middle to late Pleistocene, Earth experienced sea-level changes that were similar in magnitude to those in the middle to late Pleistocene. The researchers hypothesize that the long-term cooling, which they reported in 2024, caused the Southern Ocean to become more stratified, which would have resulted in atmospheric carbon being stored in deep water for long periods of time. As glaciation intensified, sea level dropped precipitously and reached as low as 150 m below today's sea level multiple times throughout the Pleistocene, including about 21 000 years ago, during the Last Glacial Maximum.

Alex Lopatka

Reference

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Micron-sized wave pools offer insights into nonlinear wave dynamics

Superfluid helium flowing on a silicon wave flume operates in a regime of nonlinear hydrodynamics that conventional fluid experiments can't access.

Nonlinear wave dynamics are challenging to model computationally. To validate theoretical models, researchers often rely on the results of experiments done with wave flumes—long channels filled with water, much like the Scottish canal where, in 1834, John Scott Russell first observed long-lived solitary waves, now commonly known as solitons (see the 2012 Physics Today story "Interacting solitary waves"). Flumes are used to study nonlinear hydrodynamics that emerge in shallow-water waves, like tsunamis, tidal bores, and turbulence. But even the largest constructed wave flume, the 300-m-long Delta Flume in Delft, the Netherlands, can't replicate the degree of nonlinearity observed in some natural settings.

Now researchers at the University of Queensland, led by Warwick Bowen and Christopher Baker, have found a way to access hydrodynamic nonlinearity beyond even the most extreme terrestrial examples.[1] They did it by going small: The team built a silicon wave flume just 100 μm long, about the width of a human hair, that guides waves of superfluid helium, as shown in figure 1. "What we've been able to do is to re-create, on a chip, nonlinear physics that is even more extreme than what can be modeled in these huge wave flumes," Baker says.

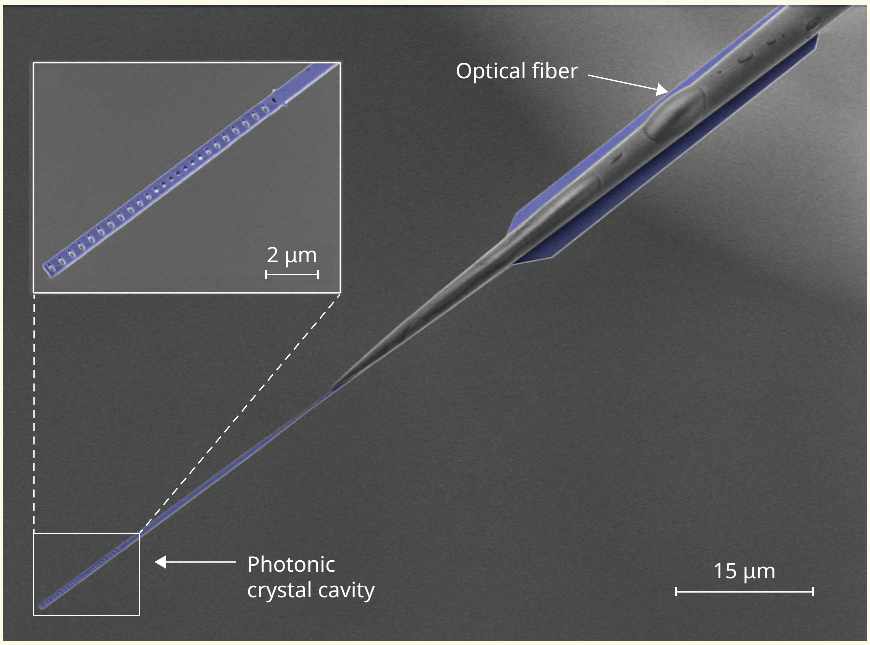

FIGURE 1. A 100-μm-LONG WAVE FLUME is used to observe nonlinear wave dynamics in superfluid helium. To induce waves in the channel of helium (shaded purple), an optical fiber delivers light to a photonic crystal cavity, shown in the inset, at one end of the flume. First, heat from laser pulses generates waves. Then, as freely evolving waves pass over the crystal cavity, its resonance frequency shifts in proportion to the wave height, which enables readout of the wave activity through the optical fiber. (Figure adapted from ref. 1.)

The team built the tiny flume using lithography, a standard semiconductor manufacturing technique. The device is glued to a tapered optical fiber that delivers laser light to a photonic crystal cavity at one end of the flume. Pulses of heat from the cavity start helium waves, and subsequent flow is measured by changes to the resonance of the cavity as waves pass over it. The advantage of using superfluid helium to observe fluid behavior at small scales is that unlike water, it has no viscosity and so can host waves in just nanometers of fluid. In a film of superfluid helium, it's the van der Waals force, not gravity, that provides the restoring force.

Nonlinearity in shallow waves is quantified by the Ursell number, which reflects wave height, wavelength, and fluid depth, as shown in figure 2. The shallow 6.7 nm depth of the superfluid helium allowed the researchers to access nonlinearities that were five orders of magnitude higher than what can be achieved in conventional experiments. They observed wave steepening—much like at the beach when waves steepen and break as they come to shore, but with a twist: The waves steepen on their back side, away from their direction of travel. The researchers also saw soliton fission, a process in which shock fronts evolve into a train of solitons. But unlike the solitons observed in macroscale fluids, the waves move as a depression, not a hill, in the fluid.

The research team plans to continue exploring wave dynamics with the new

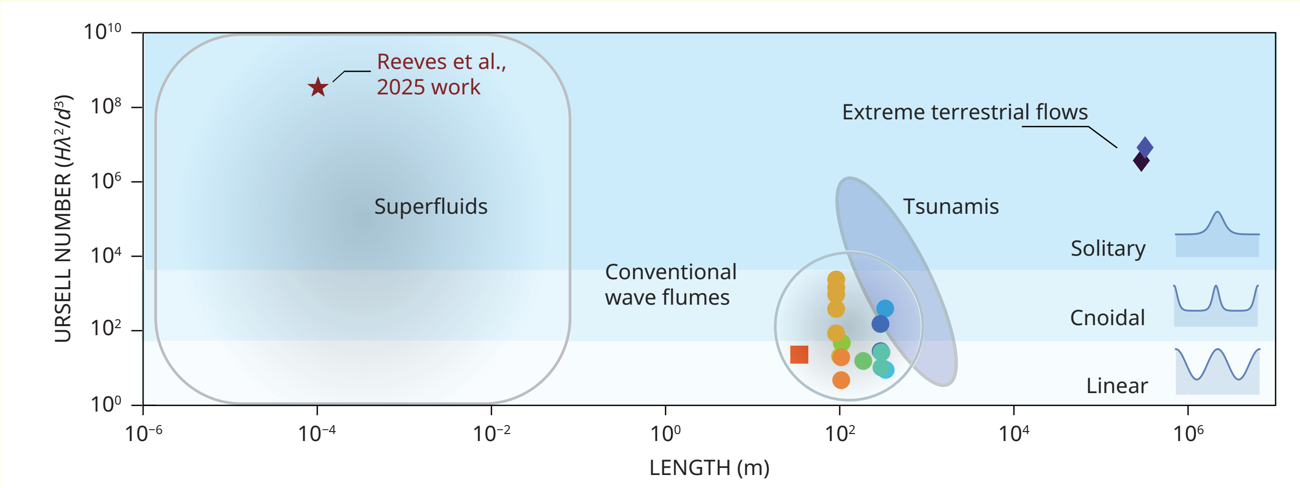

FIGURE 2. THE NONLINEARITY OF SHALLOW-WATER WAVES can be quantified through the Ursell number, which is described by the relationship between the wavelength λ and height H of a wave and the water depth d. The degree of nonlinearity determines whether waves operate in linear-, cnoidal-, or solitary-wave regimes. Small experiments that access a more extreme degree of nonlinearity open a path to new insights about nonlinear wave phenomena like turbulence. (Figure adapted from ref. 1.)

platform. It is much easier to create different shapes and lengths with the nanoscale flumes than with their macroscale counterparts. The researchers' simulations suggest that in future experiments, the system could generate what's known as a soliton gas—a random collection of hundreds of interacting solitons. "What soliton gas portends is the possibility of a turbulence theory, a statistical theory of nonlinear wave interactions, that could be solvable," says Mark Hoefer, an applied mathematician at the University of Colorado Boulder. "To be able to see it in this fluid system would be very exciting."

Laura Fattaruso

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