

DIRECT VALIDATION OF DUNE INSTABILITY THEORY C. Narteau¹, P. Lü², Z. Dong², P. Claudin³, S. Rodriguez¹, Zhishan An⁴, Laura Fernandez-Cascales¹, Cyril Gadal¹ and S. Courrech du Pont⁵. ¹Université de Paris, Institut de Physique du Globe de Paris, CNRS (F-75005 Paris, France, narteau@ipgp.fr), ²School of Geography and Tourism, Shaanxi Normal University (620 Chang'an West Av., Xi'an, Shaanxi 710119, China, lvping@lzb.ac.cn), ³Northwest Institute of Eco-Environment and Resources (320 West Donggang Road, 730000 Lanzhou, Gansu, China, anzhishan@lzb.ac.cn), ⁴Physique et Mécanique des Milieux Hétérogènes, CNRS, ESPCI, PSL, Sorbonne Univ., Université de Paris (10 rue Vauquelin, 75005 Paris, France, claudin@pmmh.espci.fr), ⁵Laboratoire Matière et Système Complexes, Université de Paris, CNRS (Bâtiment Condorcet, 10 rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France, sylvain.courrech@univ-paris-diderot.fr).

Introduction: Dune research has always been stimulated by the question of the origin of periodic bedforms that are ubiquitous in planetary sand seas at all scales. However, the size-selection mechanism associated with the emergence of periodic dunes have never been observed and quantified in a natural aeolian environment.

Underwater experiments have shown that, as soon as the flow is strong enough to transport grains, a flat sand bed destabilizes into periodic bedforms migrating at a constant speed [1]. Wind tunnel experiments and Ralph Bagnold's attempts in the field to create artificial dunes have failed because the initial sand piles were not large enough [2]. There is indeed a minimum length-scale for the formation of dunes, which has been estimated to be of the order of 10 m in aeolian systems on Earth based on the smallest wavelength of the superimposed bedforms observed on the flanks of large dunes [3]. After 20 years of intensive research, this characteristic length-scale is assumed to be regulated by the balance between a destabilizing process associated with the turbulent flow response to the topography and a stabilizing process due to transport inertia.

Linear stability analysis of flat sand beds sheared by a fluid flow provide the so-called dispersion relation [4-7], i.e., the growth rates $\sigma(k)$ of sinusoidal bed perturbations over the whole range of possible wave numbers k (wavelength $\lambda=2\pi/k$). These stability analysis are by definition restricted to the linear regime of incipient dune growth, the period during which the amplitude of each mode (wavelength) grows exponentially and independently from one another. The theoretical relation writes

$$\sigma(k) = Q k^2 (B - A k l_{\text{sat}}) / (1 + (k l_{\text{sat}})^2),$$

where Q is the mean sand flux and l_{sat} the distance required for the sand flux to reach saturation (i.e., transport inertia). The perturbation of wind streamlines is described with the aerodynamic parameters A and B . Here we present the results of a long-term field experiment in which we have been able to measure in

the same desertic area all these parameters. Thus, we obtain a comprehensive description of incipient dune growth under the natural action of wind, which is directly confronted to the dune instability theory [8].

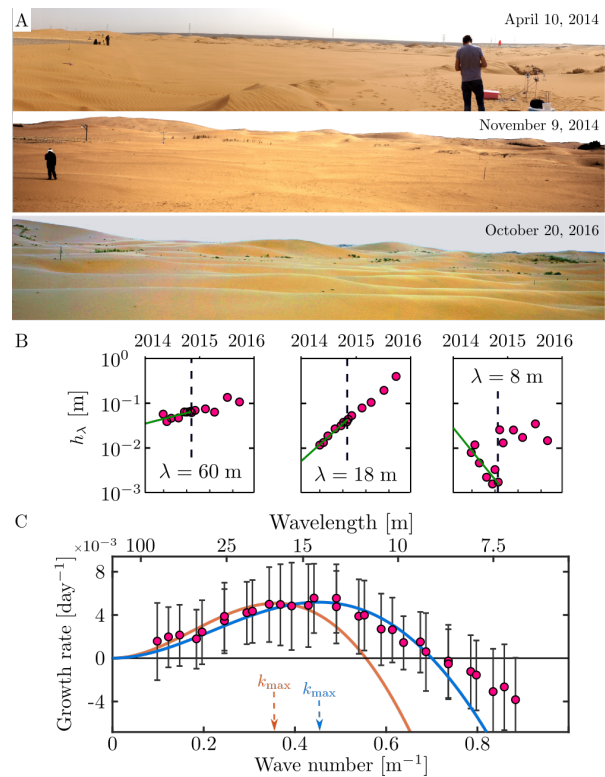


Figure 1: (A) The sand bed after flattening (top), incipient dunes at the end of the linear phase of dune growth (middle) and mature dunes during the non-linear phase (bottom). (B) Amplitude of different wavelengths with respect to time. Vertical dashed lines on October 30, 2014 show the transition from the linear and non-linear phases. (C) The experimental dispersion relation during the linear phase (dots). Solid lines show theoretical dispersion relations (see equation) using the best fit to the data $\{l_{\text{sat}}, A, B\} = \{0.7, 1.96, 0.96\}$ (blue) and the parameters independently measured in the field $\{l_{\text{sat}}, A, B\} = \{0.95, 3, 1.5\}$ (orange). In both cases, $Q = 18.4 \text{ m}^2 \text{ yr}^{-1}$. k_{max} is the most unstable mode (wavelength).

Method: The landscape scale experiments have been conducted from April 2014 to November 2017 [8-9]. Preexisting dunes were leveled to form a flat rectangular bed 100 m long and 75 m wide (Fig. 1A). The long axis of this rectangular area is aligned with the direction of the primary wind. We monitored dune growth over the following 42 months through a series of 20 topographic surveys using a ground-based laser scanner. To get a better resolution on the early stage of dune growth and to account for windy periods, these topographic data are more frequent in 2014 as well as in the spring and fall of each year.

Results: Using an impact sensor placed above a flat sand bed, we monitored saltation activity under winds of varying strength and estimate the threshold wind speed for aerodynamic entrainment of sand grains, $u_{th}=0.23\pm0.04$ m/s [8]. Combining this threshold value with local wind data, we calculate a mean saturated sand flux $Q=18.4\pm4.2$ m²y⁻¹. To estimate the saturation length, we measure after a wind event the erosion profile of a 12-m-long, 3-m-wide, and 20-cm-high flat sand berm built immediately downwind of the bed covered with gravels. We obtain $l_{sat}=0.95\pm0.2$ m [8]. To estimate the values of the aerodynamic parameters A and B , we recorded wind speed at heights of 4, 12, 50, and 100 cm above the bed by moving an anemometer mast upwind of a known elevation dune profile, which includes a succession of crests and troughs. Based on the upwind shift (≈ 1 m) and the amplitude of the perturbation in wind speed recorded by the two bottom anemometers, we get $A=3\pm1$ and $B=1.5\pm0.5$ for dune aspect ratios varying from 0.012 to 0.025 [8].

For each topographic survey, we performed a spectral decomposition of the elevation data to isolate the contribution of individual modes (wavelengths) to the overall topography. The variation of the amplitude of these surface waves is not homogeneous over time and displays a sudden change in rate at the end of 2014 (Fig. 1B) for a mean slope of the order of 0.03. We ascribe it to the transition from the linear to the nonlinear phases of the dune growth instability. During the linear phase, we obtain the experimental dispersion relation of the dune instability by plotting the growth rate of the different modes as a function of their wave number k (Fig. 1C). It provides eolian experimental evidence of the difference in growth rates of nascent dunes of various wavelengths when they are not large enough to generate flow recirculations. These results are consistent with the theoretical prediction of the linear stability analysis with a clear maximum and a continuous trend from unstable (growing waves, $\sigma > 0$) to stable regimes (decaying waves, $\sigma < 0$). The most

unstable mode corresponds to the wavelength of the emerging dune pattern in the field (≈ 15 m); the neutral mode ($\sigma = 0$) is about 9 m [8].

Concluding remarks: In a unique landscape scale experiment, we verify that dunes can emerge from a flat sand bed and elucidate the origin of periodic bedforms, showing the wavelength selection as dunes increase in height. We provide an original dataset for an in-depth understanding of the linear phase of the dune instability, when the growth rates of the different modes evolve independently from each other. We find that this linear phase is at work from the earliest stage of dune growth, as soon as sand transport starts even when, at first glance, no regular structure seems to be in place. When periodic dunes are observed, the nonlinear phase has already taken over, aerodynamic nonlinearities have developed, and the different modes interact with each other to lead to pattern coarsening [8].

Based on our comprehensive assessment of the dune instability, we show here that successive topographic surveys and spectral analysis can be combined to characterize different environments on Earth and other planetary bodies where dunes actively participate in landscape dynamics. We provide quantitative evidence that such an inverse problem can be solved over relatively short timescales relative to those involved in the dynamics of major dune systems. This approach can be used to remotely assess sediment and atmospheric quantities. It is particularly relevant on planetary and cometary surfaces where bedforms can grow under exotic conditions with unusual parameter values.

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