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Barchan-Parabolic Dune Pattern Transition From Vegetation Stability Threshold

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Abstract

Many dune fields exhibit a downwind transition from forward-pointing barchan dunes to stabilized, backward-pointing parabolic dunes, accompanied by an increase in vegetation. A recent model predicts this pattern transition occurs when dune surface erosion/deposition rates decrease below a threshold of half the vegetation growth rate. We provide a direct test using a unique data set of repeat topographic surveys across White Sands Dune Field and find strong quantitative support for the model threshold. We also show the threshold hypothesis applied to a barchan dune results naturally in its curvature inversion, as the point of threshold crossing progresses from the horns to the crest. This simple, general threshold framework can be an extremely useful tool for predicting the response of dune landscapes to changes in wind speed, sediment supply, or vegetation growth rate. Near the threshold, a small environmental change could result in a drastic change in dune pattern and activity.

Keywords

aeolian, pattern transition, parabolic dune, vegetation feedback, threshold

Disciplines

Atmospheric Sciences | Earth Sciences | Environmental Indicators and Impact Assessment | Environmental Sciences | Physical Sciences and Mathematics

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Barchan-parabolic dune pattern transition from vegetation stability threshold

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[1] Many dune fields exhibit a downwind transition from forward-pointing barchan dunes to stabilized, backward-pointing parabolic dunes, accompanied by an increase in vegetation. A recent model predicts this pattern transition occurs when dune surface erosion/deposition rates decrease below a threshold of half the vegetation growth rate. We provide a direct test using a unique data set of repeat topographic surveys across White Sands Dune Field and find strong quantitative support for the model threshold. We also show the threshold hypothesis applied to a barchan dune results naturally in its curvature inversion, as the point of threshold crossing progresses from the horns to the crest. This simple, general threshold framework can be an extremely useful tool for predicting the response of dune landscapes to changes in wind speed, sediment supply, or vegetation growth rate. Near the threshold, a small environmental change could result in a drastic change in dune pattern and activity. **Citation:** Reitz, M. D., D. J. Jerolmack, R. C. Ewing, and R. L. Martin (2010), Barchan-parabolic dune pattern transition from vegetation stability threshold, *Geophys. Res. Lett.*, *37*, L19402, doi:10.1029/2010GL044957.

1. Introduction

[2] Aeolian dune morphology is determined by wind regime, sediment supply, and vegetation [*Wasson and Hyde*, 1983; *Rubin and Hunter*, 1987]. Barchan dunes arise under the influences of a unidirectional wind, a low sediment supply, and the absence of vegetation. The barchan form is a crescent with its horns pointing downwind and a slipface in its interior, and has been modeled extensively [*Sauermann et al.*, 2000; *Andreotti et al.*, 2002; *Hersen et al.*, 2002; *Schwämmle and Herrmann*, 2005]. With an increase in sediment supply, barchan dunes laterally link to form crescentic dunes, which have continuous, sinuous ridges. Parabolic dunes are vegetated dunes that have arms that point upwind and noses that point downwind. They arise commonly as a result of the stabilization of barchan dunes by vegetation [*Hack*, 1941; *Gaylord and Stetler*, 1994; *Muckersie and Shepherd*, 1995; *Anthonsen et al.*, 1996; *Tsoar and Blumberg*, 2002], though they can also arise from crescentic dunes and blowout features. The barchan-parabolic transition process has been observed on individual dunes where changes in climate or human land use have introduced vegetation to a dune surface, and the reversal of parabolic to barchan shape upon the removal of vegetation has also been observed [*Hack*, 1941; *Anthonsen et al.*, 1996; *Tsoar and Blumberg*, 2002; *Wolfe and Hugenholtz*, 2009].

[3] The common qualitative consensus that has emerged from these observations is that the transition process begins as vegetation initially colonizes the dune horns, because the horns have lower erosion/deposition rates (collectively referred to as 'total surface change' [cf. *Wiggs et al.*, 1995]) than the dune center. Then, when vegetation does take hold, shielding effects and stabilization by roots decrease dune migration rate and total surface change [*Lancaster and Baas*, 1998; *King et al.*, 2005]. Because the center of the dune is migrating faster than the horns, the dune crescent inverts. Plants work their way to the center of the dune, resulting in the parabolic shape, which migrates forward at a slower rate [*Gaylord and Stetler*, 1994; *Anthonsen et al.*, 1996; *Durán and Herrmann*, 2006; *Durán et al.*, 2008]. Although observations have provided a qualitative understanding of the barchan-parabolic transition process, no quantitative framework of the process has been confirmed. Thus, predicting the stability of a barchan or parabolic dune field with changing external conditions, which may arise from climate or human-induced landscape changes, is not currently feasible. At the dune scale, a quantitative understanding of how the final shape of an individual parabolic dune is established is also missing.

[4] Cellular automaton and continuum models have simulated parabolic dune formation and furthered our quantitative knowledge of the barchan-parabolic transition. The cellular model of *Nishimori and Tanaka* [2001] partially succeeded in capturing the transition. In their simulation, barchan dunes temporarily gave rise to parabolic forms that were unstable. A cellular model by *Nield and Baas* [2008], which simulated the development of parabolics from blowouts rather than barchans, produced stable parabolics by incorporating two plant species requiring different growth environments.

[5] The only continuum model that simulates the barchan-parabolic transition is that of *Durán and Herrmann* [2006], which uses a set of differential equations relating the relative timescales of vegetation growth and dune surface erosion/deposition. Their simulation succeeds in qualitatively reproducing the transition process and predicts a critical ratio $\boldsymbol{\theta}_c$ (cf. "fixation index" [*Durán and Herrmann*, 2006]) of total surface change to vegetation growth rate above which a barchan is stable, and below which vegetation takes hold and a parabolic dune forms. The predicted $\boldsymbol{\theta}_c$ is 0.5; or, a total surface change of half the representative vegetation growth rate [*Durán and Herrmann*, 2006]. *Durán et al.* [2008] compare the vegetation cover on a dune blowout in

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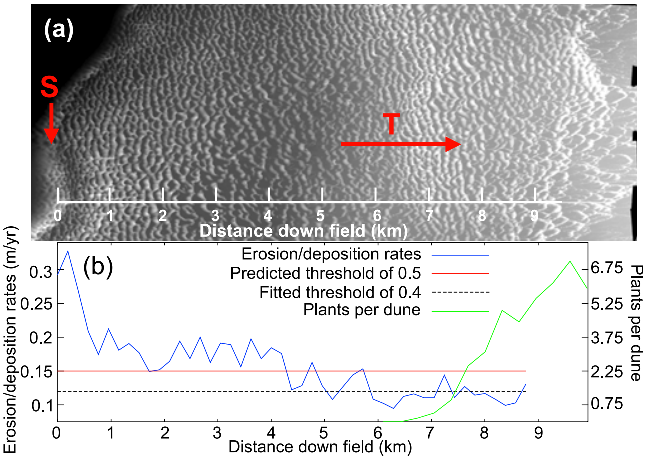

Figure 1. (a) DEM derived from LiDAR of White Sands. Transport is from southwest (left) to northeast (right). Dunes upwind ('S') are crescentics, which break into individual barchans as sediment availability decreases. Downwind-pointing barchans then transition ('T' arrow) to upwind-pointing parabolics in the downwind margin. (b) Total surface change (blue line) decreases downwind. Red line indicates the predicted transition threshold. Green line shows sharp increase in vegetation density (measured from 6 km), occurring just downwind of threshold crossing. Threshold crossing corresponds most closely with $\boldsymbol{\theta}_c = 0.4$ (dotted black line), a value not significantly different from the predicted 0.5.

Brazil to a simulated blowout with an arbitrarily selected fixation index and find qualitative similarity; though this is an encouraging result, it does not test the model conclusively.

[6] Dunes commonly transition spatially across dune fields from active crescentic ridges and barchan dunes into stabilized parabolic dunes. *Durán and Herrmann*'s [2006] model predicts that this transition should occur where the total surface change drops below half the growth rate of the dominant plant species. We test this prediction by measuring the relationship between total surface change and the growth rate of the dominant vegetation types across the barchan-parabolic transition at White Sands Dune Field. We conclude that (1) the field-scale transition occurs near the predicted critical ratio of 0.5 and (2) the critical ratio also applies to the transition of an individual barchan dune into a parabolic shape because of spatial variations in total surface change across a dune surface.

2. Field Test and Methods

[7] White Sands Dune Field occupies ~400 km^2 within the Tularosa Basin in New Mexico. The formation of the dune field began approximately 7,000 years ago, when a lake-drying event released a pulse of gypsum sediment, which forms the upwind sediment source for the dune field [*Langford*, 2003; *Kocurek et al.*, 2007]. In the downwind portion of the field, dune morphology transitions from continuous crescentic ridges to barchan dunes and crescentic ridges with distinct barchanoid segments, and finally into fully stabilized parabolics [*McKee*, 1966]. *Langford et al.* [2009] attributed the transition to parabolics to a lens of fresh water in the downwind parabolic region, outside of which the groundwater is too saline to support plant life. For White Sands or any dune field, numerous parameters may impact both the growth rate of vegetation and the total surface change on the dunes. However, in this paper we assume that a single-valued total surface change threshold may be applied to our entire study area at White Sands: i.e., that growth conditions are constant enough across the field that vegetation growth rate may be held as a constant, and therefore that dune morphology changes are dictated by changes in total surface change alone. We find that the barchan-parabolic transition at White Sands can be explained simply and generally in terms of the total surface change threshold crossing predicted by *Durán and Herrmann*'s [2006] model, without reference to additional environmental complexity.

[8] We measured dune total surface change across White Sands using topographic data derived from airborne Light Detection And Ranging (LiDAR) flown over a 10-km by 4-km area of White Sands in June 2007 and June 2008 (Figure 1a). The data are gridded at 1 m/pixel spatial resolution with ~0.1 m vertical resolution. We generated a map of the absolute values of elevation differences between these years, which is equivalent to total surface change values. Total surface change was averaged within 50 boxes, 191 m long (downwind) and 3842 m wide (along-crest) (Figure S1 of the auxiliary material).[1] A typical box with average value 0.230 m has a high standard deviation of 0.303 m, because averaging takes place over both active dunes and inactive interdunes. Because the relevant and nonzero values are the total surface change rates on dune surfaces, we isolated the dune areas using the NIH (National Institutes of Health)-developed software ImageJ and measured the changing dune-area fraction downwind, averaged over the same 50 boxes as the total surface change measurements (Figure S2). We normalized the total surface change by the dune-area fraction. Rates measured across individual dunes were averaged over circular zones of radius 9 m to reduce noise (Figure S3). A typical averaged measurement of 0.104 m has a standard deviation of 0.076 m. For comparison, we also used aerial photos to count the number of large (>1 m^2 aerial extent, with a typical size of 10–15 m^2 on an average dune of 8000 m^2) plants per dune in the downwind region. Our plant counts are used to demonstrate bulk plant behavior in the vicinity of the dune transition; other metrics such as percent vegetation cover could also be used to analyze the same trend. Measurements begin 6 km down the field and are averaged within 13 boxes, 318 m long (downwind) and 2544 m wide (along–crest). The total surface change rates obtained through our methods are typically in the range of 0.1 m/yr − 0.3 m/yr. We verify that these values are comparable to those obtained for erosion rates measured alternatively as the product of typical dune migration rates, ~2 m/yr, and dune slopes, ~0.1. See Figure S4 for a plot of typical slope–celerity products measured over the barchan dune of Figure 2b.

[9] A vegetation growth rate (V_v) of 0.3 m/yr represents the average of reported growth rate values for the dominant plant species on the parabolic dunes in White Sands: Skunkbush Sumac, 0.30–0.45 m/yr (Michigan State University, Extension Ornamental Plants plus Version 3.0

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL044957.

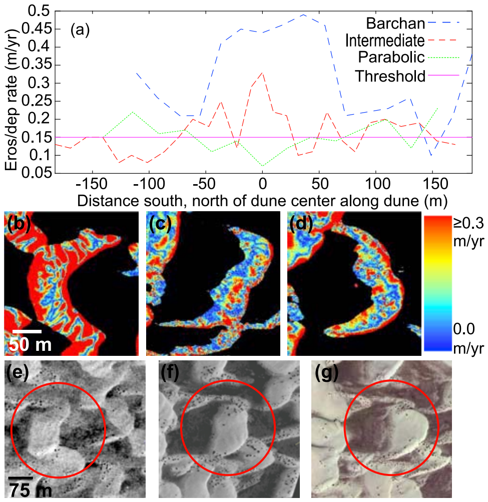

Figure 2. (a) Averaged total surface change for the case study examples of (b) barchan dune, (c) intermediate transitional dune and (d) parabolic dune, compared to the predicted vegetation threshold. Figures 2b–2d are color-scaled maps of total surface change over dune surfaces. Aerial images following a migrating dune from (e) 1963 to (f) 1985 to (g) 2005. The dune shape changes from barchanoid to parabolic, as the dune center outpaces horns stabilized by vegetation. Aerial photos from 1963 and 1985 were provided by White Sands National Monument.

database, accessed 10 May 2010, available at http://web1.msue.msu.edu/imp/modzz/masterzz.html); Soaptree Yucca, 0.30 m/yr (National Park Service A Checklist of Plants of White Sands National Monument, accessed 10 May 2010, available at http://www.nps.gov/whsa/naturescience/checklist-of-plants.htm); Salt Cedar, 0.15–0.25 m/yr (Plants For A Future (PFAF) database, accessed 10 May 2010, available at http://www.pfaf.org); and Rio Grande Cottonwood, 0.20–0.40 m/yr (http://www.pfaf.org). The growth rates quoted here are those of plants large enough to have the roots and resilience to impede dune migration. Although lower shrubs and grasses may make up a significant percentage of vegetation cover, we do not believe their growth rates are the pertinent ones for the barchan-parabolic transition. From aerial photos of transitioning dunes (Figures 2e–2g) and direct field observation, we observe that the larger plants anchor the dune horns as the center migrates forward. The predicted total surface change at the transition threshold is then $V_v \cdot \boldsymbol{\theta}_c$, or 0.15 m/yr.

3. Results

[10] The decrease in average total surface change down the dune field plotted along with the predicted 0.5 threshold for vegetation stabilization (Figure 1b) shows the predicted barchan-parabolic transition corresponds well with the downwind spatial pattern transition from barchan to parabolic dunes. Our measurements of plant density across the transition demonstrate an abrupt increase in vegetation cover downwind. The sharpness of this increase just after the erosion rate decreases past the predicted value provides strong support for the hypothesis that the transition results from a total surface change threshold crossing, below which plants are able to grow. A threshold fraction of 0.4 has a better fit to the observed transition and vegetation increase, but given that our total surface change data is only averaged over one year and our vegetation growth rate is an estimate, this value is not significantly different from the predicted 0.5. Total surface change fluctuations also account for the anomalous brief appearance of parabolic forms prior to the main transition.

[11] A near-surface water table traps sediment in the interdune areas and causes partial cementation of the gypsum dunes. The long-term sediment accretion rate in the dune field is about 2 mm/yr [*Kocurek et al.*, 2007]. This sediment must be extracted from the migrating dunes, and the two are related through conservation of mass: $\frac{\partial h}{\partial t} = -\frac{1}{\varphi}\frac{\partial q_s}{\partial x}$, where h is surface elevation and $\varphi \approx 0.6$ is sediment concentration. Sediment flux q_s can be estimated from dune migration rate (celerity) c and height H, $q_s \approx c\frac{H}{2\varphi}$. Dune erosion rate $E \approx c\frac{\partial h}{\partial x} \sim c\frac{H}{l}$, where l, the length to dune crest in the downwind direction, has a measured average value of 55 m over a typical dune (Figure 3c). The decrease in E across the dune field required to balance $\partial h/\partial t$ = 2 mm/yr is approximately 0.26 m/yr, close to observations (Figure 1a).

[12] Total surface change measured from profiles of individual barchan, transitional, and parabolic dunes show that the total surface change varies spatially over an individual dune and differs between dune forms (Figure 2). Barchan dunes have total surface change above the threshold for vegetation stabilization, parabolic dune rates fluctuate around the threshold, and intermediate dunes are at threshold in their trailing arms, and above threshold in the faster-migrating dune centers. These results suggest that the threshold crossing initiates at the barchan horns and migrates crestward as the dune transitions toward a parabolic form.

[13] The transition from an individual barchan into a parabolic was studied using georeferenced aerial photos of White Sands from 1963, 1985, and 2005. These photos confirmed the hypothesis that the parabolics at White Sands transition from barchans (Figures 2e–2g).

4. Discussion

[14] The barchan-parabolic transition is brought about by the interaction between vegetation and moving sediment. Because vegetation cannot grow when total surface change

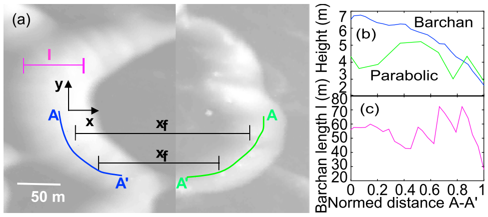

Figure 3. (a) Axes and variables of (1). Pictured are two dunes, a barchan and a parabolic, but schematically arranged to show how a single dune transitions from barchan to parabolic form. (b) Profiles of maximum transverse height from crest to horn of barchan and parabolic dunes, as shown by A-A′ lines of Figure 3a. X-axis is normalized from dune center (A) to dune horn (A′) to facilitate profile comparison. Barchan profile has a parabolic form. (c) Measurements of barchan l, length from windward edge to point of maximum dune height, also along A-A′. Length does not show a systematic trend.

is too high, the locations where vegetation can take hold are determined by total surface change, both at the field-scale and at the scale of individual dunes. Despite the complex feedbacks that may arise between vegetation and sediment transport, plant colonization and parabolic dune formation result from a simple threshold crossing; after dune total surface change falls below this threshold, the dune surface environment abruptly becomes hospitable to plant life, and plant cover increases rapidly. Because barchan total surface change is highest in the center of the dune, as a dune crosses into a zone of below-threshold total surface change within the dune field, the threshold will be crossed progressively from the horns of the barchan toward its crest. Vegetation on colonized portions of the dune significantly decreases migration rates through stabilization by roots and shielding from wind. Plant colonization freezes the progressing point of threshold crossing, relative to the non-vegetated portions of the dune, which continue to migrate at the original speed. Through this process the barchan crescent is inverted, and the resulting parabolic shape is a record of the inward-progressing threshold crossing of the original barchan erosion rate distribution.

[15] The process of planar parabolic shape formation from the threshold crossing of an original erosion rate distribution is summarized in (1):

$$[E(y) - E_c]\frac{dx}{dE} = x_f(y) \tag{1}$$

where E is erosion rate, E_c is the critical erosion rate for threshold crossing, x and y are the downwind and transverse directions, respectively, and $x_f(y)$ is the final planar shape of the parabolic dune (Figure 3a). Because the barchan volumetry has been extensively studied, a generic barchan erosion rate curve can be estimated from existing paradigms. In order to determine the resulting parabolic shape as a function of these initial conditions, the way in which erosion rate decreases across the transition must be constrained.

[16] Recall that $E \sim c\frac{H}{l}$, where l is length to dune crest in the downwind direction (Figure 3a). A migrating barchan maintaining its shape must have c constant with respect to y. Downwind length l does not vary strongly with y (Figure 3c). Dune height, however, is parabolic in y (Figure 3b) [*Sauermann et al.*, 2000]. $E(y)$ will then have a parabolic shape. Because the final shape x_f of the parabolic dune is also, roughly, 'parabolic', it follows that the $\frac{dx}{dE}$ of (1) would be ~constant; i.e., if $[E(y) - E_c] \sim Ay^2$ and $x_f(y) \sim By^2$, then $\frac{dx}{dE} \sim \frac{B}{A}$, a constant. Erosion rate would therefore fall at an approximately constant rate over the barchan-parabolic transition. We hypothesize that this decrease in E is related to mass loss from the center of the dune to the trailing arms through lateral diffusion of sediment. This idea could be tested from existing models. A quantitative understanding of the mass loss of a transitioning dune would complete our first-order understanding of the establishment of the parabolic shape.

[17] The threshold framework for the barchan-parabolic transition provides a useful predictive and interpretive tool for changing dune-covered landscapes. The threshold can be used to predict the way in which changes in dune migration rate or vegetation cover, resulting from changes in climate or human land use, may drastically alter a dune landscape by placing dunes above or below the threshold for transition. It can also be used to aid in geologic interpretations; records from transitional regions could be used to infer changes in migration and vegetation trends through the past, under changing environmental influences such as glacial cycles. Our confirmation of the predicted threshold for the barchan-parabolic transition and demonstration that its application to the barchan erosion-rate distribution results naturally in the establishment of a parabolic dune shape are general results that can be applied to the understanding of this dynamic in any dune field.

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