Transformation of barchans into parabolic dunes under the influence of vegetation

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Abstract

Barchan dunes were found to transform into parabolic dunes and vice versa when the amount of vegetation on and around them changes. This work presents the first numerical simulation of this effect. We propose a continuum model for the density of vegetation. An established sand transport model is used for simulating the evolution of the dunes.

1 INTRODUCTION

Sand dunes are deposits formed by aeolian sand. They occur frequently in deserts and on coasts. The shape of dunes depends on a number of factors, such as the sand supply, the wind speed, and its directional variation over the year. Low sand availability in combination with unidirectional wind leads to crescent-shaped barchan dunes.

One particular factor which can have a significant influence on the dune shape is the presence of vegetation on or around the dunes. A recent investigation of aerial photographs covering a time span of 50 years (Tsoar & Blumberg 2002) found that barchans can invert their shape to form parabolic dunes and vice versa when the amount of vegetation changes. Parabolic dunes are U-shaped dunes the arms of which point toward the direction of the prevailing wind. The amount of vegetation varied over that period because of human activities (such as grazing or stabilization) or because of wind power.

The formation of parabolic dunes has been modeled numerically with a lattice model (Nishimori & Tanaka 2001). Though the authors find intermediate formation of small parabolic dunes which then form barchans, this does not constitute the transition between full-sized barchan and parabolic dune found in (McKee & Douglas 1971; Tsoar & Blumberg 2002). This effect has not been investigated theoretically before. We propose a model for vegetation growth taking into account sand erosion and deposition and use an established saltation model for simulating the sand transport which determines the evolution of the dunes.

2 MODELS

2.1 Vegetation Growth:

We characterize the vegetation by its local height (h_v) and, for the vegetation growth rate, we propose a continuous model inspired by (Nishimori & Tanaka 2001).

We suppose, first, that vegetation can grow until it reaches a maximum height (H_v) and, second, that the growth process has a characteristic time (τ_s), determined by climatic conditions that enhance or inhibit it.

Moreover, the vegetation growth rate should be a function of the time rate of sand surface change ($\partial h/\partial t$). After any temporal change of the sand surface (h) the vegetation needs time to adapt to the new conditions. We introduce this effect only as a delay in the vegetation growth. Thus:

$$\frac{dh_v}{dt} = \frac{H_v - h_v}{\tau_s} - \left|\frac{\partial h}{\partial t}\right| \qquad (1)$$

However, equation 1 is not enough for describing the evolution of vegetation. Under a continuous sand erosion the vegetation dies because its roots are exposed (Tsoar & Blumberg 2002) . In this case what is important is the total erosion of the sand bed and not its time rate. Thus, we choose the following criterion: if the local sand level is reduced by more than 10% of the vegetation height above it, then the plant dies. This parameter just takes into account a limit for the exposition of the plant's root and the results does not depend on its exact value.

Another important assumption is related to the places at which vegetation can grow. We considered that in those places that have been covered by sand the vegetation cannot grow before a time interval (t_v) necessary for the soil recovery. We choose this time interval as 8 months, approximately the turn over time of the Barchan dune we use in the simulation.

2.2 Shear Stress Partitioning:

The shear stress partitioning is the main dynamical effect of the vegetation on the flow field and, hence, on the sand transport. The vegetation acts as roughness that absorb part of the momentum transfered to the soil by the wind, thus, the total surface shear stress is divided into two components, one acting on vegetation and the other on the sand grains. The fraction of the total shear stress acting on the sand grains can be described by the expression (Buckley 1987):

$$\tau_s = \left(1 - \frac{\rho_v}{\rho_c}\right)^2 \tau \qquad (2)$$

where τ is the total surface shear stress, τ_s is the shear stress acting on the non-vegetated ground, ρ_v is the vegetation density, defined as $(h_v/H_v)^2$, and ρ_c is a critical vegetation density that depends mainly on the geometric properties of the vegetation (Pye & Tsoar 1990).

Equation 2 represents a reduction of the shear stress acting on the sand grains that also implies a reduction of the sand flux. Both equations (1 and 2) contain the interaction between the vegetation and the sand surface. In those places where the sand erosion or deposition is small enough the vegetation grows (1). Then, the shear stress, and also the sand flux, decreases (2) and

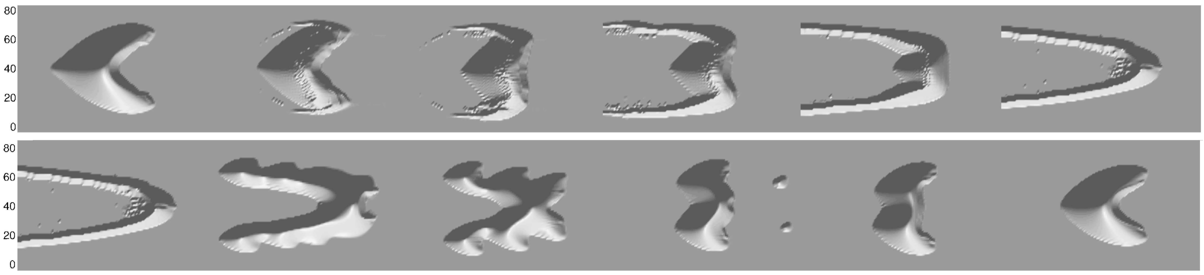

Figure 1: Evolution of an initial barchan dune to a fixed parabolic shape and vice versa. For the first transformation we allowed that the vegetation grows with a characteristic growth time (τ_s) of 7 days (the evolution of vegetation appears in figure 2). Whereas for the second, the vegetation is removed and the dune is left to evolve normally.

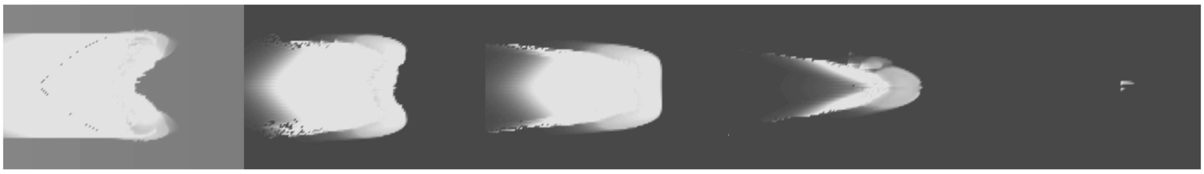

Figure 2: Evolution of the vegetation density in a barchan-parabolic transformation for a vegetation characteristic growth time of 7 days (see upper part of Figure 1). The gray value represents the vegetation density: black means complete cover, white, no vegetation.

starts the sand deposition, which in turn slows down the vegetation growth.

2.3 Sand Transport:

For the dune evolution we use an established sand transport model (Sauermann, Kroy, & Herrmann 2001; Schwämmle & Herrmann 2003) that consists of three coupled equations for the wind shear stress, the sand flux and the avalanches, and the resulting change in the sand surface using mass conservation.

3 RESULTS

We performed simulations placing a $4.2\,m$ high barchan dune on a rock bed and then allowing the vegetation to grow. A zero influx and a $0.5\,m/s$ upwind shear velocity are set. We also fixed $\rho_c = 0.5$, a typical value for spreading herbaceous dune plants (Pye & Tsoar 1990) and $H_v = 1.0\,m$. Finally, the dune model parameters have been specified in (Sauermann 2001).

We studied the influence of the vegetation characteristic growth time (τ_s) which contains the information of the growth rate and, hence, controls the strength of the interaction between the dune and the vegetation.

The upper part of Figure 1 shows snapshots of the evolution of a barchan dune under the influence of vegetation with a characteristic growth time of 7 days. The evolution of the vegetation density is shown in

Figure 2. Initially, the vegetation invades those places where the sand erosion or deposition is small, the horns, the crest and the surroundings of the dune except upwind. There, the soil was covered by sand, and, as a consequence of our model, it needs a time (τ_s) to recover. As the vegetation grows, it traps the sand, which then cannot reach the lee side. There, the vegetation cover increases. On the other hand, the vegetation on the windward side is eliminated because its roots are exposed as the dune migrates. However, at the horns the vegetation grows fast enough to survive the small sand deposition and, there, the sand accumulates. Hence, whereas the central part of the dune moves forward a sand trail is left behind at the horns. This process leads to the stretching of the windward side and a formation of a parabolic dune.

This picture agrees well with a recent conceptual model to explain such transformation based on field observations (Tsoar & Blumberg 2002).

The bottom of figure 1 shows the inverse process. After eliminating all vegetation and setting a constant influx of $0.005\,kg/ms$, the parabolic dune is fragmented into small barchanoid forms that nucleate into a final barchan dune. Although the transformation from parabolic into barchan or transversal dunes have been observed (Anton & Vincent 1986), this fragmentation does not occur in natural conditions because the vegetation is eliminated gradually from the parabolic dune, leaving first the central part but still remaining at the lateral trails.

The barchan to parabolic transition and also the parabolic shape, strongly depend on the vegetation growth rate. Figure 3 (b),

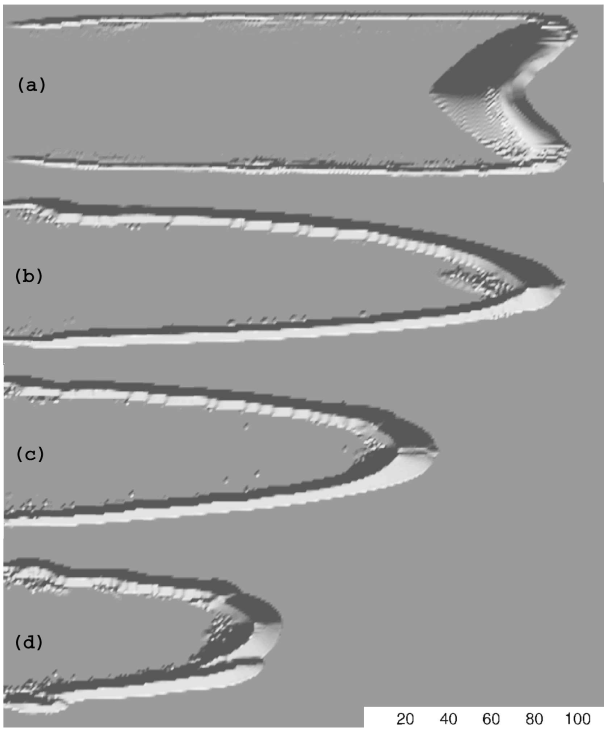

Figure 3: Final or stationary states starting with one barchan dune under the influence of vegetation with different growth rates.The vegetation characteristic growth times are: (a) 12, (b) 8, (c) 7 and (d) 4.6 days. The parabolic dunes are (b) $260\,m$, (c) $200\,m$ and (d) $130\,m$ long. Note that in (a) the vegetation cover is not dense enough to transform a barchan dune into a parabolic one.

(c) and (d) show the final parabolic dune for three values of τ_s (see figure caption). As we expected a longer parabolic dune emerges for a smaller vegetation growth rate, i.e. a higher τ_s. On the other hand, if τ_s is too high ,the vegetation cover is not enough to complete the inversion process (Figure 3 (a)). In this case the barchan keeps its shape but leaves lateral sand trails covered by plants. However, due to the constant loss of sand in the arms, the Barchan size is reduced until finally being stabilized by vegetation.

Notice that the parabolic dunes are slightly asymmetric (Figure 3) despite the initial condition being symmetric. This surprising result is the consequence of the interaction of the vegetation with the sand bed. Once vegetation grows it protects the soil from erosion. This enhances the growth process, which in turn, increments the soil protection and so on. This mechanism amplifies small asymmetries in the vegetation cover. In our simulation, the initial small asymmetries are due to numerical inaccuracies, in nature, they are a consequence of random factors influencing vegetation growth. When the vegetation cover is small or zero these asymmetries disappear.

4 CONCLUSIONS

We performed a numerical simulation of the influence of varying amounts of vegetation on dune shapes. We proposed a continuum model describing vegetation growth (Equation 1). Taking into account the partitioning of the shear stress between the plants and the ground, we used a saltation model to simulate the evolution of the dune shape.

We have reproduced the observed effect of the transition between barchans and parabolic dunes. When vegetation is allowed to grow on a barchan according to (Equation 1), it inverts its curvature to become a parabolic dune. When the vegetation is removed, it transforms back into a barchan. In the latter process, we apply a small sand influx to compensate for the loss of sand which is no longer trapped by the vegetation.

After a parabolic dune is formed, it is completely covered by vegetation and rendered inactive. We have found that the final shape of the parabolic dune evolving from a barchan depends strongly on the growth rate of the vegetation. Slow-growing plants only slow down the arms of the barchan and do not transform it completely into a parabolic dune. The faster the plants grow, the faster the transformation is completed and the shorter are the arms of the resulting parabolic dune.

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