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Answers in the Ice

Harvard researchers probe frozen landscapes for clues to Earth's past and future

by Alvin Powell

James G. Anderson, Philip S. Weld professor of atmospheric chemistry, on a research expedition in Greenland. The island's barren landscape holds critical insights to understanding the behavior—and environmental implications—of melting ice.

COURTESY OF JAMES ANDERSON

On the wall of Jim Anderson's Harvard office is a photograph of a man on a glacier, a small, dark figure in a vast expanse of snow and ice.

The man is Anderson, a Harvard professor who last year visited Greenland as part of a new research project to probe the mysteries of the ice there. Anderson, who calls Greenland "a very worrisome and impressive place," says there's something elemental about being on the ice, knowing it extends down a kilometer beneath his feet but not knowing exactly what it holds and what lies beneath.

Ice and uncertainty. Talk to scientists about the world's ice and they'll tell you tales of uncertainty. Even as they confirm that climate change is real and driven by human hands, researchers studying the world's ice confess to how little they really know about its current state and behavior. That lack of knowledge makes predicting the future difficult.

"The composition of the cryosphere represents one of the great unknowns, both in terms of what global warming is doing to the planet now and in the great impacts it will have on human society in the future," says Hooper professor of geology and professor of environmental science and engineering Daniel Schrag, who directs the Harvard University Center for the Environment (HUCE).

Though there are large gaps in our knowledge, we're not entirely ignorant about ice. We know the globe's cryosphere is massive, the largest part of the world's climate system after the ocean. It contains 75 percent of the world's fresh water, covers about 10 percent of the globe's land surface, and caps 7 percent of the oceans. Its shiny, reflective surface, a property scientists describe in terms of albedo, plays an important role in how much heat the Earth absorbs, a critical consideration as scientists ponder feedback effects of human-driven climate change.

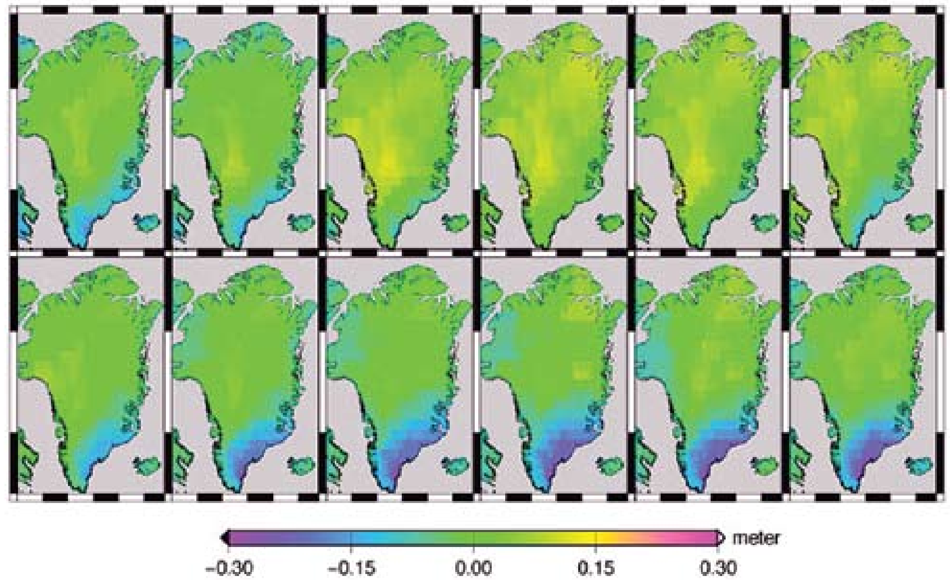
We know that a warming world means less ice bound up in mountain glaciers and in the world's great ice caps, not to mention more familiar parts of the cryosphere: snow blanketing the land during winter and the ice crystals that bind up the frozen ground in permafrost. We also know that melting land-based ice means rising seas. But when asked where the ice will melt, how much, and—most critically for those interested in sea level rise—how fast, scientists will tell you we're way behind in our understanding of a world racing toward a warmer future.

Researchers affiliated with the Center for the Environment are working to fill those gaps. How much ice will melt, they say, is an open question. How fast is another critical issue about which we don't have enough information. There are indications that the ice on Greenland, for example—whose complete melting would raise sea levels 7 meters—may disappear faster than originally thought, in centuries rather than millennia.

Consensus sea level estimates of the Intergovernmental Panel on Climate Change (IPCC) reflect that uncertainty. A 2008 IPCC technical paper on how climate change will affect sea level rise projects an increase of between 0.18 meters and 0.59 meters by the end of this century. It cautions, however, that thermal expansion of gradually warming ocean water is the largest part of this estimate, 70 to 75 percent, and that models do not include the full effect of potential changes in ice sheet flow, something that makes the definition of an upper bound impossible.

"Partial loss of the Greenland and/or Antarctic ice sheets could imply several metres of sea level rise, major changes in coastlines and inundation of low-lying areas, with the greatest effects in river deltas and low-lying islands," the report says. "Current modeling suggests that such changes are possible for Greenland over millennial time-scales, but because dynamic ice flow processes in both ice sheets are currently poorly understood, more rapid sea level rise on century timescales cannot be excluded."

We're farthest ahead in understanding *where* ice will melt. The world's mountain glaciers have been shrinking since the 1800s, their retreat slowing between 1970 and 1990, only to speed up again in the time since. The vast East Antarctic ice sheet, on the other hand, appears to be stable, though the smaller West Antarctic sheet, which holds the equivalent of five meters of sea level rise, is not. Sea ice, which plays a role in the world's energy flows but not in sea level rise because it's already floating, is disappearing in the Arctic Ocean at an alarming rate.



NASA/JPL

Monthly changes in the mass of Greenland's ice sheet observed by satellites during 2005. Purple and dark blue areas indicate areas of largest mass loss.

"The ice on Greenland—whose complete melting would raise sea levels 7 meters—may disappear...in centuries rather than millennia."

But it may be Greenland that is of greatest concern. With lakes of summer ice melt, iceberg-filled fjords, and the near-certainty of melting at today's atmospheric carbon dioxide levels, Greenland fills observers with a train-wreck fascination and sends scientists rushing to figure out the nature of its ice melt.

Greenland's ice sheet is vast, reaching depths of three kilometers along the gigantic island's spine. The ice sheet is fed by high-altitude central snowfall that gets compressed and eventually moves into some 40 outlet glaciers that bulldoze their way to the sea in long, narrow fjords. Those glaciers act as buttresses for the central ice sheet, and, as they speed up, so does ice flow from that enormous central area. Though it expresses uncertainty about the estimates, the IPCC says that Greenland lost between 50 billion and 100 billion tons of ice annually between 1993 and 2003, and even more in 2005.

HUCE-affiliated scientists are examining issues critical to understanding the behavior of Greenland's ice and how fast it will reach the ocean: the topography of the bed beneath the glaciers, the behavior of melt water when it reaches the bed, and the calving of icebergs where the glaciers meet the sea.

"The level of our ignorance of the details of the Greenland glacial structure and its underlying topography—which controls the flow of the glacial subsystems—is shocking," Anderson says. "Greenland contains seven meters of sea level rise. It is in many ways the cusp of the public policy problem, yet we are profoundly ignorant about what the future holds, 10 years, 20 years, 40 years, 60 years out."

Anderson, who for many years focused his research team's efforts on atmospheric ozone, has grown so concerned about the problem of climate change that he has shifted his research to concentrate on it.

"One thing we do know, Greenland isn't stable under the current level of carbon dioxide. It's not a question of whether Greenland's glacial system will disappear, it's a question of how quickly," Anderson says.

Understanding the interface between the ice and the ground, Anderson says, is critical if we're to understand the behavior of the glaciers that stream from Greenland's central ice sheet to the sea. He believes that the nature of that interface—smooth or irregular, obstructed or clear—is a factor in determining how quickly the glaciers move.

Anderson and his research team have therefore equipped a small, four-seater airplane, a Diamond DA42, with ice-penetrating radar and modified it to fly robotically. The plane, Anderson says, is extremely fuel efficient and robust enough to withstand Greenland's weather. When the plane flies over the ice, its radar will bounce a signal from both the ice surface and the ground deep beneath, providing two kinds of information. The craft, which Anderson hopes to begin flying in early 2011, will greatly increase the volume of data on the glacier beds, which is currently being collected by human crews flying in large manned aircraft. It should boost observing time from current levels of just 100 to 120 hours per year to between 2,000 and 3,000 hours per year.

After three years of observing, Anderson hopes to have not just an enhanced understanding of the ground beneath the glaciers, but also a thickness map of the entire ice sheet and thus an understanding of ice thickness and structure in areas where it is flowing to the sea.

"Each of those glaciers' flow basins has a different geometry and the way in which the geometry affects ice dynamics—the movement of the ice—is right at the cusp of our understanding of how the systems operate," Anderson says. "The velocity of the [glacier] flow can reach a number of kilometers a year. But it can accelerate or decelerate by a factor of two in a year or two. Why is this? What idiosyncrasies are involved? The ocean temperature at the tip? The insertion of water coming down through cracks and fissures at the surface because the surface melts?"

James Rice, Mallinckrodt professor of engineering sciences and geophysics. Rice's research has highlighted the important role of iceberg calving.

"If a large volume of water flows quickly to the glacier bed, it can create pressures high enough to actually float the enormous weight of the glacier off the bedrock."

The project, called the Airborne Robotic Radar Greenland Observing System, or ARRGOS, is being conducted with the Applied Physics Lab at Johns Hopkins University and Aurora Flight Sciences, an aircraft firm specializing in the scientific application of robotic aircraft. It will involve perhaps 20 people, including full-time staff charged with data analysis and archiving based at HUCE. Operational staff will be located at bases in Thule and Kangerlussauq, Greenland, while Cambridge-based faculty members will analyze the data. The group will triage the glacial systems, Anderson says, examining the fastest flowing glaciers first.

Beyond glacier bed topography, another factor that influences glacier behavior is the action of melt water where the ice meets the ground. Earlier this decade, researchers from the University of Washington monitored a glacial lake on Greenland's ice. The lake was large, roughly 5.6 square kilometers with an average depth of 8 meters, but once it started to find its way through the ice, it disappeared in a matter of hours, pouring through cracks at a rate that must have surpassed the flow of Niagara Falls.

James Rice, Mallinckrodt Professor of Engineering Sciences and Geophysics, who has spent much of his career studying the interaction of earth materials and water, was intrigued by the researchers' report and the massive flow of water to the glacier's base. In June 2008, he and then-graduate student Victor Tsai began a project building mathematical models to explain the behavior of water as it moves through Greenland's glaciers.

The models show that if a large volume of water flows quickly to the glacier bed, it can create pressures high enough to actually float the enormous weight of the glacier off the bedrock for a short period, something that's been confirmed by GPS measurements, Rice says. When the glacier loses contact with the bedrock, it can slip downhill toward the sea more quickly than when it's anchored to the rock or sediments below.

The high pressure, however, can't be maintained forever. After a few hours, the water drains away into the subglacial water system, seeping through the till beneath the ice, and on occasion, through larger spaces and caverns.

"This is an interesting question to understand because the hydrology of a glacier is something some people think is important in deglaciation," Rice says. "In Greenland, you get lots of surface melting in summer. The water runs down like it would a bald mountain and collects in the low places and forms very large lakes. I've asked how rapidly the glacier bed can absorb that water and what the dynamics of that absorption are."

Whether due to hydrology or other factors, observers have noticed that Greenland's glaciers are speeding up in their journey to the sea. In one case, the increased pace was noticed by Harvard researchers who were exploring a new kind of earthquake, one they eventually tracked to the iceberg calving grounds at the glaciers' end.

It was then-Harvard Professor Göran Ekström who first noticed the unusual long, slow earthquakes on seismographs, Rice says. The strange quakes sent waves through the earth with a period of 100 seconds, compared with 20 seconds for the shock of a regular earthquake. The rumbling, of a magnitude of about 5 on the Richter scale, could be detected around the world.

Ekström and Tsai, now a postdoctoral fellow at the U.S. Geological Survey in Colorado, narrowed the location of these earthquakes to the coast of Greenland, an area not tectonically active. Tsai and Ekström were sure the quakes were from something dramatic happening to the ice, perhaps a sudden slip of a glacier that would take it down its bed hundreds of meters. Whatever was going on, it was happening more often. In 2006, they reported that the number of these earthquakes had doubled over the previous five years.

When Ekström moved to Columbia University, Tsai began working with Rice

Shrinking Alpine Glaciers

Continental ice sheets are not the only ones embroiled in the climate mystery. Glaciers in the high places of the world, from the poles to the equator, also play a role. Though mountain glaciers are thought to be better understood and are known to be retreating on average, estimates of their behavior are based on measurements of just a small fraction of the world's roughly 100,000 mountain glaciers. With one-sixth of the world's population relying on glacier-fed rivers for their drinking water and populations imperiled by glacial lakes bursting their dams, two Harvard professors are teaming up because they think the stakes are too high to rely on shaky estimates.

"After I read the IPCC report [on mountain glaciers], I said, 'That's it? That's all we have to go on?'" says assistant professor of Earth and Planetary Sciences Peter Huybers. "A glacier is really exquisitely sensitive to the environment it exists in. And if you change its temperature and change its precipitation, you can pretty much predict what's going to happen. In so much as we know which regions are warming and where precipitation is changing, I don't think there are going to be big surprises. But not being surprised by just how quickly glaciers are receding or how they tie into other things, like public water supplies, is quite different from having an accurate estimate with which to prepare for the future."

Huybers is beginning a new cross-faculty collaboration with Armin Schwartzman, an assistant professor of biostatistics at the Harvard School of Public Health and an expert in image analysis. Their project, which recently received HUCE seed funding, seeks to harness Huybers' experience with glaciers and modeling and Schwartzman's expertise in medical image analysis to do something glaciologists have generally found to be difficult: interpret the ample supply of satellite images of the world's mountain glaciers to better understand just what they've been doing in recent decades.

"If glaciers existed on a perfectly flat plain, under a cloudless sky, with no dirt on them, it would be an extremely easy problem," Huybers says. "But glaciers carve their own canyons.... As they're in these valleys, they're shaded so you go from places that have bright sun to places that have shadowing.… Impurities collect on a glacier over time, and as you get toward the terminus, those impurities tend to gather toward the surface—rocks and dust, for example—so you have a more gradual transition from ice to terminus. Thus, gauging their size from space is not easy."

Armin Schwartzman, an assistant professor of biostatistics at the Harvard School of Public Health, sees many parallels between the analysis of medical and satellite imagery.

Schwartzman got in touch with Huybers out of his own concern about climate change and a desire to lend his statistical skills to the problem. Schwartzman says there are many parallels between analysis of medical scans of the brain, for example, and satellite images of a glacier.

"It's a similar type of data," Schwartzman says. "In brain imaging—MRI, PET—you have to identify regions with changes where there's a tumor. There are many techniques that can transfer to other kinds of image analysis. Studies may have a sequence of images, for example, [where we] try to find areas in the image that might be changing over time, perhaps as a function of disease.

"In the case of Landsat [satellite images of glaciers], if you are taking pictures of the same site over and over again, you also have a sequence of images where most things stay constant and it's all those small changes that you're after.… Being able to track the extent of a glacier over time will allow us to make better predictions for the future: How long will a village have water, for example."

For a glacier, Schwartzman says, they may measure the intensity of pixels along its path and use an edge detection algorithm to estimate the location of its terminus. They're initially going to use images from NASA's Landsat satellite missions, which have observed the Earth since 1972. But they may also examine images from satellites using other wavelengths to help determine the glaciers' edges.

In its early stages, the project will focus on developing that edge detection algorithm using well-studied glaciers, such as New Zealand's dramatic Franz Josef, which Huybers has visited twice and on which he has ongoing projects. The well-studied glaciers will allow them to check their techniques against data gained on the ground, the two say. Once the project is up and running, they'll focus on critical glaciers, like those in the Himalayas which supply essential drinking water.

Within a year, the two say, they'd like to have the algorithm developed and the analysis under way. The goal, Huybers says, is to set up a system in which a student can work up the history of a glacier—analyzing the available imagery taken during recent decades—in a single day.

on the problem. The two shifted their focus from the idea that the quakes were caused by sudden accelerations of glaciers to calving events at the glaciers' terminus. Tsai's models showed that the calving had to be relatively sudden, as a more gradual release of ice wouldn't generate the necessary seismic waves.

Rice says the quake-generating events are quite dramatic. Though the ice thins by the time it reaches the sea, the glaciers can still be a half-kilometer thick there.

"When these glaciers come to the fjords they are towering objects, so you have to think of something like a vast skyscraper standing above the level of the water in the fjord," Rice says. "And that skyscraper —and all the skyscrapers on the block with it—suddenly fall over."

When the ice falls, the top either pitches into the sea, grinding the base against the ice behind, or it slides bottom first into the fjord, grinding the top against the glacier as it goes. The scraping slows the event down providing the long-period seismic waves that were detected. Rice's and Tsai's suspicions were confirmed by a research team that was on a glacier when one of the glacial earthquakes occurred. GPS monitoring equipment showed no sudden increase in movement as would happen if the glacier began to slide very rapidly on its bed. It did, however show a more gradual acceleration, as would happen to a glacier that lost a binding ice plug at its terminus.

Rice says the research solved a scientific puzzle and may have focused people's attention on the important role played by iceberg calving. "What we do not understand is what physical attributes of the surrounding water—temperatures and the like—would promote calving." It's one of the main things, Rice says, "that would help an ice flow to speed up. Ice buttresses itself at the head of the fjord. If the buttress falls down it removes resistance to flow." Developing a better understanding of calving Rice says, is therefore "very important."

Fractures in the Antarctic

Less well understood than Greenland's glaciers is ice in the Antarctic. Amply illustrating this is the fact that the IPCC, which aggregates data in an attempt to reach scientific consensus, says it doesn't know whether Antarctic ice grew or shrank between 1993 and 2003.

Specifically, competing estimates say that Antarctica's ice may have shrunk by 200 billion tons a year in that period or that it may have grown by 50 billion tons a year—or any amount in between. In case the large range of the estimates isn't caution enough about their reliability, the IPCC further notes that the small number of measurements used in forming the estimates, the differing techniques used in the measurements, and the presence of systematic errors makes the estimates so uncertain that they can't assign statistical confidence limits. The IPCC further cautioned against using the midpoint as a best estimate.

Behind those official figures, scientists believe that the vast East Antarctic ice sheet, which covers the bulk of the continent, is either stable or growing. The West Antarctic ice sheet, however, is another story. Just as Greenland's central ice sheet is buttressed by its glaciers, scientists say the ice of West Antarctica is being buttressed by enormous floating ice shelves that extend into the surrounding ocean. It is these ice shelves, scientists say, that are preventing West Antarctica's land ice from sliding into the sea and raising sea level as much as five meters.

A Hat Trick!

Peter Huybers receives three prestigious honors

Peter Huybers, assistant professor of Earth and Planetary Sciences, HUCE faculty associate, and former Environmental Fellow, had quite a fall semester. First, he was named a 2009 MacArthur Fellow. Fellowship recipients are awarded "genius" grants of $500,000 to pursue "their own creative instincts for the benefit of society."

Huybers (High-bers) also received the 2009 James B. Macelwane medal, which is awarded by the American Geophysical Union "for significant contributions to the geophysical sciences by an outstanding young scientist less than 36 years of age." HUCE Director Dan Schrag, also a former Macelwane medalist and MacArthur Fellow, presented the award to Huybers at the annual AGU meeting in December.

And to finish off his fall of accolades, Huybers was also named a David and Lucille Packard Fellow, an honor accompanied by a five-year, $875,000 grant to support his research.

Taking a multifaceted look at climate change, Huybers studies the history of Earth's glaciers and ice sheets, as well as the temperature fluctuations seen across the planet's surface over the course of a typical year. He has also participated in efforts to reconstruct Earth's past climate based on the relatively little evidence available to us. Huybers' research seeks to clarify the as yet poorly understood processes that have driven the waxing and waning of Earth's stores of ice over the past 3 million years.

During the planet's ice ages, ice has covered much of the northern continents; today's relatively ice-free conditions represent something closer to a historic minimum.

Huybers also studies the tremendous annual temperature variations seen across much of the Earth's surface. Earlier this year, his analysis of global temperatures between 1850 and 2007 shed new light on this question, showing that winter temperatures have risen more rapidly than summer temperatures.

Among other effects, this imbalance has led spring to arrive, on average, nearly two days earlier than just 50 years ago, with implications for everything from the budding of trees to bird migration to the annual dissolution of sea ice. Huybers became an assistant professor in Harvard's Department of Earth and Planetary Sciences in 2007, in the midst of postdoctoral work as an HUCE Environmental Fellow. He received his B.S. in physics from the U.S. Military Academy in 1996 and his Ph.D. in climate physics and chemistry from the Massachusetts Institute of Technology in 2004.

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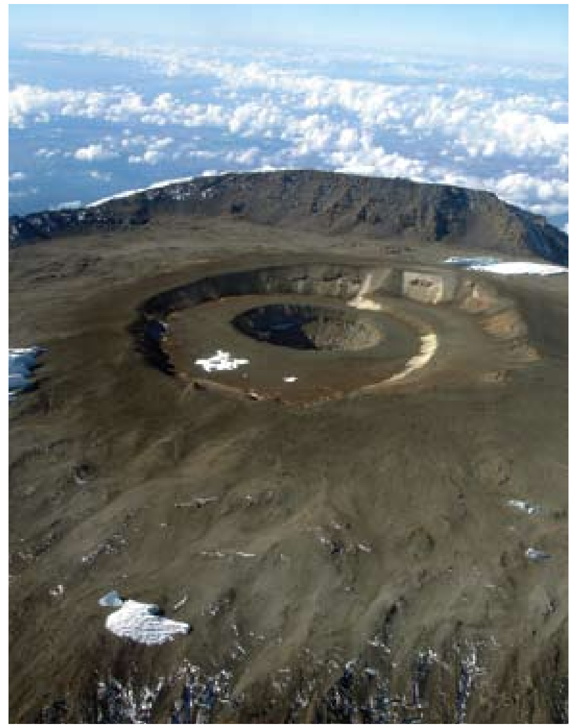
The peak of Mount Kilimanjaro in east Africa as seen from an aircraft in 1992 (left) and 2005 (right). The famous ice field that is just three degrees south of the equator could completely melt away in the next 20 years, scientists say, if the earth continues to warm at the current rate.



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Like Greenland, West Antarctica makes scientists concerned about climate-induced sea level rise nervous. The region has surprised scientists before, and not in a good way. In 2002, the massive Larsen B ice shelf—a mass of floating ice more than 200 meters thick and covering an area the size of Rhode Island, broke up in less than a month after an estimated 5,000 to 12,000 years of stability, a speed that one researcher called "staggering."

HUCE Director Schrag says that, in understanding the future of West Antarctica, as in other places, the problem is the lack of information. For example, he says, it is known that even *slightly* warmer water can rapidly erode ice shelves from beneath, but researchers don't understand conditions and potential changes to the seawater beneath Antarctica's large ice shelves. "Our best observations of temperature and salinity come from instruments strapped to the backs of seals," he says, when what we really need to know about are changes 600 meters deep in the water creeping in over the Antarctic ice shelf. "The ice shelves of Antarctica—the big Ross and Ronne ice shelves—buttress the land ice." If those shelves collapse, as Larsen B did, they would expose grounded ice in West Antarctica that not only would most likely begin flowing into the sea more quickly, but, since it sits on land that is below sea level, could pop off in larger chunks. Glaciologists say that if the ice shelves collapse, all bets are off on estimates of sea level rise. "We are really flying blind on this one," says Schrag.

At Harvard, Roiy Sayag GSAS '09, under the tutelage of Eli Tziperman, the McCoy professor of oceanography and applied physics, examined one way Antarctica's ice gets to the sea: little-known areas of fast-moving, land-based ice that, though they cover just 10 percent of the ice sheet surface, account for 90 percent of its discharge into the sea. These moving rivers of ice, called ice streams, can be tens of kilometers across, hundreds of kilometers long and flow at hundreds or thousands of meters a year, compared with just meters per year in the surrounding ice sheet.

The work involved designing computer models of the ice, whose motion is believed to be independent of the topography of the ground beneath and rather to be related to the flow of water where the ice and ground intersect. As with the lubricated beds under Greenland's glaciers, it is thought that when water pressure becomes high enough, it allows ice in the region of the stream to flow more quickly than that surrounding it.

A Stark Warning

With ice and ocean tightly intertwined, scientists say it is critical to consider not only what the ice is doing to the ocean, but also to listen to what the ocean is telling us about the ice.

Harvard's ice whisperer is professor of geophysics Jerry Mitrovica, a recent arrival from the University of Toronto. Mitrovica employs an unusual ally in his efforts to read the seas for signs of ice melt: gravity.

When one considers gravity, Mitrovica says, one realizes that perhaps the biggest misconception about sea level rise due to melting ice is that it will be uniform like the changes that occur when you drop an ice cube in a glass of water or add a bucket of water to a bathtub.

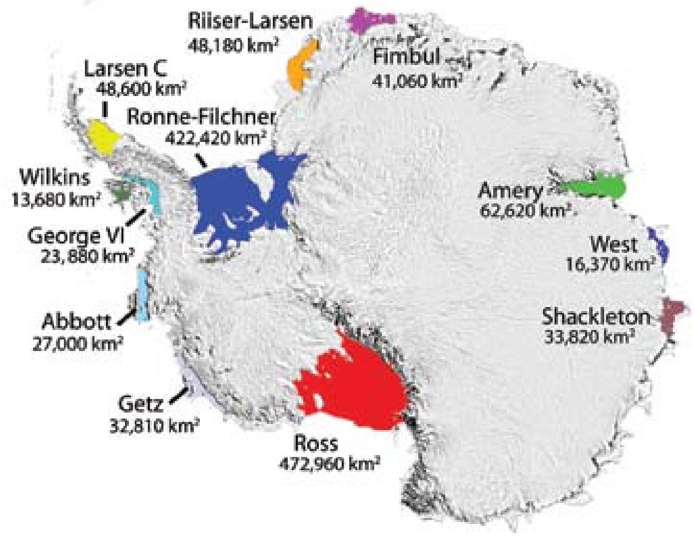
Because we often think of gravity's attractive force in the context of planets, it is easy to overlook when thinking about smaller masses. But ice, Mitrovica realized, has a gravitational pull just like anything else. And a lot of ice, like that stored in the ice sheets of Greenland and Antarctica, has a significant gravitational pull.

Mitrovica uses this idea to better understand the reason that sea level change has not been uniform around the world. This lack of uniformity was once used as an argument against the idea that global warming was resulting in sea level rise. But Mitrovica says that something far more intricate, subtle, and intriguing is actually going on.

The change in sea levels around the world results, in part, from the gravitational effects of the enormous masses of ice from which the water comes. The ice is so massive that it exerts a strong gravitational pull on the water itself. That means two things happen when the ice melts. The first is that, as expected, more water goes into the ocean, adding to its overall volume. The second, however, is a gravitational shift as the ice loses mass and its pull against the water becomes weaker.

The result is one of the most counterintuitive findings Mitrovica says he has ever been involved with. If the ice melts in a

LEFT: NASA; RIGHT: COURTESY OF TED SCAMBOS, NATIONAL SNOW AND ICE DATA CENTER, UNIVERSITY OF COLORADO, BOULDER



Left: Satellite view of Antarctica. Right: Antarctica's major ice shelf areas. While the eastern sheet is thought to be relatively stable, scientists are gravely concerned about the disappearing western sheet and its implications for potentially dramatic sea-level rise.

place like Greenland, sea level will actually *decrease* close to Greenland because the lessened gravitational pull will mean that water will move away from the melting ice sheet. It will also cause water levels to rise disproportionately higher in the ocean farther from Greenland.

Recent work by a graduate student of Mitrovica's showed that, though estimates of sea level rise in the case of the West Antarctic ice sheet's collapse are about five meters globally, adding in the gravitational change means sea level will actually rise higher farther from Antarctica. New estimates of that change are nontrivial, putting the rise along the U.S. east coast at closer to seven meters than five.

These global variations in sea level present a potential treasure trove for scientific sleuths, Mitrovica says. Sea level rise at each point on the globe is a function not just of how much ice has melted into the sea, but the distance from the melt point. The signals may be complex, Mitrovica says, but researchers can read the varying sea levels as overlaid patterns like fingerprints that, once untangled, can tell them not just how high the sea is rising, but also where the meltwater is coming from.

Mitrovica's work tracking the fingerprints of past episodes of sea level rise has him looking worriedly at West Antarctica today. His research indicates that 14,000 years ago sea level rose suddenly—20 to 25 meters in just 200 years. He traces that rise back to Antarctica, and argues that the past shows there may be more danger from sea level rise right now than people think.

"I personally think that ice sheet is more unstable than people think, and that it's more unstable than the IPCC reports suggest," Mitrovica says. "I don't think there's any doubt whatsoever that sea level is doing anomalous things: the ice sheets are melting, sea level is changing, and it's changing in relatively predictable patterns. I see significant cause for concern."

Switches and Feedbacks

Not only does melting and freezing land ice affect sea level in ways both mundane and surprising, as revealed by Mitrovica, floating sea ice plays a modulating role in the dance of ice and ocean in at least two distinct ways.

By changing the planet's reflectivity, or albedo, and by serving as a gatekeeper for oceanic moisture, sea ice serves as a climate "switch," turning on and off the great glaciations of the past, according to work by Tziperman and his student at the time, Hezi Gildor, now at the Weizmann Institute of Science in Israel.

Because sea ice can rapidly expand and retreat—as we're seeing now in the Arctic—the switch that controls its extent and thickness can flip on and off relatively quickly, according to theories worked out by Gildor and Tziperman. Sea ice, they theorize, plays a role not only in the long, 100,000-year glacial cycles of the ice ages, but also in shorter, more abrupt warming events called Dansgaard-Oeschger oscillations, which occur over a matter of decades, as well as in Heinrich events, which occur over centuries.

Events leading up to the sea ice switch begin in the warm interglacial periods, with an ice-free ocean and land ice just beginning to form. With ample atmospheric moisture from the oceans, snow accumulation exceeds melting, allowing land ice to grow. This increases the planet's albedo, reflecting more energy into space and lowering temperatures—locally at first. This process continues for tens of thousands of years, during which the global atmospheric and ocean temperatures fall, while land ice continues to grow. Once ocean temperatures drop far enough, sea ice begins to form, increasing the planet's albedo even more and dropping temperatures further. This creates a positive feedback which spurs rapid sea ice growth.

Eventually, however, the ice covers enough of the ocean to both insulate it from further cooling and to cut off the ocean's moisture from the atmosphere. This point is the glacial maximum and the point at which the sea ice switch flips again, triggering a warming cycle.

The planet begins to warm because the ice has reduced the flow of moisture from the ocean to the air, cutting off snowfall to the glaciers. As glaciers shrink, the planet's albedo declines, causing temperatures to slowly increase. After several thousand years, the ocean warms enough to cause sea ice to retreat, decreasing the albedo further and causing temperatures to climb further, sending the planet once again into an interglacial period.

Gildor and Tziperman's work on this sea ice switch is one example of scientists looking to the past to understand the climate system's workings and, perhaps, gain some insights for the present, or even the future. Those looking at Earth's deep history, in fact, have discovered evidence for extreme climate states in the distant past.

In 1998, Harvard scientists Paul Hoffman, Dan Schrag, and co-authors revitalized an idea from the 1960s and 1980s that the Earth may once have been almost entirely glaciated. Such a Snowball Earth scenario, they hypothesized, resulted from a runaway feedback where the albedo of the growing sea and land ice reflected ever larger amounts of radiation into space, causing greater and greater cooling. Hoffman and Schrag found evidence of such an extreme glaciation event in cap carbonate sediments in Namibia. The Earth, according to the theory, was trapped in this extreme frozen form for millions of years until carbon dioxide-laden volcanic emissions raised atmospheric carbon dioxide to levels high enough that rising temperatures from the resulting greenhouse effect melted the ice.

Researchers struggling to understand all possible climate futures are now examining a period in the earth's past called the Eocene, which, with warm temperatures from the equator to the poles, was the climate opposite of Snowball Earth. Their efforts, however, have met with more than a little frustration.

During the Eocene, which extended from 55 million to 38 million years ago, the planet was not just warmer on average than today, but the extremes of temperature between the equator and the poles were far less—today's 50 degree Celsius difference was perhaps half as large then. This so-called "equable" climate existed at a time when there was no ice anywhere in the world. Evidence of 12 to 15 degree Celsius ocean water flowing from the poles toward the equator along the sea floor—water that today is 2 degrees—prove that even the polar seas were ice-free year-round.

Places considered cold today were warm enough to support tropical life then, including crocodiles and palm trees. Eocene-era fossils of both these cold-intolerant species have been found as far north as Wyoming, "which is remarkable because temperatures there can sink into the minus tens of degrees Celsius in winter," Tziperman says. "The fossils mean that temperatures never dropped below freezing…, even in the coldest winter. [The Eocene] was very, very warm."

Until recently, however, climate scientists had been unable to explain the fossil evidence. Their climate models couldn't sufficiently warm the globe—no matter how high researchers jacked up the carbon dioxide content—to account for the warmth so far north.

The answer to this anomaly may lie in the role of clouds.

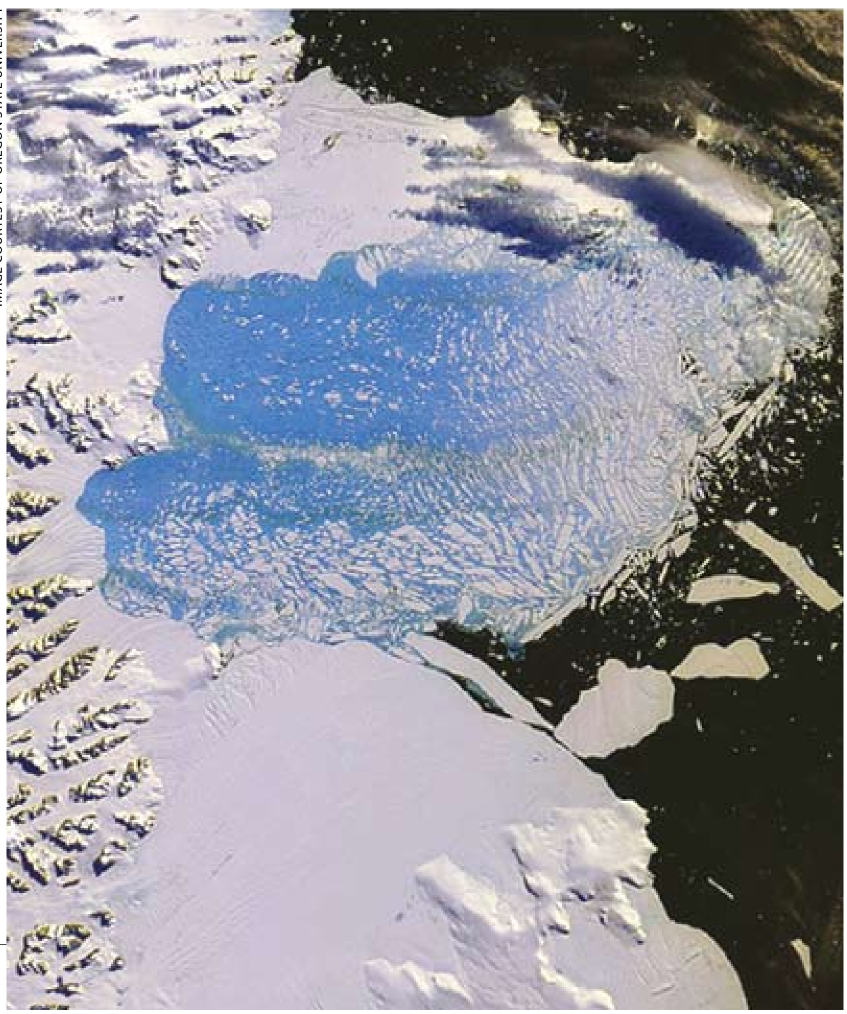
Schrag and Anderson have proposed that the development of high stratospheric clouds in the Arctic would have warmed the region by trapping heat during the polar night. The two believe that carbon dioxide-induced greenhouse warming could lead to the formation of such high clouds, which would have the effect of decreasing the temperature difference between the equator and the poles. This, in turn, would trigger decreased interactions between the lower atmosphere, called the troposphere, and the upper atmosphere, called the stratosphere. This self-reinforcing stratification would result in a warmer tropical stratosphere, which would absorb more moisture. A moister stratosphere would lead to higher stratospheric clouds, which would act as a blanket, retaining heat over the poles.

Tziperman and former doctoral student Dorian Abbot, Ph.D. '08, propose a different wrinkle, suggesting changes to the circulation in the troposphere, or lower atmosphere, over the poles. Induced by levels of carbon dioxide triple those of today, such changes would make the polar troposphere look much like that of the modern tropics, with tropical-like convection, more rain, and increased cloud cover.

This would look "exactly [like] what we have in the tropics today," Tziperman explains. When you account for cloud cover, suddenly—at high concentrations of carbon dioxide—the Arctic atmosphere becomes tropical. "It develops tropospheric clouds and these high clouds keep it nice and warm."

Though the work is intended to explain a warm period in the Earth's past, Tziperman points out that the computer models he uses were intended to predict the Earth's future and, if current carbon dioxide release rates aren't reduced, 1,000 parts per million of carbon dioxide in the atmosphere is possible as early as 2150.

"You'll have an ice free ocean," Tziperman says of the potential return of equable climate to the world. "You'll be able to take a tropical vacation in the Arctic during the polar night."



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Collapse of the Larsen B ice shelf in Antarctica in 2002.