Geophysical Research Abstracts
Vol. 21, EGU2019-18518, 2019
EGU General Assembly 2019

Phase transitions in geophysical flows

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Phase transitions abound in geophysical flows. For example: Apparently solid soil fails to produce landslides; apparently static river beds commence bed-load transport at a critical stress; bed load becomes suspended; and submarine debris flows transition to turbidity currents. Each phase of transport is modeled indepedently, but such models have little to say about the transitions themselves. The standard Mohr-Coulumb failure criterion for the yield transition — which is more-or-less the model for both landslide failure and the onset of bed-load transport — does not account for sub-critical creep. Recent progress in the physics of grains and glasses provides a new framework for collecting these disparate flow transitions and understanding their origins. In particular: (1) A dynamical view of yield for glassy materials describes the percolation of plastic rearrangements giving rise to failure; and (2) a unification of granular and suspension rheology provides a compact description of friction μ as a function of dimensionless shear rate I, the so-called "$\mu(I)$ rheology". We present a set of experiments that examine phase transitions on fluid-particle flows through the lens of (1) and (2). An annular flume sets up laminar sediment transport by driving the motion of plastic beads with a viscous oil. Using refractive-index matched scanning, we image and track particles in the interior of the flow (away from the walls), from the fluid-sediment interface to 30-particle diameters down. Particle velocities observed from milliseconds to months cover almost the entire range of geophysical flows in nature; surface grains move 10 million times faster than grains at the bottom, spanning suspension to creep. We demonstrate that the creep $\rightarrow$ bed-load transition is a continuous one consistent with a glass transition, and inconsistent with Mohr-Coulumb models, and also that the entire range of bed load to suspension may be described by $\mu(I)$ rheology. We then use numerical experiments of a dry-granular heap flow to show that the creep $\rightarrow$ landslide transition is identical. Finally, we present findings from new experiments on the generation of turbidity currents, and sub-critical creep in a sandpile, to demonstrate the generality of these concepts to a wide range of geophysical flows.