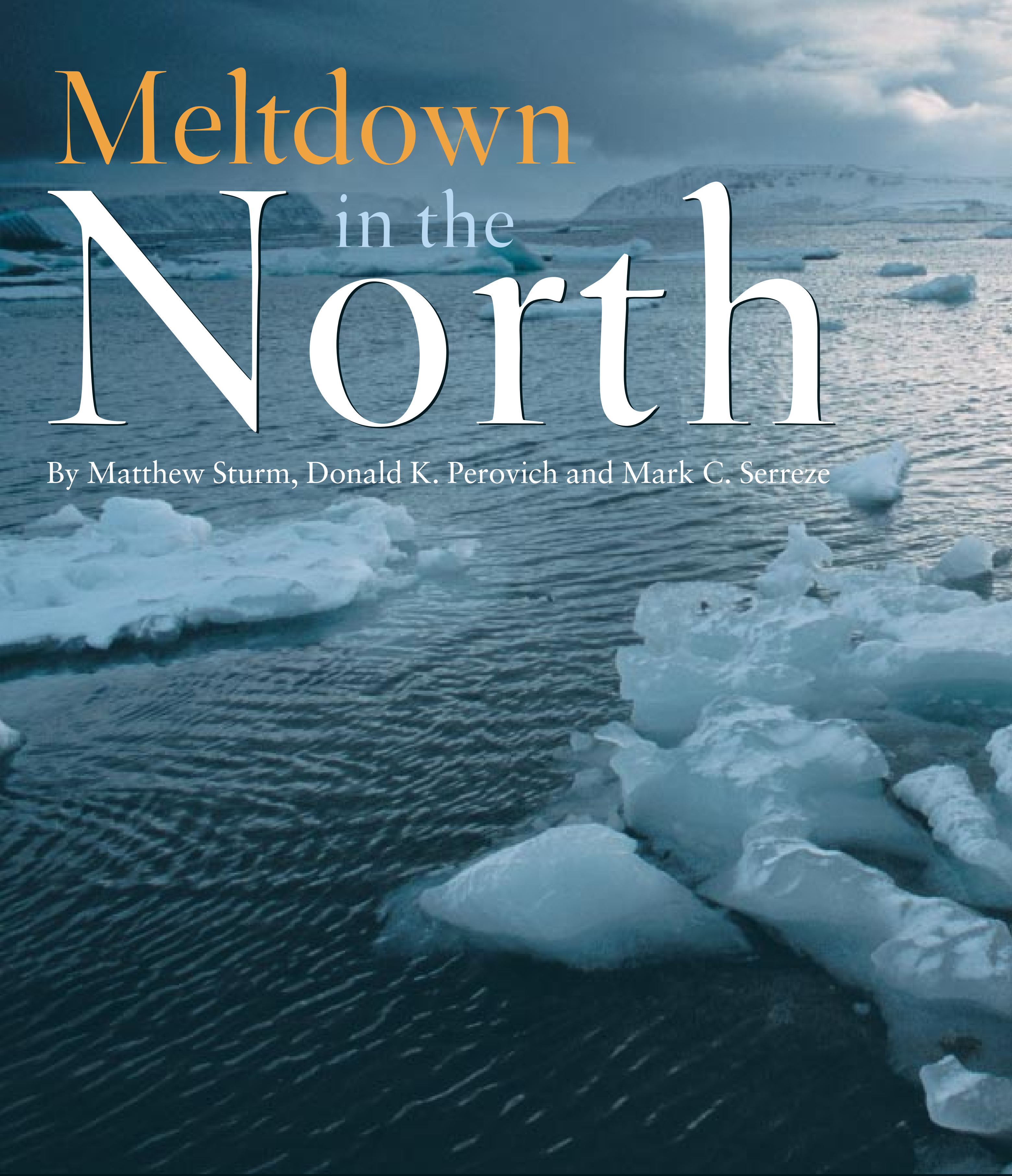
Meltdown in the North

By Matthew Sturm, Donald K. Perovich and Mark C. Serreze



Sea ice and glaciers are melting, permafrost is thawing, tundra
scientists are struggling to understand how these

REDUCTION IN SEA ICE is one of the most striking measures of change in the Arctic. The total area covered by sea ice has shrunk by 3 percent during each of the past three decades. Thickness has decreased even more over this same period—as much as 40 percent in some places. The image shows the Arctic Ocean near Russia.

is yielding to shrubs—and changes will affect **not just the Arctic but the entire planet**

Snow crystals sting my face and coat my beard and the ruff of my parka. As the wind rises, it becomes difficult to see my five companions through the blowing snow. We are 500 miles into a 750-mile snowmobile trip across Arctic Alaska. We have come, in the late winter of 2002, to measure the thickness of the snow cover and estimate its insulating capacity, an important factor in maintaining the thermal balance of the permafrost. I have called a momentary halt to decide what to do. The rising wind, combined with −30 degree Fahrenheit temperatures, makes it clear we need to find shelter, and fast. I put my face against the hood of my nearest companion and shout: "Make sure everyone stays close together. We have to get off this exposed ridge."

At the time, the irony that we might freeze to death while looking for evidence of global warming was lost on me, but later, snug in our tents, I began to laugh at how incongruous that would have been. —Matthew Sturm

The list is impressively long: The warmest air temperatures in four centuries, a shrinking sea-ice cover, a record amount of melting on the Greenland Ice Sheet, Alaskan glaciers retreating at unprecedented rates. Add to this the increasing discharge from Russian rivers, an Arctic growing season that has lengthened by several days per decade, and permafrost that has started to thaw. Taken together, these observations announce in a way no single measurement could that the Arctic is undergoing a profound transformation. Its full extent has come to light only in the past decade, after scientists in different disciplines began comparing their findings. Now many of those scientists are collaborating, trying to understand the ramifications of the changes and to predict what lies ahead for the Arctic and the rest of the globe.

What they learn will have planetwide importance because the Arctic exerts an outsize degree of control on the climate. Much as a spillway in a dam controls the level of a reservoir, the polar regions control the earth's heat balance. Because more solar energy is absorbed in the tropics than at the poles, winds and ocean currents constantly transport heat poleward, where the extensive snow and ice cover influences its fate. As long as this highly reflective cover is intact and extensive, sunlight coming directly into the Arctic is mostly reflected back into space, keeping the Arctic cool and a good repository for the heat brought in from lower latitudes. But if the cover begins to melt and shrink, it will reflect less sunlight, and the Arctic will become a poorer repository, eventually warming the climate of the entire planet.

Figuring out just what will happen, however, is fraught with complications. The greatest of these stems from the intricate feedback systems that govern the climate in the Arctic. Some of these processes are positive, amplifying change and turning a nudge into a shove, and some are negative, behaving as a brake on the system and mitigating change.

Chief among these processes is the ice-albedo feedback [*see box on page 66*], in which rising temperatures produce shorter winters and less extensive snow and ice cover, with ripple effects all the way back through the midlatitudes. Another feedback is associated with the large stores of carbon frozen into the Arctic in the form of peat. As the climate warms and this peat thaws, it could release carbon dioxide into the atmosphere and enhance warming over not just the Arctic but the whole globe—a phenomenon commonly referred to as greenhouse warming.

The key problem is that we don't fully understand how some of these feedback processes work in isolation, let alone how they interact. What we do know is that the Arctic is a complex system: change one thing, and everything else responds, sometimes in a counterintuitive way.

Heating Up

THE MORE WE LOOK, the more change we see. Arctic air temperatures have increased by 0.5 degree Celsius each decade over the past 30 years, with most of the warming coming in winter and spring. Proxy records (ice and peat cores, lake sediments), which tell us mostly about summer temperatures, put this recent warming in perspective. They indicate that late 20th- and early 21st-century temperatures are at their highest level in 400 years. The same records tell us that these high levels are the result of steady warming for 100 years as the Arctic emerged from the Little Ice Age, a frigid period that ended around 1850, topped off by a dramatic acceleration of the warming in the past half a century.

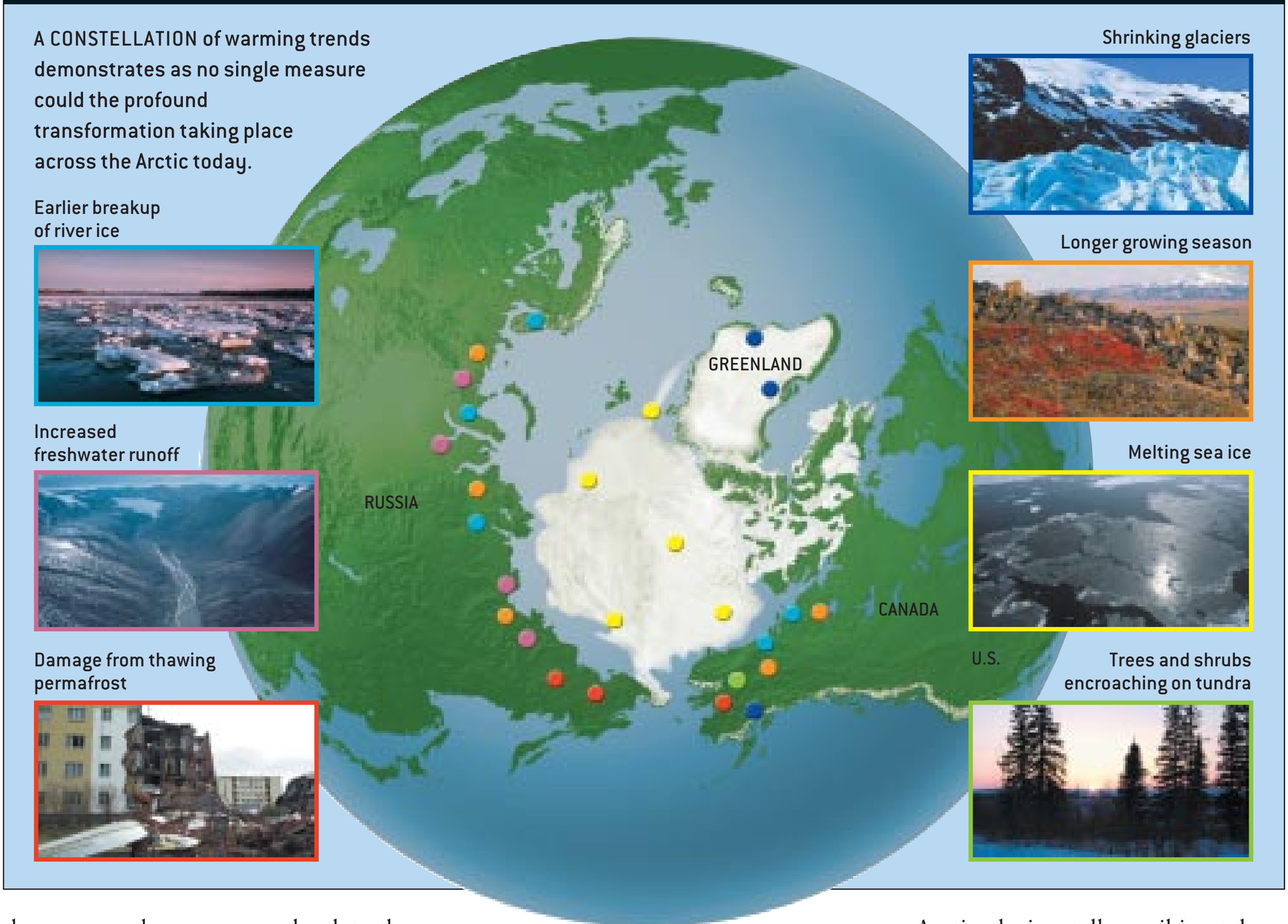
The recent temperature trends are mirrored in many other time series. One example is that Arctic and Northern Hemisphere river and lake ice has been forming later and melting earlier since the Little Ice Age. The total ice-cover season is 16 days shorter than it was in 1850. Near one of our homes (Sturm's) in Alaska, a jackpot of about $300,000 awaits

Overview/*Arctic Warming*

- Signs of warming are everywhere in the Arctic, and these changes are bound to affect conditions on the rest of the planet because the polar regions exert an outsize control on the earth's heat balance.
- A complex web of climatic feedback systems makes it extremely difficult to know whether greenhouse warming is the primary cause of the transformation in the Arctic.
- But whatever is causing the changes, scientists face the urgent task of predicting what lies ahead rather than waiting to react to the consequences as they unfold.

GALEN ROWELL *Corbis (preceding pages)*

A CATALOGUE OF CHANGES



A CONSTELLATION of warming trends demonstrates as no single measure could the profound transformation taking place across the Arctic today.

LUCY READING (*illustration*); CLOCKWISE FROM TOP RIGHT: CORBIS; SCOTT T. SMITH *Corbis*; JACQUES LANGEVIN *Corbis Sygma*; GLEN LISTON; VLADIMIR ROMANOVSKY; JIM BRANDENBURG *Minden Pictures*; GALEN ROWELL *Corbis*

the person who can guess the date the Tanana River will break up every spring. The average winning date has gotten earlier by about six days since the betting pool was instituted in 1917. Higher-tech data—satellite images—show that the snow-free season in the Arctic has lengthened by several days each decade since the early 1970s. Similarly, the growing season has increased by as much as four days.

Shrinking Glaciers, Thawing Permafrost

THERE WAS NOTHING *complex about my first research in Arctic climate change: march around a small glacier on Ellesmere Island, drill holes in the ice, insert long metal poles in the holes, measure them, come back a year later and see if more pole was showing.*

We put in most of the pole network in the warm summer of 1982 and returned in 1983 to a very different world—week after week of cold, snow and fog. It looked like the start of a new ice age. Our plan had been to go back annually, but as so often happens, funding dried up, and my Arctic experiences became fond memories.

But memories sometimes get refreshed. In 2002 I got a call from an excited graduate student. He had revisited the glacier. It was rapidly wasting away. 1983 had been an anomaly. My stakes were there, except they were all lying on the surface of the ice. How deeply had I installed them? Did I still have my field notes? He need not have worried. There was my field book, dusty but safe in my bookcase. Now I'm going back to Ellesmere Island, to see what's left of the glacier that in 1983 seemed like such a permanent feature of the landscape but that I now realize may well die before I do.

—Mark C. Serreze

Arctic glaciers tell a striking tale as well. In Alaska, they have been shrinking for five decades, and more startlingly, the rate of shrinkage has increased threefold in the past 10 years. The melting glaciers translate into a rise in sea level of about two millimeters a decade, or 10 percent of the total annual rise of 20 millimeters. Determining the state of the much larger and more slowly changing Greenland Ice Sheet has been something of a Holy Grail for Arctic researchers. Older field and satellite results suggested that the ice sheet was exhibiting asymmetrical behavior—the west side thinning in a modest way and the east side remaining in balance. Recent satellite images indicate that the melt rate over the entire ice sheet has been increasing with time. The total area melting in a given summer has increased by 7 percent each decade since 1978, with last summer setting an all-time record. Winter snowfall appears insufficient to offset this heavy summer melt, so the sheet is shrinking.

The permafrost—the permanently frozen layer below the surface—is thawing, too. In a study published in 1986, researchers from the U.S. Geological Survey carefully logged temperature profiles in deep oil-exploration boreholes drilled through the permafrost of northern Alaska. When they extrapolated the profiles to the surface, they found an anomalous curvature that was best explained by a warming at ground level of two to four degrees C during the preceding few decades. More recently, preliminary results suggest an additional increase of two to three degrees C has occurred since 1986. Because the Arctic winter lasts nine months of the year, snow cover controls the thermal state of the ground as much as air temperature does, so these borehole records almost certainly reflect a change in the amount and timing of winter precipitation as well as an increase in temperature. More snow means thicker insulation and therefore better protection for the ground from frigid winter temperatures. Ground that is not chilled as much in the winter is primed for more warming in the summer.

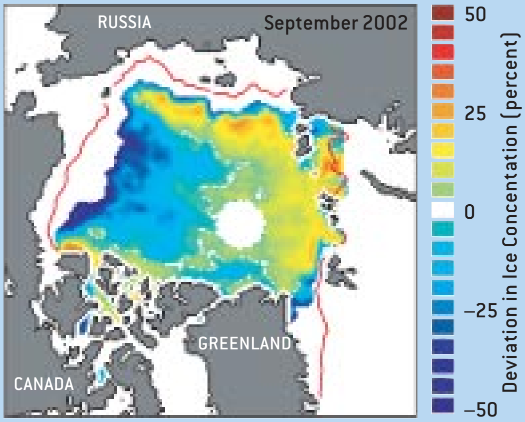
Regardless of why it is occurring, one thing is certain. Thawing permafrost is trouble. It can produce catastrophic failure of roads, houses and other infrastructure. It is also implicated in another recently detected change: over the past 60 years, the discharge of freshwater from Russian rivers into the Arctic Basin has increased by 7 percent—an amount equivalent to roughly one quarter the volume of Lake Erie or three months of the outflow of the Mississippi River. Scientists attribute the change partly to greater winter precipitation and partly to a warming of the permafrost and active layer, which they believe is now transporting more groundwater. This influx of freshwater could have important implications for global climate: the paleo-record suggests that when the outflow of water from the Arctic Basin hits a critical level of freshness, the global ocean circulation changes dramatically. When ocean circulation changes, climate does as well, because the circulation system—essentially a set of moving rivers of water in the ocean, such as the Gulf Stream—is one of the prime conveyors of heat northward toward the pole.

Greening of the Arctic

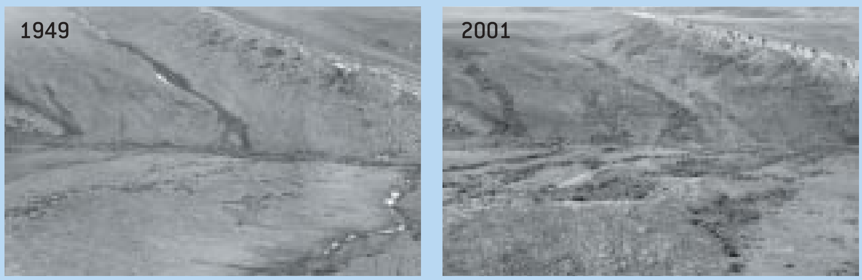
THE ARCTIC LAND COVER is also shifting. Based on warming experiments using greenhouses, biologists have known for some time that shrubs will grow at the expense of the other tundra plants when the climate warms. Under the same favorable growing conditions, the tree line will migrate north. Researchers have been looking for these modifications in the real world, but ecosystem responses can be slow. Only in the past few years, by comparing modern photo-

THE HARD, NOT SO COLD FACTS

SCIENTISTS PUZZLING over alterations in the Arctic now have the benefit of many years of data from various sources to help them. The patterns they have extracted from these records reveal that the warming trend is far greater than would be expected if the climate were following a natural progression from the Little Ice Age to a less frigid temperature regime—which indicates that greenhouse warming cannot be ruled out as a cause.



RECORD for minimum sea ice was measured in September 2002; the red line shows average sea ice cover for this time of year. Colors indicate the deviation in ice concentration from the historic norm. For example, the dark blue areas to the north of Alaska had between 30 and 40 percent lower concentration of ice than the average value for that time of year.

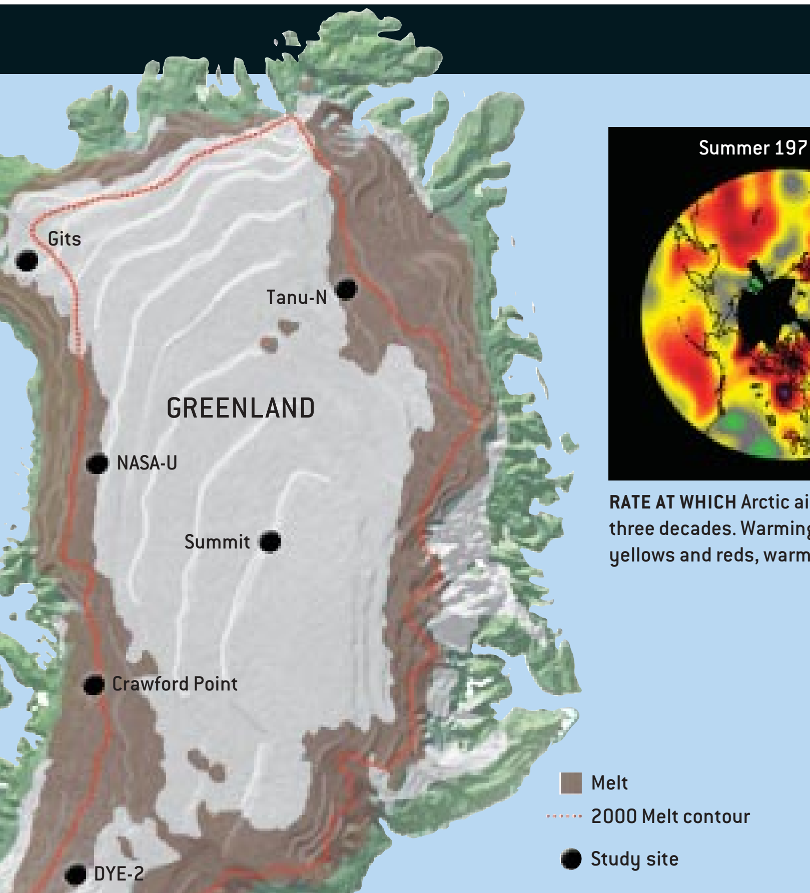


INVASION OF TUNDRA by shrubs (*dark bands*) over the past half a century is evident in these photographs taken of the same area near the Chandlar River in Alaska in 1949 and in 2001.

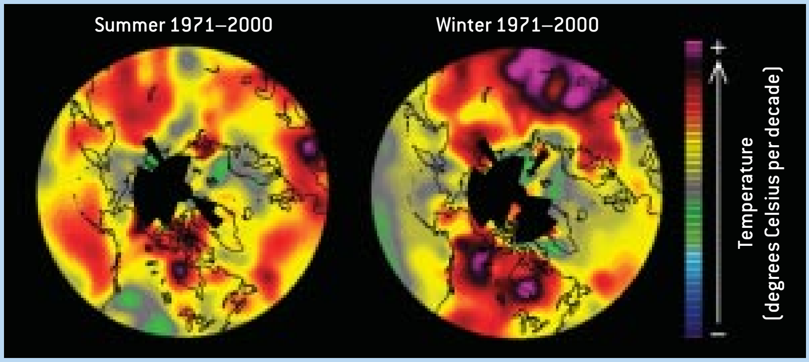
THE AUTHORS

MATTHEW STURM, DONALD K. PEROVICH and *MARK C. SERREZE* have spent most of their research careers trying to understand the snow, ice and climate of the Arctic. In 16 years at the U.S. Army Cold Regions Research and Engineering Laboratory–Alaska, Sturm has led more than a dozen winter expeditions in Arctic Alaska, including most recently a 750-mile snowmobile traverse across the region. Perovich is with the New Hampshire office of the U.S. Army Cold Regions Research and Engineering Laboratory. His work has focused on sea ice and the ice-albedo feedback. Perovich was chief scientist on Ice Station SHEBA, a yearlong drift of an icebreaker frozen into the Arctic pack ice. Since 1986 Serreze has been with the National Snow and Ice Data Center at the University of Colorado at Boulder. His studies have emphasized Arctic climate change and interactions between sea ice and the atmosphere.

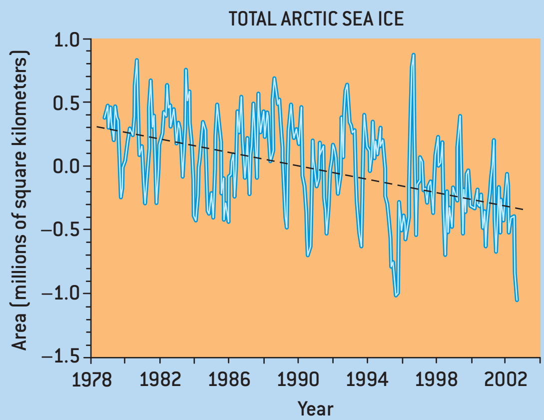
MARK C. SERREZE ET AL., 2003 (*map*); U.S. NAVY (*1949*); KEN TAPE (*2001*)



MELTING on the Greenland ice sheet set a record during the summer of 2002. The brown color shows where the ice sheet (*light-colored area*) underwent melt during the summer. The green indicates ice-free areas. Near the Dye-2 site, summer melting, usually confined to the edges of the ice sheet, extended all the way to the summit.



RATE AT WHICH Arctic air temperatures have been warming is shown for the past three decades. Warming has been greater in winter. Greens and blues indicate cooling; yellows and reds, warming. The scale bar runs from –1 to +1 degree Celsius per decade.



STRIKING REDUCTIONS in the extent of Arctic sea ice have been recorded since 1978.

LUCY READING, *SOURCE:* K. STEFFAN AND R. HUFF (*map*); CHAPMAN AND WALSH, 1993, UPDATED TO THE PRESENT BY CHAPMAN (*temperature maps*); LUCY READING, *SOURCE:* NATIONAL SNOW AND ICE DATA CENTER, BOULDER, COLO. (*graph*)

graphs with ones taken 50 years ago, and by using satellites to detect the increasing amount of leaf area, have researchers been able to document that both types of transformations are under way. As the vegetation alters, so does the role of the Arctic in the global carbon cycle. Vast stores of carbon in the form of peat underlie much of the tundra in Alaska and Russia, evidence that for long periods Arctic tundra has been a net carbon sink; about 600 cubic miles of peat are currently in cold storage. In recent years, warming has produced a shift: the Arctic now appears to be a net source of carbon dioxide. The change is subtle but troubling because carbon dioxide and methane constitute the primary greenhouse gases in the atmosphere, returning heat to the earth instead of allowing it to escape into space.

Warmer winters have driven some of the shift. When the air is warmer, more precipitation falls from the sky, some of it coming as snow. The thicker snow holds more warmth in the earth, resulting in a longer period during which the tundra is releasing carbon dioxide. But as the tundra becomes shrubbier and as the soil becomes drier in the summer as a result of higher temperatures, the balance could swing back the other way, because plants, particularly woody ones, will fix more carbon and lock it back into the Arctic ecosystem. The most recent studies suggest, in fact, that the magnitude and direction of the Arctic carbon balance depend on the time span that we are examining, with the response varying as the plants adapt to the new conditions.

Melting Sea Ice

*"*THIS SEA ICE *is ridiculously thin," I thought as I broke through the ice for the second time that morning in August 1998. There was no real danger, now that personal flotation devices had become the de rigueur fashion accessory, but the thin ice was troubling for other reasons.*

My journey to this place, 600 miles from the North Pole, had begun 10 months earlier on board the icebreaker Des Groseilliers, *which we had intentionally frozen into the pack to begin a yearlong drift. Our mission was to study ice-albedo and cloud-radiation feedbacks. When we started the journey, I was surprised at how thin the ice was. Now, after a much longer than expected summer melt season, it was thinner still, even though we had been drifting steadi-*

ly north. I was uncertain which would come first: the end of the summer or the end of the ice. Little did I know that this summer the record for minimum ice cover was being set throughout the entire western Arctic Ocean. Unfortunately for the long-term survival of the ice pack, it was a record that was easily broken in 2002. —*Donald K. Perovich*

Of all the changes we have catalogued, the most alarming by far has been the reduction in the Arctic sea-ice cover. Researchers tracking this alteration have discovered that the area covered by the ice has been decreasing by about 3 percent each decade since the advent of satellite records in 1972. This rate might be low for a financial investment, but where time is measured in centuries or millennia, it is high. With the sea ice covering an area approximately the size of the U.S., the reduction per decade is equivalent to an area the size of Colorado and New Hampshire combined, the home states of two of us (Perovich and Serreze). The change in the thickness of the ice (determined from submarines) is even more striking: as much as 40 percent lost in the past few decades. Some climate models suggest that by 2080 the Arctic Ocean will be ice-free in summer.

The melting sea ice does not raise sea level as melting glaciers do, because the ice is already floating, but it is alarming for two other reasons. Locally, the demise of the sea ice leads to the loss of a unique marine ecosystem replete with polar bears, seals and whales. Globally, an ice-free Arctic Ocean would be the extreme end point of the ice-albedo feedback—far more solar radiation would be absorbed, warming not just the Arctic but eventually every part of the earth.

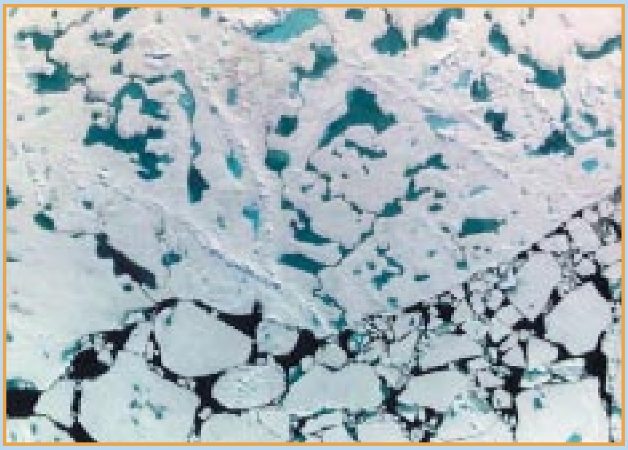
The shrinking sea-ice cover has not escaped the attention of businesspeople, tourists and politicians. Serious discussions have been under way about the feasibility of transporting cargo via Arctic waters—including through the fabled Northwest Passage, now perhaps close to being a practical shipping route because of climate change. Roald Amundsen, the redoubtable Norwegian polar explorer, took more than three years to complete the first transit of the passage in 1906, when the Arctic was still under the influ-

A COMPLEX WEB

THE MANY FEEDBACK SYSTEMS operating in the Arctic make predicting the future state of the region a challenge. The ice-albedo feedback is the granddaddy of all these systems. It works this way: land, ocean and ice reflect a fraction of the incoming sunlight, which consequently escapes into space and does not contribute to heating the climate. This fraction is called the albedo. A surface with an albedo of 1 reflects all light, and a surface with an albedo of 0 reflects none. Strikingly, the Arctic Ocean spans nearly this entire range. Where it is frozen and snow-covered, it has the highest albedo of any naturally occurring material, about 0.85, but where it is ice-free, it has the lowest, around 0.07.

In late spring the ice pack is snow-covered—bright and white. The surface reflects most, but not quite all, of the incident sunlight. Some of the ice melts, causing the ice edge to retreat and replacing the bright, highly reflecting snow-covered ice with the dark, absorbing ocean water. Moreover, away from the ocean's edge, melting snow produces ponds of water that also have a low albedo. Melting in both these areas decreases the albedo, which leads to even greater melting, and so on and on.

If the ice-albedo feedback operated in isolation, predicting its ramifications on global climate might be possible even now. But it does not. Instead multiple feedbacks, some positive and some negative, work in concert, and their net effect is difficult to assess. For example, if the albedo is reduced, the effect is to warm the climate, but then the atmosphere can hold more water vapor, and cloud cover will increase. Clouds act as an umbrella that reduces the amount of sunlight reaching the surface (resulting in cooling), but they also trap long-wave radiation from the surface like a blanket (resulting in warming). In the winter the effect is clear—no sunlight, no umbrella, only the blanket. The cloud feedback is positive.



BIRD'S-EYE VIEW of melting sea ice: turquoise water is melt pond, freshwater from melting snow on the surface of the ice; the nearly black water is ocean. Both types are much more heat-absorbing than the bright ice.

But what about in summer, when sunlight is plentiful? Field studies have shown that the feedback depends on the nature of the clouds. For high, thin clouds composed primarily of ice, the umbrella effect dominated and the cloud-radiation feedback was negative. But for the low, liquid-water clouds that are prevalent in the summer, the blanket dominated and the feedback was positive. Indeed, when these low clouds were present, more ice melted than on sunny days.

Scientists are now trying to sort out which of the feedbacks in the complex web that constitutes the Arctic are the ones we need to worry about the most. These are the ones—such as the ice-albedo feedback—that can amplify changes already under way, speeding them up and magnifying them. They are the ones that can push the system over the edge. —*M.S., D.K.P. and M.C.S.*

DONALD K. PEROVICH

ence of the Little Ice Age. Many explorers before him had died trying to make the journey. In the past few years, however, dozens of ships have completed the route, including Russian icebreakers refurbished for the tourist trade. These events would have been unimaginable, even with icebreakers, in the more intense ice conditions of 100 years ago.

Is Greenhouse Warming the Culprit?

THIS INVENTORY of startling transformation in the Arctic inevitably raises the question of whether we are still emerging from the Little Ice Age or whether something quite different is now taking place. Specifically, should we interpret these changes as being caused by the increased concentration of atmospheric greenhouse gases overriding a natural temperature cycle? Or are they part of a longer-than-expected natural cycle?

The intricate web of feedback interactions renders this question exceedingly complicated—and we don't know enough yet to answer it unequivocally. But we know enough to be very worried.

Whatever is causing the melting and thawing now wracking the Arctic, these modifications have initiated a cascade of planetwide responses that will continue even if the climate were suddenly and unexpectedly to stop warming. Imagine the climate as a big, round rock perched on uneven terrain. The inventory tells us that the rock has been pushed a little—either by a natural climate cycle or by human activity—and has started to roll. Even if the pushing stops, the rock is going to keep rolling. When it finally does stop, it will be in a completely different place than before.

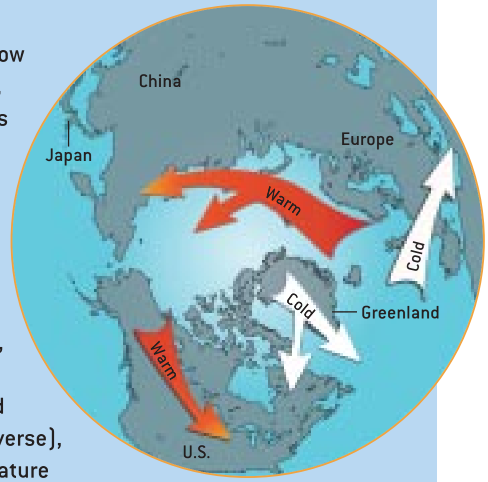
To cope with the constellation of changes in the Arctic in a concerted fashion and to develop an ability to predict what will happen next rather than just react to it, several federal agencies have begun to coordinate their Arctic research in a program called SEARCH (Study of Environmental Arctic Change). Early results give some promise for success in teasing out the linkages among the tightly coupled systems that shape the climate of the Arctic and thus the earth. A recent discovery about the patterns of wind circulation, for example, helps to explain previously puzzling spatial patterns of increasing temperature [*see box above*]. Equally important, high-quality records of climate change now extend back 30 to 50 years.

Soon these records and other findings should allow us to determine whether the Arctic transformation is a natural trend linked to emergence from the Little Ice Age or something more ominous. Our most difficult challenge in getting to that point is to come to grips with how the various feedbacks in the Arctic system interact—and to do so quickly. SA

WINDS OF CHANGE

EVEN IN THE DAYS of the Vikings, people knew that when winters in northern Europe were mild, they tended to be severe in southern Greenland, and vice versa. Today we know that this seesaw in temperature affects more than just Greenland and Europe. It is related to an atmospheric circulation pattern known as the North Atlantic Oscillation (NAO, which may be part of an even larger pattern, the Arctic Oscillation, or AO). The NAO describes the linked variation of a major low pressure area centered near Iceland with a major high pressure area centered near the Azores. When both pressure features are strong, the NAO is in its positive mode. When both are weak, it is in its negative mode.

A key feature of the NAO is that winds blow counterclockwise around the Icelandic Low, while they blow clockwise around the Azores High. In positive mode, the winds around the Icelandic Low are stronger than normal and warm air from the south streams over northern Europe and northern Eurasia. At the same time, the circulation pattern sweeps cold air down from the high Arctic over parts of Greenland, the North Atlantic and northeastern North America. When the NAO is negative, the wind pattern weakens (and at times can even reverse), which leads to roughly the opposite temperature pattern. Since about 1970, the winter NAO has been largely "stuck" in its positive mode, which helps to explain why we have observed widespread warming over Alaska, western Canada and Eurasia but regional cooling in eastern Canada and southern Greenland. The pattern has also caused increased precipitation in northern Eurasia and contributed to the reduction in sea ice. *—M.S., D.K.P. and M.C.S.*



NORTH ATLANTIC OSCILLATION is depicted in its positive mode.

A segment based on this article will air September 25 on *National Geographic Today,* a program on the National Geographic Channel. Please check your local listings.

MORE TO EXPLORE

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Global Warming and Terrestrial Ecosystems: A Conceptual Framework for Analysis. G. R. Shaver et al. in *BioScience,* Vol. 50, No. 10; 2000.

Observational Evidence of Recent Change in the Northern High-Latitude Environment. Mark Serreze et al. in *Climatic Change,* Vol. 46, pages 159–207; 2000.

The Surface Heat Budget of the Arctic Ocean (SHEBA). Special section in *Journal of Geophysical Research,* Vol. 107, No. 15; October 2002.

SEARCH Web site: **http://psc.apl.washington.edu/search/**

NOAA Arctic Climate Change Web site: **www.ngdc.noaa.gov/paleo/sciencepub/front.htm**

LUCY READING