three-dimensional turbulent wind field over the dune. The average shear stress field ($\boldsymbol{\tau}$) is calculated through solving a set of analytical equations developed by Weng et al. (1991).

In the absence of dunes, the wind velocity $\boldsymbol{v}(z)$ within the atmospheric boundary layer increases logarithmically with the height (z) above the flat ground. That is,

$$\boldsymbol{v}(z) = [\boldsymbol{u}_{*0}/\kappa]\ln(z/z_0), \tag{1}$$

where $\kappa = 0.4$ is the von Kármán constant and $\boldsymbol{u}_{*0}$ is the wind shear velocity, which is used to define the (undisturbed) shear stress $\boldsymbol{\tau}_0 = \rho_{\rm fluid}|\boldsymbol{u}_{*0}|\boldsymbol{u}_{*0}$, with $\rho_{\rm fluid}$ standing for the air density (Bagnold, 1941; Sullivan et al., 2000). Furthermore, z_0 is the surface roughness, which scales with the average grain size (d) composing the sand bed. We take $z_0 \approx d/20$ based on a recent theoretical work on modeling saturated sand flux (Durán and Herrmann, 2006a).

A smooth hill or dune introduces a perturbation in the wind field. The Fourier-transformed longitudinal and transverse components of the shear stress perturbation ($\hat{\boldsymbol{\tau}}$) due to the local topography are computed using following equations,

$$\tilde{\hat{\tau}}_x = \frac{\tilde{h}_s k_x^2}{|\vec{k}|}\frac{2}{U^2(l)}\left\{-1 + \left(2\ln\frac{l}{z_0'} + \frac{|\vec{k}|^2}{k_x^2}\right)\sigma\frac{K_1(2\sigma)}{K_0(2\sigma)}\right\}, \tag{2}$$

$$\tilde{\hat{\tau}}_y = \frac{\tilde{h}_s k_x k_y}{|\vec{k}|}\frac{2}{U^2(l)}2\sqrt{2}\sigma K_1(2\sqrt{2}\sigma), \tag{3}$$

where x and y are parallel, respectively, perpendicular to the wind direction, $\sigma = \sqrt{\mathrm{i}Lk_x z_0/l}$, k_x and k_y are the components of the wave vector $\vec{k}$, i.e., the coordinates in Fourier space, K_0 and K_1 are modified Bessel functions and $\tilde{h}_s$ is the Fourier transform of the height profile; U is the vertical velocity profile which is suitably nondimensionalized, l is the depth of the inner layer of the flow and L is a typical length scale of the hill or dune and is given by 1/4 the mean wavelength of the Fourier representation of the height profile. In the presence of the saltating grains, the roughness of the dune's surface increases to an apparent value z_0', the aerodynamic roughness (Bagnold, 1941). The wind velocity over the dune is calculated using $z_0' = 1$ mm, a value based on experimental observations (Bagnold, 1941; Andreotti, 2004). The surface shear stress field is obtained, then, with the equation,

$$\boldsymbol{\tau} = |\boldsymbol{\tau}_0|(\boldsymbol{\tau}_0/|\boldsymbol{\tau}_0| + \hat{\boldsymbol{\tau}}), \tag{4}$$

where $\boldsymbol{\tau}_0$ is the undisturbed shear stress over the flat ground.

Flow separation at the dune brink due to the strong local curvature of the surface gives rise to a zone of recirculating flow (Walker and Nickling, 2002; Herrmann et al., 2005; Araújo et al., 2013), which cannot be described by the analytical model (Weng et al., 1991). This problem is overcome introducing the so-called "separation bubble": for each longitudinal slice of the dune, a separation streamline connecting the brink to the reattachment point is introduced at the lee. Each separation streamline is fitted to a third-order polynomial, the parameters of which are determined as described in detail by Kroy et al. (2002). The wind model (Weng et al., 1991) is then solved for the smooth "envelope" that comprises the separation bubble and the dune surface (Kroy et al., 2002). Thereafter, the shear stress in the recirculating zone within the separation bubble is set as zero, since the net transport within the bubble essentially vanishes.

2.2. Sand flux

Next, the mass flux of particles in saltation — which is the dominant transport mode and consists of grains hoping in ballistic trajectories and ejecting new particles upon collision with the ground — is computed. The saltation cloud is regarded as a thin, fluid-like layer that can exchange sand with the immobile sand bed (Sauermann et al., 2001).

When the wind shear stress exceeds a minimal threshold and saltation begins, the sand flux first grows exponentially due to