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A unified model of bedforms across the turbulent roughening transition

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The emergence of bedforms as result of the coupling between fluid flow and sediment transport is a remarkable example of self-organized natural patterns. The size of subaqueous and aeolian bedforms generated by unidirectional water or wind 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, is still not understood in terms of mechanical and hydrodynamical mechanisms. Here, we provide a physical explanation for bedform formation that disentangles the different regimes and show that the change of morphology is associated with an anomalous hydrodynamic response to relief in the range of wavelength exciting the turbulent transition. This anomaly gradually disappears in the rough regime. Our conclusions are based on a quantitative, yet reductionist, numerical model that couples hydrodynamics over a modulated bed to sediment transport and resolves both initial and mature bedforms. Numerical predictions are tested for subaqueous and aeolian bedforms, for which all components of the theory are independently calibrated. The resulting classification of hydrodynamical regimes provides a new mechanistic framework to compare ripples and dunes in Mars and Venus planetary environments to their terrestrial counterparts.