# Relevant Length Scale of Barchan Dunes

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A new experiment can create small scale barchan dunes under water: some sand is put on a tray moving periodically and asymmetrically in a water tank, and barchans rapidly form. We measure basic morphological and dynamical properties of these dunes and compare them to field data. These favorable results demonstrate experimentally the relevance of the so-called "saturation length" for the control of the dunes physics.

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Sand dunes are the results of complex physical interactions between wind flow and sand bed in desert area. Schematically, the wind is able to set sand grains into motion, and by this mean, to change the shape of the dune. Reciprocally, the dune is large enough to modify the flow pattern of the wind. The equilibrium between the two leads to the selection of shape and dynamics of dunes. The results have been studied in deserts for 50 years by geologists and geographers [1–3]. They have mainly reported field observations about barchans [4–8], which are crescentic shaped dunes, horns downwind, and propagating on solid ground under monodirectional wind (see Fig. 3). However, geologists' field measurements suffer intrinsically from the lack of control on meteorology conditions as well as the large length scale and time scale (100 m and 1 year) involved in the physics of dunes.

Questions of general interest, such as conditions of nucleation of dunes, their dynamics behavior, their shape and size selection, and even their stability, therefore have remained open up to now. Creating dunes in a controlled way would be the key for all these questions and thus, it has became a challenging problem. Following this idea, some experiments of sand piles blown by air flow have been performed to reproduce small aeolian barchan dunes. They all lead to barchan-shaped piles, but these piles disappear quickly, because of erosion [1,3,9,10]. This failure is directly related to a well-known field observation: no steady dune smaller than 1 m high and 10 m long has ever been reported in a desert area [1]. It means that there is a critical length involved in the physics of dunes. As the wind air flow is turbulent, it does not present any characteristic length scale which could explain this minimal size [11]. Bagnold [1] related this critical size to the existence of a transient length for the sand flux stabilization. To understand the origin of this saturation length, consider the wind blowing over a sand surface. It can dislodge grains, and accelerate them until they reach the wind velocity. During this process, a grain covers a distance depending on its inertia in the surrounding fluid, and consequently scaling with

$$l_{\mathrm{drag}} = \frac{\rho_s}{\rho_f} d, \tag{1}$$

where $\rho_s$ and $\rho_f$ are, respectively, the grain and fluid density, and $d$ the mean grain diameter. When a dragged grain collides back the sand bed it dislodges and pushes new grains, some of them being again accelerated by the wind. Thus the sand flux increases. After a few times $l_{\mathrm{drag}}$, all the grains that can be accelerated by the wind are mobilized, and no new grain can quit the sand bed without another grain being deposited: the sand flux gets saturated. From this description, the flux saturation length appears to be proportional to this inertia length, $l_{\mathrm{drag}}$, as recently proposed by Sauermann *et al* [12].

On a dune smaller than this length, the flux is always increasing, and therefore the dune can only be eroded. On the contrary, for a larger dune, the grain flux becomes oversaturated on the downwind slope and can deposit sand grains. Consequently, larger dunes can survive to the erosion by the wind. This description not only works when there is no incoming flux on the sand dune, but also, as observed in the field, for an incoming flux, generally much smaller than the saturated flux on the upwind dune slope.

So reproducing barchan dunes at small scale comes to reducing $l_{\mathrm{drag}}$. Actually it turns out that decreasing the particle size is not possible because of the cohesion that appears between grains below a certain size (typically 100 $\mu$m). Thus, it is only the density ratio that can be modified to check the relevance of $l_{\mathrm{drag}}$. In this purpose, we use another driving fluid, water: in this case $l_{\mathrm{drag}}$ becomes of the order of the grain diameter.

The experiment consists of a tray moving horizontally in a water tank (Fig. 1). It is moved with a periodic and strongly asymmetric motion. The initial motion is fast enough to displace glass beads, while the return is below the threshold of motion of the grains. In this way we reproduce the effect of a unidirectional and intermittent wind, as observed in deserts. Typical amplitude and duration of the motion are 10 cm and 1 s for the initial movement, and more than 2 s for the way back. The granular material used is glass beads with an average diameter of 150 $\mu$m.

Starting from a homogenous grains layer, we finally obtain typically after a few hours (depending on the tray

  

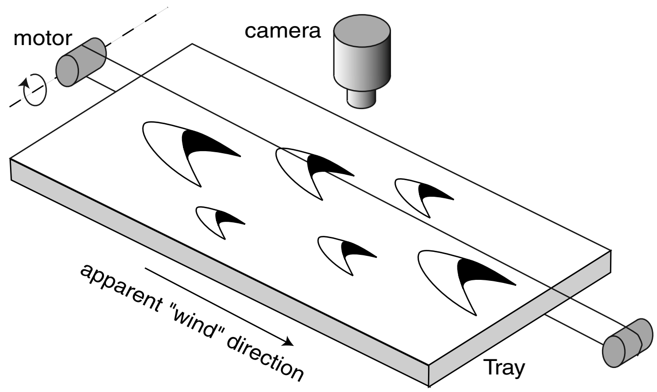


FIG. 1. Experimental set-up. The tray (30 cm by 15 cm) is moved by a motor driven by a wave generator. A video camera is placed at the vertical of the tray to capture one image at each period of the motion. A typical imposed motion of the tray has a 3 sec period and a 10 cm amplitude.

motion) many barchan dunes. These dunes propagate on the tray along the apparent wind direction. Figure 2 shows a typical aquatic dunes field in regard to an aeolian one.

Even if there is a global matching between the aeolian dune field and aquatic one, this kind of system is still too complex for a proper study of dunes characteristics, especially because of dune-dune interactions. It is thus useful to create a single barchan dune from a conical sandpile. In this last case, the sandpile quickly becomes (typically after 20 min) a propagating barchan dune.

Figure 3 shows that this aquatic dune has a crescentic shape, with two horns and a slip face downwind, as regularly observed on the field [1–3].

The submarine barchan dunes thus present the main qualitative morphological characteristics of the aeolian ones, but at a much smaller scale. Quantitatively, typical sizes of these barchans range from 1 to 10 cm in length [13] and width and 1 to 10 mm in height, depending on the initial amount of glass beads used. For aeolian barchan dunes, dimensions are 10 to 100 m long and wide and 1 to 10 m high. There is thus approximately a factor 1000 between the dimensions of these two kinds of dunes.

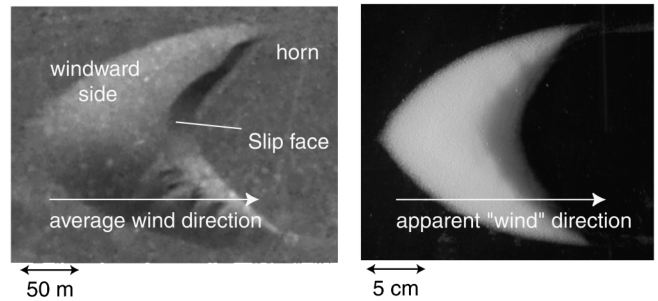


FIG. 3. Real and artificial dunes. The picture on the left exhibits a typical aeolian barchan dune (from southern Morocco). The modulation on both horns are due to the fluctuation of the wind direction for the aeolian case. The position of the dune parts are pointed out. On the right, a picture of a typical aquatic dune is shown.

To make a more definite comparison, Figs. 4 and 5 show measured dimensions of aeolian dunes and aquatic ones, once rescaled by $l_{\mathrm{drag}}$. Notice that to reduce the large fluctuations of the field measurements [4–7], the data have been averaged by size categories [10]. To make the rescaling, we assume a mean diameter of 250 $\mu$m for the

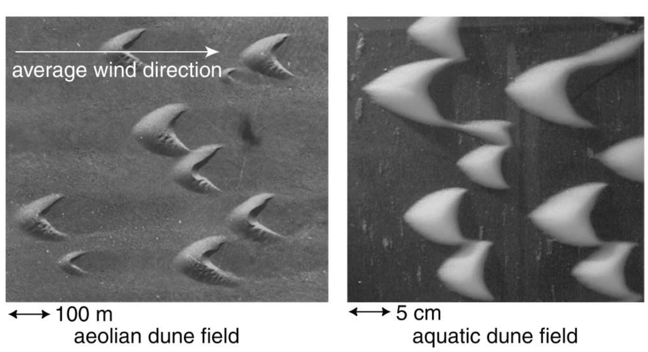


FIG. 2. Aeolian and aquatic barchans field. The aeolian picture comes from an aerial photography taken in southern Morocco. The crescentic shape is quite similar in both cases.

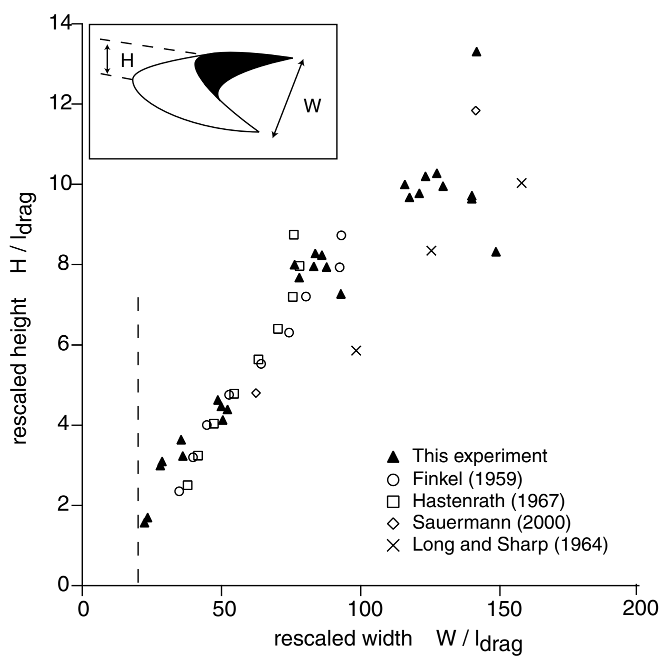


FIG. 4. Morphological characteristics. Experimental data for glass beads are compared with field measurements [4–7], once rescaled by the characteristic length $l_{\mathrm{drag}} = \rho_p/\rho_f d$. The height is measured in the experiment by means of an inclined laser sheet. The existence of a minimal width of the order of 20 times $l_{\mathrm{drag}}$ is pointed out by the dashed line: no dune smaller than this length appeared in the experiment nor in field measurements

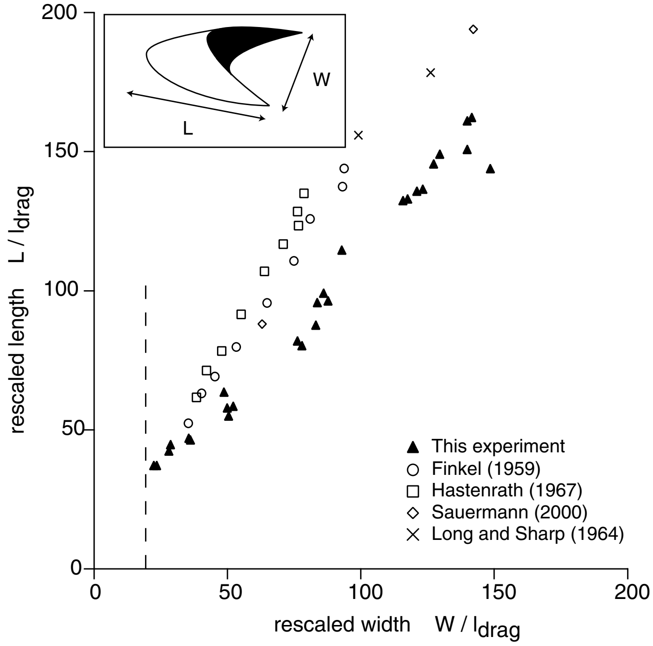


FIG. 5. Morphological characteristics. As in the previous figure, data have been rescaled by $l_{\mathrm{drag}}$. In both figures, the experiment presents a roughly linear relationship close to the field measurements [4–7]. Again, the existence of a minimal width of the order of 20 times $l_{\mathrm{drag}}$ is pointed out by the dashed line. Notice that Hastenrath has measured the dunes length without taking into account the horns' sizes, so we have interpolated these datas according to Finkel ones.

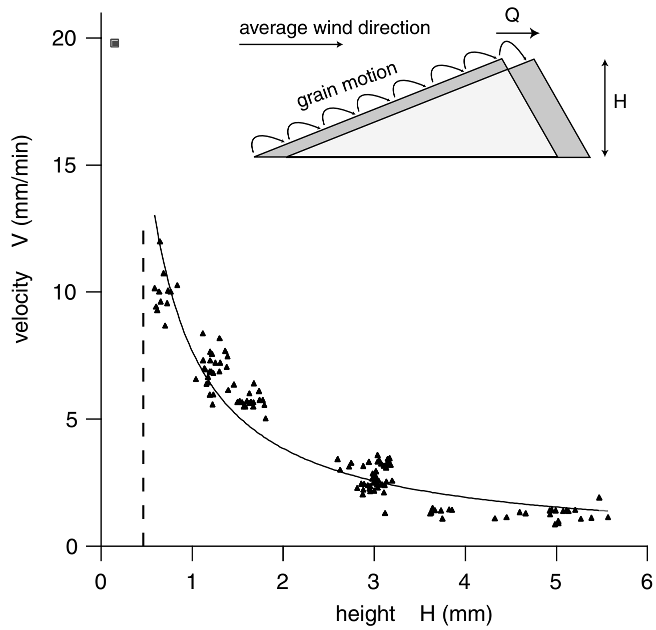


FIG. 6. Velocity measurements of the experimental barchans of various sizes under the same conditions. The last upper point corresponds to the velocity of a patch of one grain height. The data are fitted by a Bagnold-like relation $V = Q/H$. The experimental existence of a minimal height, of the order of $l_{\mathrm{drag}}$, is shown by the dashed line.

field data, which gives $l_{\mathrm{drag}} = 625$ mm while $l_{\mathrm{drag}} = 0.375$ mm in the experiment. Figures 4 and 5 show that the two kinds of dunes have roughly the same relationships between their characteristics dimensions.

Until now, we have just mentioned another main aspect of the physics of barchan dunes: their great mobility. Typically, a 3 m high barchan travels over 50 m per year. As said in the introduction, in wind tunnel experiments, a sandpile takes a qualitative barchanlike shape, but such pile hardly propagates before disappearing. It is just blown away by the air flow, because of its small size with regard to the saturation length.

During the experiment our aquatic barchans also propagate, as the aeolian ones, from one side of the tray down to the opposite side, along the apparent wind direction without disappearing. Looking at the individual path of grains in the air [14,15] allows to understand this propagation. The grains set into motion by the wind are transported until they reach the crest, where they sediment, because of the drastic decrease in the wind velocity. When the sand deposit is too steep, an avalanche [16] nucleates and bring sand grains down the slip face, while the deposit relaxes to the equilibrium angle. In water, the mechanism is the same except that avalanches are not visible (due to the small number of grains in height). So, grains pass from the back of the dune onto the slip face (see Fig. 6), and by this way, the dune moves along the wind direction without loosing mass. In fact, dunes loose a small amount of sand at the horns while propagating, but this loss, small, is under investigation as it can be essential for size selection. If we keep in mind the simple picture of a mass keeping dune, it can be inferred from mass conservation that the velocity of the dune $V$ is related to the flux of grains $Q$ at the crest and the height $H$ by

$$V = \frac{Q}{H}. \tag{2}$$

Following the Bagnold argument [1], the flux $Q$ is almost independent of $H$ for a dune larger than the saturation length, so that the speed $V$ scales as the inverse of $H$, as observed on the field [3,17]. Figure 6 shows that we recover this variation: the smallest dunes move 10 times faster than the largest ones. Moreover, the Bagnold's relation fits experimental points.

As said at the beginning of this Letter, the time scale involved in the study of desert dunes raises also difficulties for making measurements on the field. So another important characteristic of dune dynamics is the typical time for a dune to travel over its own length. It is of the order of 1 year for a small 3 m high aeolian dune, while we obtain about 30 min for the equivalent 3 mm high aquatic dune.

This experiment is thus able to reproduce the barchans characteristic shape, but at a much smaller scale. The morphology presents the same linear relationships between the height, the width, and the length, once rescaled by the saturation length. It can be surprising at first sight as we use particles of the same size as in the field, while the dunes are at a $1/1000$ scale. This means that it is the global shape of the dune which is significant and not its elements.

But the essential point is that, contrary to wind blown sand pile, this experiment is able to produce small scale dunes that propagate with the same characteristic height/velocity relation, without disappearing. This is also surprizing as the mechanisms for the grain motion are quite different in water and in air. In the latter case, the grains jump in air and dislodge other grains when colliding back the sand bed. In water, the viscosity is high enough to reduce the effect of collisions on the sand bed: the grains are directly dragged by the fluid. This shows that it is the existence of sand flux which is important, and not the precise physical mechanisms involved in the particle motion. The coincidence of the shapes also shows that it is only the similarity of the global geometries of the flow around the dune which matters.

At the same time the efficiency of the rescaling proves that it is this saturation length which governs the dune shape and dynamics as was proposed by Bagnold. In favor of this rescaling, we can also point out that we also recover the existence of a minimal size in our experiment. The smallest observed aquatic dune presents a height $H_0 \sim 0.5$ mm of the order of $l_{\mathrm{drag}}$ (Fig. 6) and a width of the order of 20 times $l_{\mathrm{drag}}$ (Fig. 6). In the desert, the minimum height can be approximately found from field measurements [4–6] of the order of $l_{\mathrm{drag}}$ too. This experiment thus allows one to obtain small scale dunes with all the characteristics of barchans by reducing this saturation length. Apart from the scale reduction in time and space, an essential interest of such an experiment is that, now, all the ingredients can be controlled: the input of grains, the wind strength, and its variations.

Hence this experiment can be used to study precisely all the fundamental questions about sand and wind interactions, namely, dune shape selection and dynamics.


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