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Gallery of Fluid Motion

Lab icebergs melt down and flip out

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Ice in nature is dynamic at all scales, from glacial sheets that deform and flow to icebergs that melt down and capsize [1,2]. For the latter, much of the ice and much of the action is unseen beneath the surface [3–5]. Here we study laboratory-scale icebergs that freely float and melt, where direct visualizations show interesting and interconnected changes in the shape of the ice, its posture, and the flows of the surrounding water.

Our experiments reveal that free-floating ice persistently melts into unstable geometries, causing it to repeatedly capsize. Figure 1 shows the shape progression for a cylindrical piece of ice floating at the surface of room temperature water. It locks to an orientation, melts in place for several minutes, then abruptly rotates to a new posture and again locks. This process repeats for about 10 to 15 flips over the 30 minutes it takes to melt away. The photographs sample some of the locked orientations. Figure 2 displays the flows of the melt waters beneath the iceberg, where the two photos capture views along the axis and from the side, respectively. Below we describe the specialized techniques that enabled these images.

We start by making pure ice free of contaminants. Freezing typically proceeds outside in and inevitably traps bubbles and other impurities that cloud the ice and which may affect its posture while floating and disturb the flows during melting. We make pure ice by a directional freezing method in which the solid grows bottom up while the liquid is stirred [6]. This ensures that the dissolved gases and contaminants expelled from the solid do not accumulate at the freezing front but escape upward into the liquid. Cylindrical molds made of freezer-safe plastic are dipped into a bath of supersaturated salt water in a chest-style freezer. The water in the mold is continuously recirculated by a gear pump whose intake and outflow tubes are inserted through the top of the mold. The pumping action slightly warms the water while the bath strongly conducts heat away, causing ice to form at the bottom. Successively immersing the mold deeper and lowering the pump rate yields crystal-clear ice topped by a layer of concentrated contaminants that are cut away after removal from the mold. Trial-and-error refinement of the procedures allows cylinders 8 cm in diameter and 20 cm high to be grown over about 30 hours.

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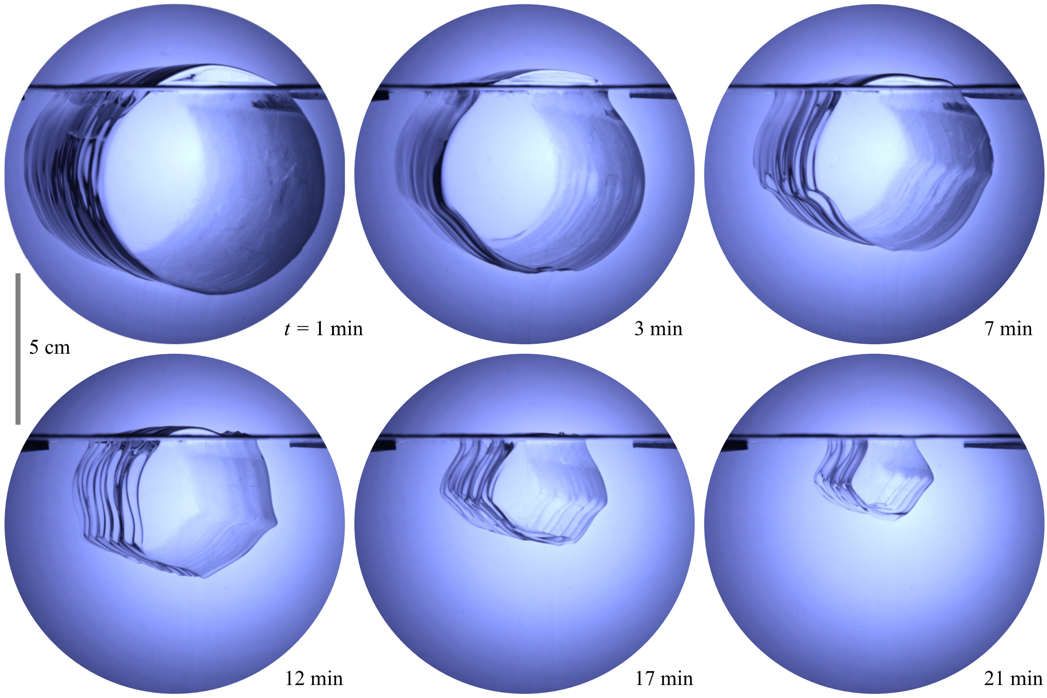

FIG. 1. A laboratory iceberg melting in room-temperature water. The ice repeatedly locks to an orientation then abruptly flips. The face shape develops corners and facets while the sides are patterned with waves.

Clear ice is nearly invisible when placed in the large glass tank used for our melting experiments, whose setup is shown in Fig. 3(a). We visualize the shape and posture by a method that uses gradients in background lighting to highlight the difference in refractive index of liquid water and ice [6]. A display monitor behind the tank is lit up with an intensity field that is controlled through a computer and custom Matlab script. We employ a circular design that is brightest at the middle and fades outward to black. The ice water interfaces in Fig. 1 appear sharp due to refraction, from which one sees facets and corners in the shape of the face or cross section. The camera is positioned at the height of the waterline (which conveniently remains fixed as the ice melts), and posing the ice at an angle helps to show the wavy patterns along the sides.

Free-floating ice tends to drift out of the camera view. To enable the consistent views achieved in Figs. 1 and 2, we devised a method that loosely confines the ice while allowing it to freely roll over. The ice is trapped without direct contact by exploiting the same surface-tension interactions that underlie the so-called Cheerios effect [7]. The tip of the iceberg that breaches the water surface is met on either side by upward-bending menisci. We devise a "capillary trap" by positioning thin bars that run parallel along either side of the ice and at several centimeters away [Fig. 3(a)], and which are slightly depressed below the surface to form negative menisci. This arrangement causes the ice to be repelled via capillary interactions from both sides and therefore stably centered between the bars. Covering the upper surfaces of the bars with hydrophobic wax helps to prevent spillover, and incrementally moving the bars inwards over time keeps an appropriate distance with the shrinking ice.

Finally, we visualize the flows around and beneath the ice by again exploiting refractive index, which slightly differs throughout the liquid due to varying temperature and density. We use the color schlieren method that transmits collimated white light through the sample and focuses it through color filters [8]. The rays deflect one way or another depending on the local index of the fluid through which they pass and therefore show up on a camera as different colors and intensities via the design of the filter. We use the Z-shaped optical assembly shown in Fig. 3(b): light from a

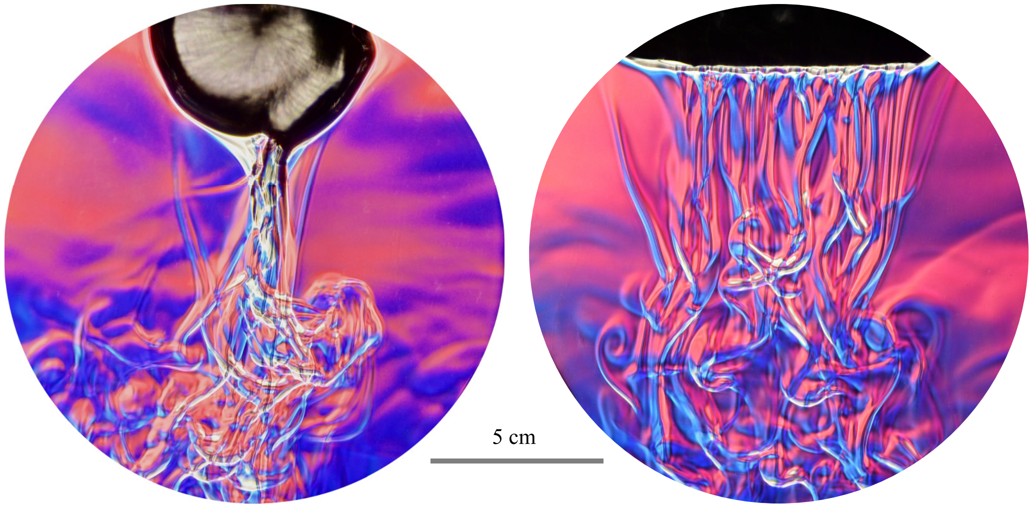

FIG. 2. Color schlieren imaging of the flows from views along the axis of the ice and from the side. The cold, dense melt waters course downward along the ice in boundary layers that detach at the bottom in plumes.

bright source passes through a pinhole iris, travels to a spherical mirror that reflects and collimates it through the sample (here a water tank with floating ice), after which it reflects off a second mirror so as to focus through filters and into a camera. The results are sensitive to many details, especially the placement and coloration of the filters. The photos of Fig. 2 were obtained by drawing stripes with red, blue, and purple markers on glass and finely adjusting their placement and orientation near the focal region. The images reveal boundary-layer flows of cold, dense liquid that detach at the bottom in drips, whose regular spacing may be related to the most unstable wavelength that appears in the stability analysis of the Rayleigh-Bénard problem [9,10].

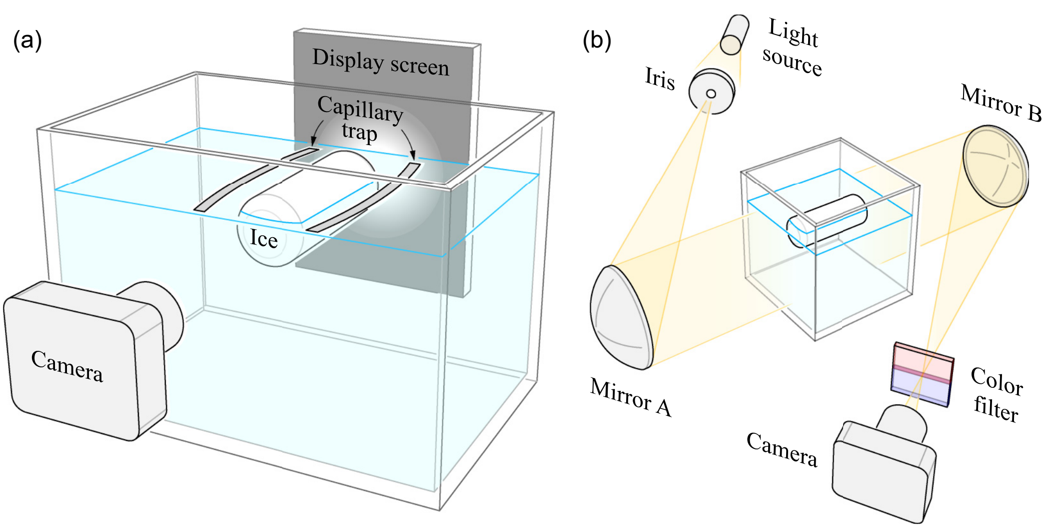

FIG. 3. Experimental setups. (a) System for imaging ice shape and flip dynamics. Free-floating ice is loosely confined by capillary traps, and a camera captures the shape and motion against a background provided by a computer-controlled display screen. (b) System for imaging flows. A Z-configuration schlieren optical assembly causes gradients in refractive index to appear as variations in intensity and color.

The methods combine to shed light on why ice flips as it melts down, how repeated flips create a quasipolygonal shape, and why the surface becomes patterned with waves. Once the ice locks into position, the wetted undersurface melts significantly faster than the top portion exposed to air, and this mismatch causes cornerlike features to appear at the waterline. Melting from below also leaves the body increasingly top heavy and therefore gravitationally unstable, which eventually triggers a capsize event. The ice then settles into a new gravitationally stable position that typically has a corner at one of the intersections with the waterline, and subsequent melting thereby carves another corner at the other intersection. When repeated over many flips, the ice cross section is patterned with quasiregularly spaced corners that yield the polygonlike shapes seen in Fig. 1. All the while, the flows of the cold melt waters drip off the body in plumes whose regularity is imprinted as undulations on the surface, as seen in Fig. 2.

Ice in nature differs from our experiments in terms of the melting conditions, including the temperature range of the surrounding water and its salinity [2–5]. These and other factors could also be investigated in laboratory experiments where their effects can be understood at fundamental scales. Better understanding the coupled ways that melting and movement influence one another could lead to improvements in models of the capsizing and dispersal of icebergs in the oceans, which are factors in global climate models [2]. Visualizations can play useful roles by informing on the physics of melting and bringing attention to these timely problems.

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