

PROFILE: KEN GOLDEN

## Cold Equations

Far from his cozy office in landlocked Utah, a mathematician grapples with the secrets of polar sea ice



The fire alarm woke Ken Golden up at 2:37 a.m. “My first thought was, why are they having a fire drill now?” he says. But as he walked down the hall of the *Aurora Australis* and into the frigid Antarctic night, he smelled smoke. As the 54 scientists and passengers mustered on the helicopter deck, he could see thick smoke belching out of the ship’s smokestacks.

“Pretty soon I heard a muffled explosion, deep inside the ship,” Golden says. “We later found out that there was a massive fireball that some of the brave crew had missed being caught in by less than 30 seconds.

“Eventually, the first mate came out to talk with us. In his Scottish accent, in a very calm and confident voice, he announced, ‘Please don’t be alarmed, but we have an uncontrolled fire in the engine room.’ Fifteen minutes later, he came back and said, ‘Please don’t be alarmed, but we are lowering the lifeboats.’ Right then I’m thinking: I prove theorems for a living! What have I gotten myself into? What am I doing down here?” Golden says.

What he was doing—and has continued to do in the 11 years since—was taking mathematics to places it had never been before. Golden, an applied mathematician at the University of Utah in Salt Lake City, is convinced that mathematics can answer some of the unresolved questions of climate change. As chair of the 2009 Mathematics Awareness Month ([www.mathaware.org](http://www.mathaware.org)), which is happening this month and is focusing on climate change, Golden has found himself turning into a public spokesperson for this viewpoint. He has given talks about sea ice and climate change in venues that include university seminars and congressional luncheon briefings. Considering his rich trove of

Antarctic and Arctic stories and the relish with which he tells them, it seems like a part he was born to play.

“Embracing the misery index, that’s certainly not unique among polar scientists,” says Donald Perovich of the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire. “But there’s something about Ken’s style. You’re out there in a storm in Antarctica, or knee-deep in ice water in Barrow, and he’s saying, ‘Let’s go and take another 200 meters of measurements.’ Or ‘Let’s consider these variables.’ Or ‘I’ve got something I really want to show you.’ That’s his enthusiasm, and it’s very rare.”

“Ken has a boundless enthusiasm for the subject matter, and it’s infectious,” says Tony Worby of the Australian Antarctic Division, who was deputy voyage leader on the fire-shortened expedition in 1998 and also led a cruise in 2007 that Golden participated in. “He’s very popular with the support crew. When he wanted to be out on the ice at 3 a.m. to do tracer experiments, he was never short of volunteers to help him.”

### An icy passion

“Enthusiasm” is a word that comes up in nearly every discussion about Golden. It starts with his zest for adrenaline-pumping adventure, from skiing to driving his 1987 Mustang GT (recently sold) to watching the Blue Angels at an air show. Golden has been a skiing buff since elementary school and moved to Utah in 1991 because, he says, “there is no place like it in the world in terms of the quality of the snow.”

Golden’s passion for sea ice started in 1976, when he was in his final year of high

school and worked on a senior project with H. Jay Zwally of the NASA Goddard Space Flight Center in Greenbelt, Maryland. Zwally is still heavily involved in polar research, as the project scientist for NASA’s ICESat mission. It was Zwally who gave Golden some of the best advice of his life: Go to Dartmouth, work with Stephen Ackley, and “learn all the mathematics that you can.”

Golden traveled to Antarctica for the first time in 1980 as a field assistant for Ackley, a geophysicist who was then at CRREL. “He was looking at how sea ice behaves when you use ground-penetrating radar on it,” Ackley says. “The ice is anisotropic, because it has inclusions—pockets of brine—that are conducting. Ken showed that the electromagnetic reflection looks different along the long axis of the inclusions than perpendicular to it. He published a paper in the *Journal of Geophysical Research* about this—a unique thing for an undergraduate.”

As a graduate student at the Courant Institute of Mathematical Sciences in New York City, a postdoc at Rutgers University, and an assistant professor at Princeton University, Golden delved into the mathematics of composite materials. He didn’t really intend to do any more research on sea ice. “It’s one of those weird coincidences, though,” he says. “Almost everything I got involved in turned out to be relevant for sea ice when I reentered that world in the 1990s: transport in composite materials, percolation models, diffusion processes. It’s given me a leg up, in terms of how I approach these things.”

Ackley invited Golden to return to the Antarctic in 1994, on an expedition called ANZFLUX. “He was probably thinking what a hoot it would be to bring an honest-

**Ice bound.** Golden and the research vessel *Aurora Australis* on an Antarctic expedition in 2007.



to-goodness professor of mathematics to the Antarctic and see what they see,” Golden says.

### Golden’s rule

If so, it worked. On that trip, Golden was struck by the Jekyll-and-Hyde nature of sea ice. When temperatures are just below freezing, the ice becomes permeable, allowing warm water to percolate up through it. Algae trapped in the ice start blooming like mad. At slightly colder temperatures, the heat flow stops and the algae shut down.

To Golden, the sudden change from impermeability to permeability (and vice versa) looked like a phase transition. He called it the “rule of fives,” because it happens at about  $-5^{\circ}\text{C}$ , when the brine fraction of the sea ice is about 5%. He believed that at this critical temperature and brine fraction, the isolated brine pockets connect up and form brine channels, making the ice permeable. But could he prove it? And what was the significance of 5%?

Golden remembered an old paper from 1971 about silver powder imbedded in a polymer matrix, a material developed to coat stealth airplanes. What if you replaced the polymer with ice crystals and the silver particles with brine inclusions of the right size? “I just took a ruler and measured those things, figured out the corresponding ratios, plugged it into their model, and came out with [a phase transition at] 5%,” Golden says. “It all fit together beautifully.”

Ironically, Golden started writing about this idea on his third trip to Antarctica—the one with the fire. After the fire was brought under control, the *Aurora Australis* drifted in the pack ice without power for 2 days, until

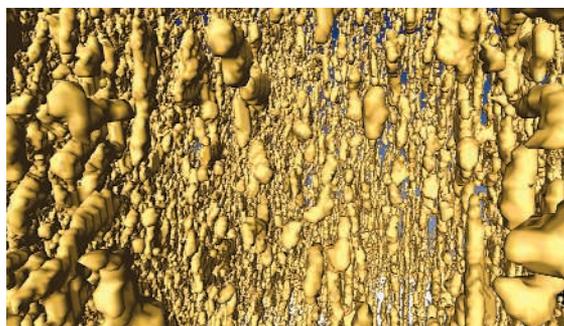
the crew finally managed to start the backup engine and the ship slowly limped back to Hobart. Golden began writing a paper en route. It ultimately appeared in *Science* and marked the beginning of a rational explanation of fluid flow through sea ice.

One skeptic was Hajo Eicken, a geophysicist at the University of Alaska, Fairbanks, who describes the composite-powder model as “too simplistic.” However, Eicken and Golden started collaborating 6 years ago, and together they have developed a much more realistic model based on three-dimensional imagery of actual brine networks. In work that has not been published yet, they substantially confirm the “rule of fives” but show that the percolation threshold is different in each of the three directions and also depends on the type of ice.

### Climatic wild cards

For many years, sea ice languished as a somewhat esoteric field of study. No longer. Over the past decade, sea ice has emerged as the most visible and perhaps the most poorly understood barometer of global climate change.

The depth of scientists’ ignorance became apparent in 2007, when the area of the summer ice pack in the Arctic dropped 40% from its historical average. The ice



**Riddled.** CT scan of brine channels in lab-grown ice shows the permeable structure that makes sea ice so vexing for modelers.

pack scarcely recovered in 2008. Not even the most pessimistic climate models foresaw such a precipitous drop.

“The amount of retreat in the summer of 2007 was just shocking,” Perovich says. “It’s a mystery, and as in any mystery there is a long list of suspects. Some people argue for preconditioning: As the ice gets thinner, it is more sensitive to warm summers than it would be if the ice were thicker. Some people argue for changes in atmospheric circulation, or export of more perennial ice to lower latitudes, or convection of heat through the Bering Strait. Then there’s my favorite, the ice-albedo feedback.”

The ice-albedo feedback comes into play as snow-covered ice is replaced by open water or is covered by seasonal melt ponds. The water absorbs more of the sun’s heat, accelerating the ice’s melting. All computerized climate models include the effect, but to some extent they all rely upon guesswork. No one at present can predict the extent, the timing, or the warming effect of the melt ponds.

“Right now, the large-scale models used in climate prediction have problems,” says Ackley. “There are several processes that aren’t done well.” From melt ponds in the Arctic (which form only if the underlying ice is impermeable) to the growth of algae in the Antarctic, many of these processes start up or shut down when the “rule of five” phase transition tells them to. Without them, an important link in the polar climate chain cannot be closed.

Golden thinks the mathematics of composite materials can also be applied to the ice pack as a whole. “When I look at these satellite images, I see a time-evolving, two-phase composite material. I am quite sure that I can bring new methods and ways of thinking to these problems, based on my bread and butter as a mathematician.” Recently, he has begun working with Elizabeth Hunke of Los Alamos National Laboratory and Cecilia Bitz of the University of Washington, Seattle, on updating the sea-ice module of the Community Climate System Model. “The salinity in sea ice is one of the things that global climate models have not incorporated yet, and we’re starting to do that now,” Hunke says.

Golden also looks forward to more journeys to high latitudes. A year after the fire cruise of 1998, he was back on the same ship, with the same crew. In 2007, he sailed on the *Aurora Australis* again—this time as the leader of his own experiment, studying the relationship between electrical conductivity and fluid permeability in sea ice.

“Would I have chosen to be on a burning ship in Antarctica? Obviously not,” he says. “But having been through it, I wouldn’t trade that experience for anything.” In particular, it taught him the most important lesson for anyone doing research in Antarctica: adaptability. “There’s always something that happens in Antarctica,” he smiles. “I’ve never been on an expedition that went according to plan.”

—DANA MACKENZIE

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