Rewriting the equation for deformation and flow of watery glacier ice

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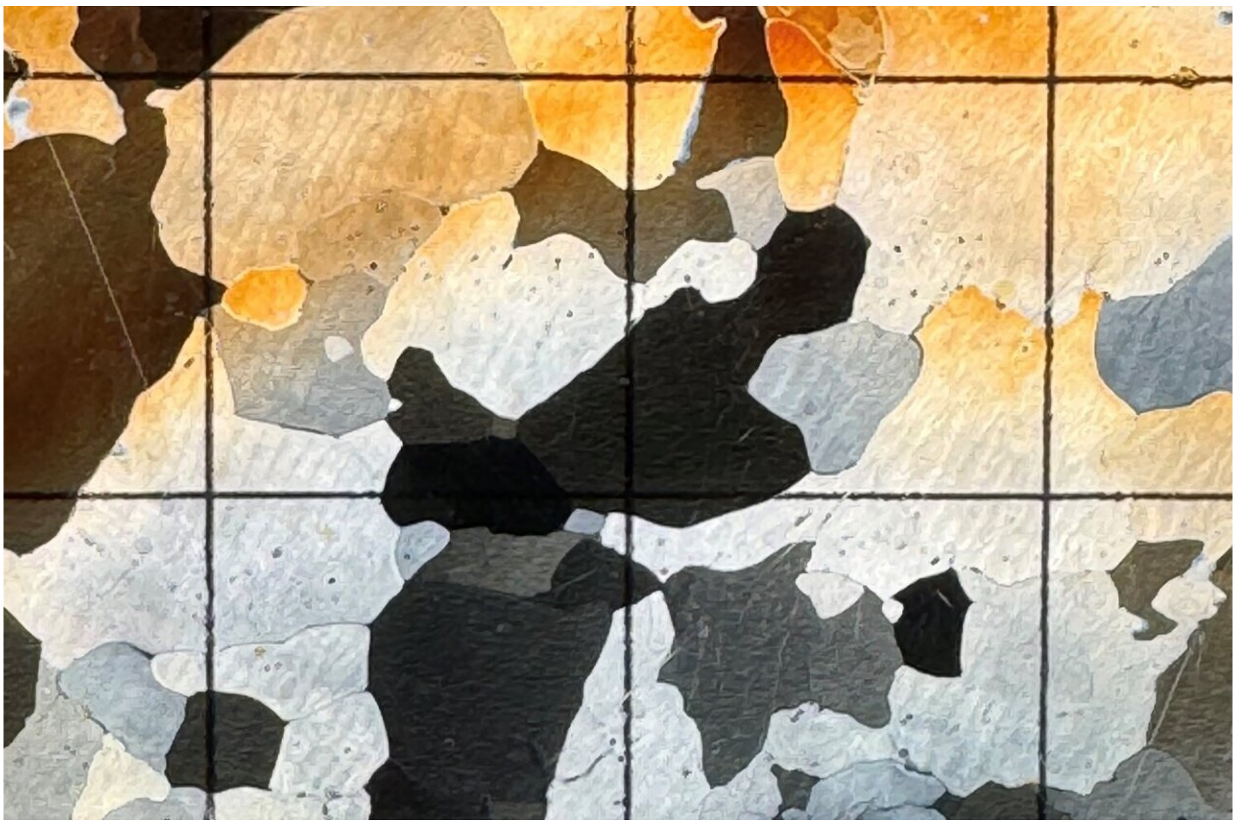


This polarized light image shows ice grains deformed in experiments with the ring-shear device in Neal Iverson's Iowa State laboratory. The experiments show that grains, on average, grow about 3 times larger during experiments and develop more irregular boundaries. The different colors indicate different orientations of the grains. Credit: Neal Iverson

Neal Iverson started with two lessons in ice physics when asked to describe a research paper about glacier ice flow that has just been published in the journal *Science*.

First, said the distinguished professor emeritus of Iowa State University's Department of the Earth, Atmosphere, and Climate, there are different types of ice within glaciers. Parts of glaciers are at their pressure-melting temperature and are soft and watery.

That temperate ice is like an ice cube left on a kitchen counter, with meltwater pooling between the ice and the countertop, he said. Temperate ice has been difficult to study and characterize.

Second, other parts of glaciers have cold, hard ice, like an ice cube still in the freezer. This is the kind of ice that has typically been studied and used as the basis of glacier flow models and forecasts.

The new research paper, "Linear-viscous flow of temperate ice," deals with the former, said Iverson, a paper co-author and project supervisor.

The paper describes lab experiments and the resulting data that suggest that a standard value within the "empirical foundation of glacier flow modeling"—an equation known as Glen's flow law, named after the late John W. Glen, a British ice physicist—should be changed for temperate ice.

The new value, when used in the flow law, "will tend to predict increases in flow velocity that are much smaller in response to increased stresses caused by ice sheet shrinkage as the climate warms," Iverson said. That would mean models will show less glacier flow into oceans and project less sea-level rise.

An acute need to account for warm glacier ice

Open the walk-in freezer in Iverson's campus lab and you're looking at a 9-foot-tall ring-shear device that's been simulating glacial forces and movement since 2009.

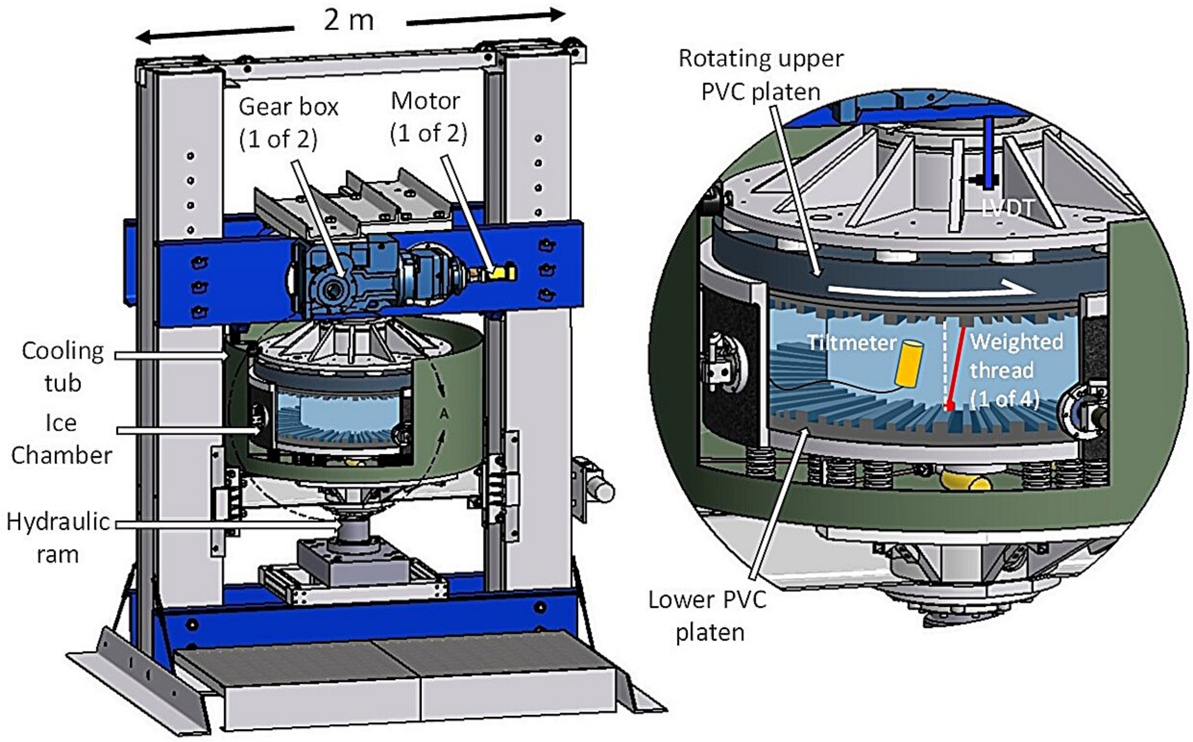
At the center of the device is a ring of ice about 3 feet across and 7 inches thick. Below the ring is a hydraulic press that can put as much as 100 tons of force on the ice and simulate the weight of a glacier 800 feet thick. The ice ring is surrounded by a tub of circulating fluid that regulates the ice temperature to the nearest hundredth of a degree. Electric motors attached to a plate with grippers above the ice ring can rotate the ice at speeds of 1 to 10,000 feet per year.

For this project, researchers modified the device by adding another gripper to the bottom of the ice ring so that rotation of the upper gripper shears the underlying ice.

Collin Schohn, a former master's degree student at Iowa State who's now a geologist with the BBJ Group based in Chicago and is the first author of the group's latest research paper, ran a series of six experiments using the modified device, each experiment lasting about six weeks. The experiments included measurements of the ice's liquid water content, something that hadn't been done in these kinds of experiments since the 1970s.

"These experiments involved deforming the ice at its melting temperatures and at various stresses," Schohn said.

Iverson likened the experiments to grabbing a bagel at the top and the bottom, then twisting the two halves to smear the cream cheese in the middle.



The ring-shear device in Neal Iverson's laboratory. Credit: Neal Iverson

The experimental data showed that ice deformed at a speed that was linearly proportional to the stress, Iverson said. Traditional thinking would have researchers expecting ice to soften with increasing stress, so increments in stress would cause increasingly large increments in speed.

Why does all this matter?

Ice is temperate near the bottoms and edges of the fastest-flowing parts of ice sheets and in fast-flowing mountain glaciers, both of which shed ice into oceans and influence sea level. "The need to model and forecast accurately the flow of warm glacier ice is, therefore, acute," the authors wrote.

Resetting n to 1.0

Glen's flow law is written as: $\dot{\varepsilon} = A\tau^n$.

The equation relates the stress on ice, τ, to its rate of deformation, $\dot{\varepsilon}$, where A is a constant for a particular ice temperature. Results of the new experiments show that the value of the stress exponent, n, is 1.0 rather than the usually assigned value of 3 or 4.

The authors wrote, "For generations, based on Glen's original experiments and many subsequent experiments mostly on cold ice (-2 degrees C and colder), the value of the stress exponent n in models has been taken to be 3.0." (They also wrote that other studies of the "cold ice of ice sheets" have placed n higher yet, at 4.0.)

That was, in part, "because experiments with ice at the pressure-melting temperature are a challenge," said Lucas Zoet, a paper co-author, a former postdoctoral research associate at Iowa State and the Dean L. Morgridge Associate Professor of geoscience at the University of Wisconsin-Madison. Zoet, a co-supervisor of the project, has built a slightly smaller version of the ring-shear device with transparent walls for his laboratory.

But data from the large-scale, shear-deformation experiments in Iverson's lab raised questions about the assigned value for n. Temperate ice is linear-viscous (n = 1.0) "over common ranges of liquid water content and stress expected near glacier beds and in ice stream margins," the authors wrote.

They proposed that the cause is melting and refreezing along the boundaries of individual, millimeter-to-centimeter-scale grains of ice, which should occur at rates linearly proportional to the stress.

This new data allows modelers "to base their ice sheet models on physical relationships demonstrated in the laboratory," Zoet said. "Improving that understanding improves the accuracy of predictions."

It took some perseverance to get the data supporting the new value of n.

"We had been batting this project around for years," Schohn said. "It was really hard to get this to work."

In the end, Iverson said, "considering all the failures and development, this was about a 10-year process."

A long process, the researchers said, that's essential for more accurate models of temperate glacier ice and better predictions of glacier flow and sea-level rise.

More information: Collin M. Schohn et al, Linear-viscous flow of temperate ice, *Science* (2025). DOI: 10.1126/science.adp7708

Provided by Iowa State University

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