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Floating extensional flows

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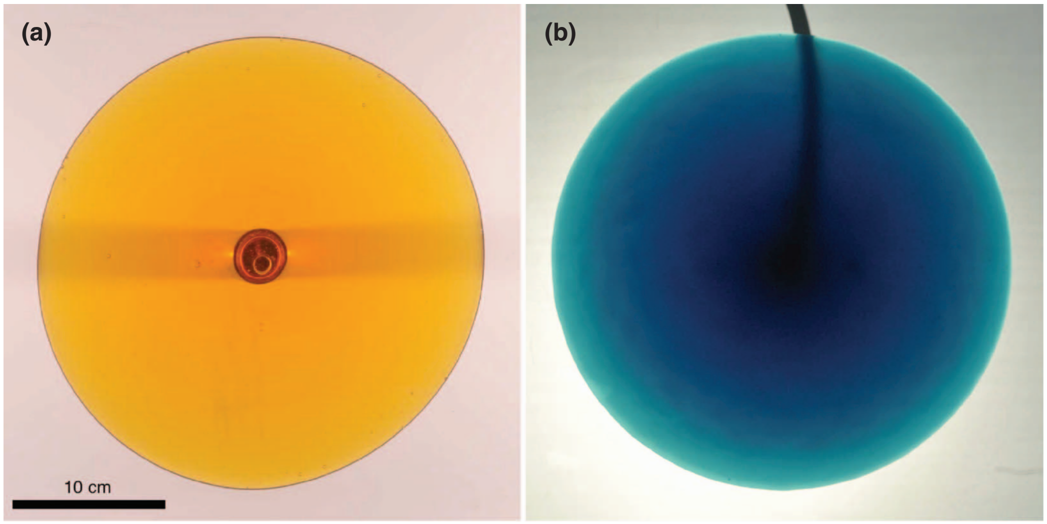

FIG. 1. Photographs (plan view) of viscous-gravity-current experiments at constant flux on a flat surface and in a cylindrical geometry using golden syrup (a) and an aqueous suspension of Xanthan gum (b). The scale applies to both (a) and (b).

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Ice sheets spread like viscous gravity currents into the surrounding oceans. As they spread they thin and can detach from the bed, owing to the hydrostatic pressure of the ocean, and float as ice shelves. The detachment position is a contact line that separates a grounded, shear-dominated flow and a floating, extension-dominated flow. Differences between these two flow regimes can be intensified because of the complex rheology of ice. In particular, floating shelves can fracture and potentially shatter, which may ultimately affect the stability of ice sheets and lead to a catastrophic rise in sea level.

We explore fundamental aspects of this problem using laboratory experiments. We model the flow of ice sheets as viscous gravity currents that propagate in a circular geometry, and focus on the influence of the fluid rheology on the flow pattern. In particular, we study the Newtonian limit using golden syrup, and the non-Newtonian response using an aqueous suspension of Xanthan gum. The latter deforms as a shear-thinning, power-law fluid,[1] and therefore may represent a more realistic analog to ice. We perform two sets of experiments: the first of gravity currents that propagate over a flat surface; the second of gravity currents that propagate into a denser, inviscid fluid that represents a steady ocean.

In the first set of experiments (Fig. 1) the viscous fluid is released at constant flux onto a flat, rigid surface. The no-slip boundary conditions at the flat interface lead to a shear-dominated flow throughout the domain, and the current is axisymmetric throughout the evolution for both the Newtonian (Fig. 1(a)) and the non-Newtonian fluids (Fig. 1(b)).

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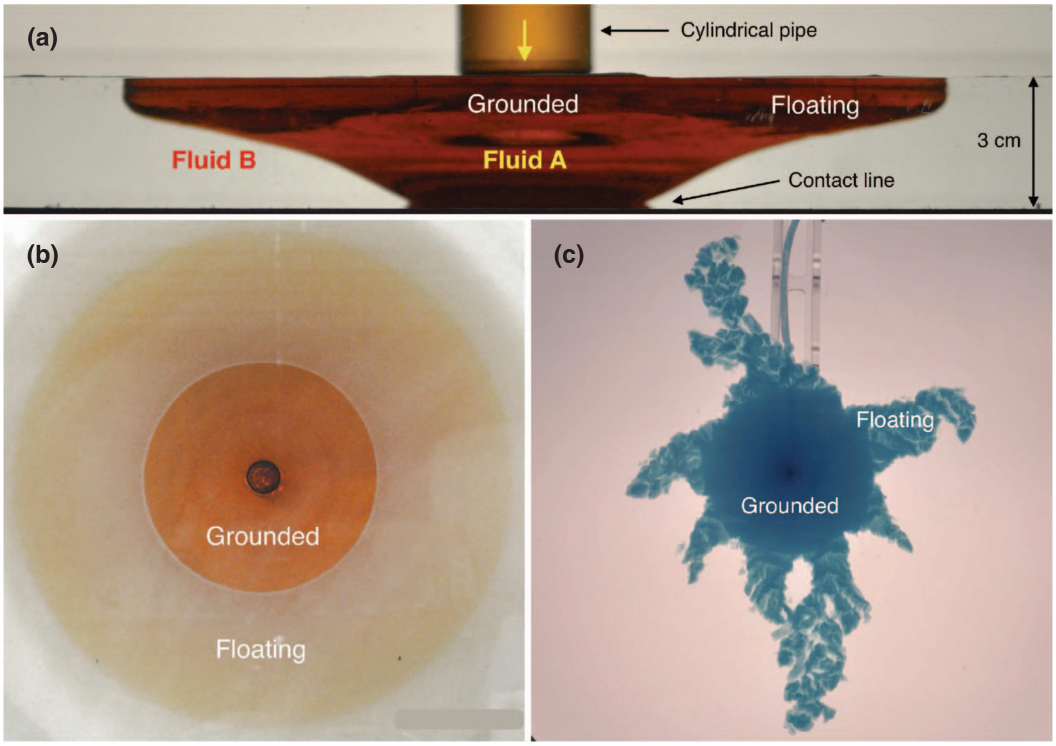

FIG. 2. Photographs of viscous gravity currents penetrating a denser inviscid fluid at constant flux and in a cylindrical geometry. (a) A side view of the apparatus showing a viscous fluid (A, dark colour) flowing under gravity from a vertical pipe into a tank filled with a denser, inviscid fluid (B, transparent). The thicker region of fluid A near the source is grounded to the base of the tank, and outside that region fluid A is floating. (b,c) Bottom views of an experiment using golden syrup (A), and an experiment using an aqueous suspension of Xanthan gum (A), respectively (enhanced online) [URL: http://dx.doi.org/10.1063/1.4747184.1].

In the second set of experiments the viscous fluid (fluid A in Fig. 2(a)) is released at constant flux into a tank filled with a denser, inviscid fluid (fluid B in Fig. 2(a)). In the vicinity of the source the gravity current is sufficiently thick to remain grounded to the flat bottom of the tank, and therefore this part of the flow is dominated by vertical shear. The radially diminishing thickness and the buoyancy force exerted by the ambient fluid lead to detachment of the viscous fluid from the bottom and the formation of a floating region where the flow is extensional (Fig. 2(a)). The contact line that separates the two regions remains circular and propagates radially.

When fluid A is Newtonian, the grounded and the floating regions are both axisymmetric (Fig. 2(b)) throughout the flow evolution.[2] However, with the non-Newtonian suspension the axisymmetry of the flow breaks down across the contact line and a structural set of floating tongues emerges (Fig. 2(c)). The part of the tongues near the contact line stretches azimuthally as the unsteady contact line propagates and eventually the tongues split in two. This symmetry breaking may be due to the sharp decrease of shear-rates across the contact line and the simultaneous increase of viscosity in the extension-dominated region.

The dynamics we present have the potential to advance better understanding of the breakup mechanisms of ice shelves and of ice-sheet stability.

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[1] R. Sayag and M. G. Worster, "Axisymmetric gravity currents of power-law fluids over a rigid horizontal surface," J. Fluid Mech. (submitted).
[2] S. S. Pegler and M. G. Worster, "Dynamics of curved grounding lines" (unpublished).