

**A UNIFIED MODEL OF RIPPLES AND DUNES IN WATER AND PLANETARY ENVIRONMENTS.** O. Duran Vincent<sup>1,2</sup>, B. Andreotti<sup>3</sup>, P. Claudin<sup>3</sup> and C. Winter<sup>1,4</sup>, <sup>1</sup>MARUM Center for Marine Environmental Sciences, Bremen University, Leobener Str., D-28359 Bremen, Germany, <sup>2</sup>Department of Ocean Engineering, Texas A&M University, College Station, TX 77843-3136, USA ([oduranvinent@tamu.edu](mailto:oduranvinent@tamu.edu)), <sup>3</sup>Laboratoire de Physique et Mécanique des Milieux Hétérogènes, PMMH UMR 7636 ESPCI – CNRS – Univ. Paris-Diderot – Univ. P.M. Curie, 10 rue Vauquelin, 75005 Paris, France, <sup>4</sup>Institute of Geosciences, Christian-Albrechts University Kiel, Otto-Hahn Pl. 1, D-24116 Kiel, Germany.

The emergence of bedforms as result of the coupling between a fluid flow and sediment transport is a remarkable example of self-organized natural patterns. Subaqueous bedforms generated by unidirectional water flows, like ripples, dunes or compound bedforms, have been shown to depend on grain size, water depth and flow velocity. However, this variety of morphologies, empirically classified according to their size, was not understood until recently in terms of mechanical and hydrodynamical mechanisms [1]. Here we present a process-based model [1] that simultaneously explain the scaling of bedforms for Water, Air, Mars and Venus, and can be potentially applied to other planetary bodies such as Titan or Pluto. The model couples hydrodynamics over a modulated bed to sediment transport and relaxation laws, and resolves pattern coarsening from initial to mature bedforms (Fig. 1).

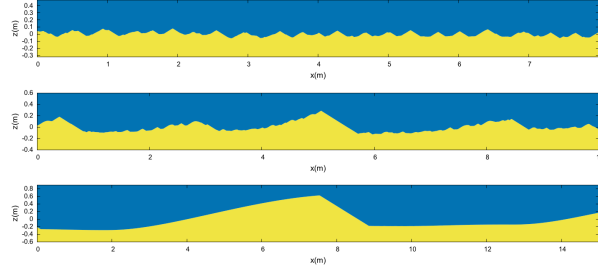


Figure 1: Example of simulated subaqueous bedforms. From top to bottom: stable mature ripples, dunes with superimposed stable ripples and dunes without ripples, corresponding to grain-based Reynolds numbers  $\mathcal{R}_d = 3, 10$  and  $35$ , respectively.

We identify two types of bedforms created by a hydrodynamic instability in the limit of large flow thickness: those inducing an inertial hydrodynamic response and those inducing a turbulent hydrodynamic response. They are separated by a gap in wavelength explained in terms of an hydrodynamic anomaly that leads to a shift of the position of the maximum shear stress from upstream to downstream of the crest. This anomaly gradually disappears when the bed becomes hydrodynamically rough. These bedform types are consistent with subaqueous ripples and dunes, which then represent a suitable reference

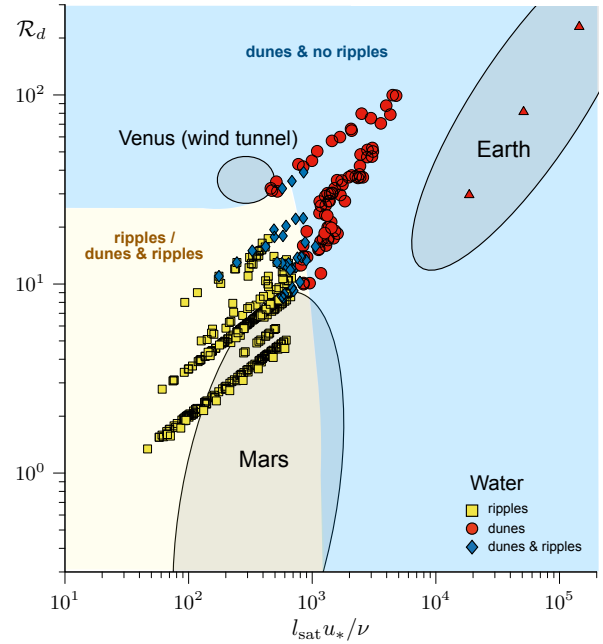


Figure 2: Phase diagram of ripples and dunes. Presence of ripples and/or dunes as function of the rescaled saturation length  $l_{\text{sat}} u_* / \nu$  and grain-based Reynolds number  $\mathcal{R}_d$ . The two distinct regimes are defined by the presence or absence of stable ripples. Symbols corresponds to water and water/glycerin mixture data and aeolian (Earth) data, both for monodisperse sand. Shadow areas correspond to ranges for different planetary conditions.

to classify bedforms in other environments (Fig. 2).

For monodisperse sand and non-suspended transport in the limit of large flow thickness, the parameter space physically relevant to determine bedform morphology is based on two strongly correlated dimensionless numbers,  $\mathcal{R}_d$  and  $l_{\text{sat}} u_* / \nu$ . The grain-based Reynolds number  $\mathcal{R}_d$  encodes the hydrodynamic roughness and controls the appearance of the hydrodynamic anomaly. The rescaled saturation length  $l_{\text{sat}} u_* / \nu$  depends on the dominant mode of sediment transport and determines the initial wavelength. The occurrence of ripple-like and dune-like bedforms is controlled by two different thresholds: the rough transition at  $\mathcal{R}_d \approx 20$ , and the stabilising effect of transport relaxation at  $l_{\text{sat}} u_* / \nu \approx 10^3$ . When-

ever ripples are present, the size of the viscous sublayer  $\nu/u_*$  determines the scale of the maximum size of steady state ripples and the minimum size of emerging dunes. When only dunes are possible, their minimum size scale with the transport saturation length. Our findings provide a unifying framework to understand planetary bedforms and suggests a correspondence between bedforms in different environments based on the formation mechanism.

## References

- [1] Orencio Duran Vincent, Bruno Andreotti, Philippe Claudin, and Christian Winter. A unified model of ripples and dunes in water and planetary environments. *Nature Geoscience*, 12(5):345–350, May 2019. ISSN 1752-0894, 1752-0908. doi: 10.1038/s41561-019-0336-4.