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THE CLIMATE OF MAN—I

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Disappearing islands, thawing permafrost, melting polar ice. How the earth is changing.

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The Alaskan village of Shishmaref sits on an island known as Sarichef, five miles off the coast of the Seward Peninsula. Sarichef is a small island—no more than a quarter of a mile across and two and a half miles long—and Shishmaref is basically the only thing on it. To the north is the Chukchi Sea, and in every other direction lies the Bering Land Bridge National Preserve, which probably ranks as one of the least visited national parks in the country. During the last ice age, the land bridge—exposed by a drop in sea levels of more than three hundred feet—grew to be nearly a thousand miles wide. The preserve occupies that part of it which, after more than ten thousand years of warmth, still remains above water.

Shishmaref (pop. 591) is an Inupiat village, and it has been inhabited, at least on a seasonal basis, for several centuries. As in many native villages in Alaska, life there combines—often disconcertingly—the very ancient and the totally modern. Almost everyone in Shishmaref still lives off subsistence hunting, primarily for bearded seals but also for walrus, moose, rabbit, and migrating birds. When I visited the village one day last April, the spring thaw was under way, and the seal-hunting season was about to begin. (Wandering around, I almost tripped over the remnants of the previous year's catch emerging from storage under the snow.) At noon, the village's transportation planner, Tony Weyiouanna, invited me to his house for lunch. In the living room, an enormous television set tuned to the local public-access station was playing a rock soundtrack. Messages like "Happy Birthday to the following elders . . ." kept scrolling across the screen.

Traditionally, the men in Shishmaref hunted for seals by driving out over the sea ice with dogsleds or, more recently, on snowmobiles. After they hauled the seals back to the village, the women would skin and cure them, a process that takes several weeks. In the early nineteen-nineties, the hunters began to notice that the sea ice was changing. (Although the claim that the Eskimos have hundreds of words for snow is an exaggeration, the Inupiat make distinctions among many different types of ice, including *sikuliaq*, "young ice," *sarri*, "pack ice," and *tuvaq*, "landlocked ice.") The ice was starting to form later in the fall, and also to break up earlier in the spring. Once, it had been possible to drive out twenty miles; now, by the time the seals arrived, the ice was mushy half that distance from shore. Weyiouanna described it as having the consistency of a "slush puppy." When you encounter it, he said, "your hair starts sticking up. Your eyes are wide open. You can't even blink." It became too dangerous to hunt using snowmobiles, and the men switched to boats.

Soon, the changes in the sea ice brought other problems. At its highest point, Shishmaref is only twenty-two feet above sea level, and the houses, many built by the U.S. government, are small, boxy, and not particularly sturdy-looking. When the Chukchi Sea froze early, the layer of ice protected the village, the way a tarp prevents a swimming pool from getting roiled by the wind. When the sea started to freeze later, Shishmaref became more vulnerable to storm surges. A storm in October, 1997, scoured away a hundred-and-twenty-five-foot-wide strip from the town's northern edge; several houses were destroyed, and more than a dozen had to be relocated. During another storm, in October, 2001, the village was threatened by twelve-foot waves. In the summer of 2002, residents of Shishmaref voted, a hundred and sixty-one to twenty, to move the entire village to the mainland. Last year, the federal government completed a survey of possible sites for a new village. Most of the spots that are being considered are in areas nearly as remote as Sarichef, with no roads or nearby cities, or even settlements. It is estimated that a full relocation will cost at least a hundred and eighty million dollars.

People I spoke to in Shishmaref expressed divided emotions about the proposed move. Some worried that, by leaving the tiny island, they would give up their connection to the sea and become lost. "It makes me feel lonely," one woman said. Others seemed excited by the prospect of gaining certain conveniences, like running water, that Shishmaref lacks. Everyone seemed to agree, though, that the village's situation, already dire, was likely only to get worse.

Morris Kiyutelluk, who is sixty-five, has lived in Shishmaref almost all his life. (His last name, he told me, means "without a wooden spoon.") I spoke to him while I was hanging around the basement of the village church, which also serves as the unofficial headquarters for a group called the Shishmaref Erosion and Relocation Coalition. "The first time I heard about global warming, I thought, I don't believe those Japanese," Kiyutelluk told me. "Well, they had some good scientists, and it's become true."

The National Academy of Sciences undertook its first rigorous study of global warming in 1979. At that point, climate modelling was still in its infancy, and only a few groups, one led by Syukuro Manabe, at the National Oceanic and Atmospheric Administration, and another by James Hansen, at NASA's Goddard Institute for Space Studies, had considered in any detail the effects of adding carbon dioxide to the atmosphere. Still, the results of their work were alarming enough that President Jimmy Carter called on the academy to investigate. A nine-member panel was appointed, led by the distinguished meteorologist Jule Charney, of M.I.T.

The Ad Hoc Study Group on Carbon Dioxide and Climate, or the Charney panel, as it became known, met for five days at the National Academy of Sciences' summer study center, in Woods Hole, Massachusetts. Its conclusions were unequivocal. Panel members had looked for flaws in the modellers' work but had been unable to find any. "If carbon dioxide continues to increase, the study group finds no reason to doubt that climate changes will result and no reason to believe that these changes will be negligible," the scientists wrote. For a doubling of CO_2 from pre-industrial levels, they put the likely global temperature rise at between two and a half and eight degrees Fahrenheit. The panel members weren't sure how long it would take for changes already set in motion to become manifest, mainly because the climate system has a built-in time delay. It could take "several decades," they noted. For this reason, what might seem like the most conservative approach—waiting for evidence of warming in order to assess the models' accuracy—actually amounted to the riskiest possible strategy: "We may not be given a warning until the CO_2 loading is such that an appreciable climate change is inevitable."

It is now twenty-five years since the Charney panel issued its report, and, in that period, Americans have been alerted to the dangers of global warming so many times that volumes have been written just on the history of efforts to draw attention to the problem. (The National Academy of Sciences alone has issued nearly two hundred reports on global warming; the most recent, "Radiative Forcing of Climate Change," was published just last month.) During this same period, worldwide carbon-dioxide emissions have continued to increase, from five billion metric tons a year to seven billion, and the earth's temperature, much as predicted by Manabe's and Hansen's models, has steadily risen. The year 1990 was the warmest year on record until 1991, which was equally hot. Almost every subsequent year has been warmer still. The year 1998 ranks as the hottest year since the instrumental temperature record began, but it is closely followed by 2002 and 2003, which are tied for second; 2001, which is third; and 2004, which is fourth. Since climate is innately changeable, it's difficult to say when, exactly, in this sequence natural variation could be ruled out as the sole cause. The American Geophysical Union, one of the nation's largest and most respected scientific organizations, decided in 2003 that the matter had been settled. At the group's annual meeting that year, it issued a consensus statement declaring, "Natural influences cannot explain the rapid increase in global near-surface temperatures." As best as can be determined, the world is now warmer than it has been at any point in the last two millennia, and, if current trends continue, by the end of the century it will likely be hotter than at any point in the last two million years.

In the same way that global warming has gradually ceased to be merely a theory, so, too, its impacts are no longer just hypothetical. Nearly every major glacier in the world is shrinking; those in Glacier National Park are retreating so quickly it has been estimated that they will vanish entirely by 2030. The oceans are becoming not just warmer but more acidic; the difference between day and nighttime temperatures is diminishing; animals are shifting their ranges poleward; and plants are blooming days, and in some cases weeks, earlier than they used to. These are the warning signs that the Charney panel cautioned against waiting for, and while in many parts of the globe they are still subtle enough to be overlooked, in others they can no longer be ignored. As it happens, the most dramatic changes are occurring in those places, like Shishmaref, where the fewest people tend to live. This disproportionate effect of global warming in the far north was also predicted by early climate models, which forecast, in column after column of FORTRAN-generated figures, what today can be measured and observed directly: the Arctic is melting.

Most of the land in the Arctic, and nearly a quarter of all the land in the Northern Hemisphere—some five and a half billion acres—is underlaid by zones of permafrost. A few months after I visited Shishmaref, I took a trip through the interior of Alaska with Vladimir Romanovsky, a geophysicist and permafrost expert at the University of Alaska. I flew into Fairbanks, where Romanovsky lives, and when I arrived the whole city was enveloped in a dense haze that looked like fog but smelled like burning rubber. People kept telling me that I was lucky I hadn't come a couple of weeks earlier, when it had been much worse. "Even the dogs were wearing masks," one woman I met said. I must have smiled. "I am not joking," she told me.

Fairbanks, Alaska's second-largest city, is surrounded on all sides by forest, and virtually every summer lightning sets off fires in these forests, which fill the air with smoke for a few days or, in bad years, weeks. This past summer, the fires started early, in June, and were still burning two and a half months later; by the time of my visit, in late August, a record 6.3 million acres—an area roughly the size of New Hampshire—had been incinerated. The severity of the fires was clearly linked to the weather, which had been exceptionally hot and dry; the average summertime temperature in Fairbanks was the highest on record, and the amount of rainfall was the third lowest.

On my second day in Fairbanks, Romanovsky picked me up at my hotel for an underground tour of the city. Like most permafrost experts, he is from Russia. (The Soviets more or less invented the study of permafrost when they decided to build their gulags in Siberia.) A broad man with shaggy brown hair and a square jaw, Romanovsky as a student had had to choose between playing professional hockey and becoming a geophysicist. He had opted for the latter, he told me, because "I was little bit better scientist than hockey player." He went on to earn two master's degrees and two Ph.D.s. Romanovsky came to get me at 10 A.M.; owing to all the smoke, it looked like dawn.

Any piece of ground that has remained frozen for at least two years is, by definition, permafrost. In some places, like eastern Siberia, permafrost runs nearly a mile deep; in Alaska, it varies from a couple of hundred feet to a couple of thousand feet deep. Fairbanks, which is just below the Arctic Circle, is situated in a region of discontinuous permafrost, meaning that the city is freckled with regions of frozen ground. One of the first stops on Romanovsky's tour was a hole that had opened up in a patch of permafrost not far from his house. It was about six feet wide and five feet deep. Nearby were the outlines of other, even bigger holes, which, Romanovsky told me, had been filled with gravel by the local public-works department. The holes, known as thermokarsts, had appeared suddenly when the permafrost gave way, like a rotting floorboard. (The technical term for thawed permafrost is talik, from a Russian word meaning "not frozen.") Across the road, Romanovsky pointed out a long trench running into the woods. The trench, he explained, had been formed when a wedge of underground ice had melted. The spruce trees that had been growing next to it, or perhaps on top of it, were now listing at odd angles, as if in a gale. Locally, such trees are called "drunken." A few of the spruces had fallen over. "These are very drunk," Romanovsky said.

In Alaska, the ground is riddled with ice wedges that were created during the last glaciation, when the cold earth cracked and the cracks filled with water. The wedges, which can be dozens or even hundreds of feet deep, tended to form in networks, so that when they melt they leave behind connecting diamond- or hexagonal-shaped depressions. A few blocks beyond the drunken forest, we came to a house where the front yard showed clear signs of ice-wedge melt-off. The owner, trying to make the best of things, had turned the yard into a miniature-golf course. Around the corner, Romanovsky pointed out a house—no longer occupied—that had basically split in two; the main part was leaning to the right and the garage toward the left. The house had been built in the sixties or early seventies; it had survived until almost a decade ago, when the permafrost under it started to degrade. Romanovsky's mother-in-law used to own two houses on the same block. He had urged her to sell them both. He pointed out one, now under new ownership; its roof had developed an ominous-looking ripple. (When Romanovsky went to buy his own house, he looked only in permafrost-free areas.)

"Ten years ago, nobody cared about permafrost," he told me. "Now everybody wants to know." Measurements that Romanovsky and his colleagues at the University of Alaska have made around Fairbanks show that the temperature of the permafrost has risen to the point where, in many places, it is now less than one degree below freezing. In places where permafrost has been disturbed, by roads or houses or lawns, much of it is already thawing. Romanovsky has also been monitoring the permafrost on the North Slope and has found that there, too, are regions where the permafrost is very nearly thirty-two degrees Fahrenheit. While the age of permafrost is difficult to determine, Romanovsky estimates that most of it in Alaska probably dates back to the beginning of the last glacial cycle. This means that if it thaws it will be doing so for the first time in more than a hundred and twenty thousand years. "It's really a very interesting time," he said.

The next morning, Romanovsky picked me up at seven. We were going to drive from Fairbanks nearly five hundred miles north to the town of Deadhorse, on Prudhoe Bay, to collect data from electronic monitoring stations that Romanovsky had set up. Since the road was largely unpaved, he had rented a truck for the occasion. Its windshield was cracked in several places. When I suggested this could be a problem, Romanovsky assured me that it was "typical Alaska." For provisions, he had brought along an oversized bag of Tostitos.

The road that we were travelling on had been built for Alaskan oil, and the pipeline followed it, sometimes to the left, sometimes to the right. (Because of the permafrost, the pipeline runs mostly aboveground, on pilings.) Trucks kept passing us, some with severed caribou heads strapped to their roofs, others advertising the Alyeska Pipeline Service Company. About two hours outside Fairbanks, we started to pass through tracts of forest that had recently burned, then tracts that were still smoldering, and, finally, tracts that were still, intermittently, in flames. The scene was part Dante, part "Apocalypse Now." We crawled along through the smoke. Beyond the town of Coldfoot—really just a gas station—we passed the tree line. An evergreen was marked with a plaque that read "Farthest North

Spruce Tree on the Alaska Pipeline: Do Not Cut.” Predictably, someone had taken a knife to it. A deep gouge around the trunk was bound with duct tape. “I think it will die,” Romanovsky said.

Finally, at around five in the afternoon, we reached the turnoff for the first monitoring station. Because one of Romanovsky’s colleagues had nursed dreams—never realized—of travelling to it by plane, it was near a small airstrip, on the far side of a river. We pulled on rubber boots and forded the river, which, owing to the lack of rain, was running low. The site consisted of a few posts sunk into the tundra; a solar panel; a two-hundred-foot-deep borehole with heavy-gauge wire sticking out of it; and a white container, resembling an ice chest, that held computer equipment. The solar panel, which the previous summer had been mounted a few feet off the ground, was now resting on the scrub. At first, Romanovsky speculated that this was a result of vandalism, but after inspecting things more closely he decided that it was the work of a bear. While he hooked up a laptop computer to one of the monitors inside the white container, my job was to keep an eye out for wildlife.

For the same reason that it is sweaty in a coal mine—heat flux from the center of the earth—permafrost gets warmer the farther down you go. Under equilibrium conditions—which is to say, when the climate is stable—the very warmest temperatures in a borehole will be found at the bottom and they will decrease steadily as you go higher. In these circumstances, the lowest temperature will be found at the permafrost’s surface, so that, plotted on a graph, the results will be a tilted line. In recent decades, though, the temperature profile of Alaska’s permafrost has drooped. Now, instead of a straight line, what you get is shaped more like a sickle. The permafrost is still warmest at the very bottom, but instead of being coldest at the top it is coldest somewhere in the middle, and warmer again toward the surface. This is an unambiguous sign that the climate is heating up.

“It’s very difficult to look at trends in air temperature, because it’s so variable,” Romanovsky explained after we were back in the truck, bouncing along toward Deadhorse. It turned out that he had brought the Tostitos to stave off not hunger but fatigue—the crunching, he said, kept him awake—and by now the bag was more than half empty. “So one year you have around Fairbanks a mean annual temperature of zero”—thirty-two degrees Fahrenheit—“and you say, ‘Oh yeah, it’s warming,’ and other years you have a mean annual temperature of minus six”—twenty-one degrees Fahrenheit—“and everybody says, ‘Where? Where is your global warming?’ In the air temperature, the signal is very small compared to noise. What permafrost does is it works as a low-pass filter. That’s why we can see trends much easier in permafrost temperatures than we can see them in atmosphere.” In most parts of Alaska, the permafrost has warmed by three degrees since the early nineteen-eighties. In some parts of the state, it has warmed by nearly six degrees.

When you walk around in the Arctic, you are stepping not on permafrost but on something called the “active layer.” The active layer, which can be anywhere from a few inches to a few feet deep, freezes in the winter but thaws over the summer, and it is what supports the growth of plants—large spruce trees in places where conditions are favorable enough and, where they aren’t, shrubs and, finally, just lichen. Life in the active layer proceeds much as it does in more temperate regions, with one critical difference. Temperatures are so low that when trees and grasses die they do not fully decompose. New plants grow out of the half-rotted old ones, and when these plants die the same thing happens all over again. Eventually, through a process known as cryoturbation, organic matter is pushed down beneath the active layer into the permafrost, where it can sit for thousands of years in a botanical version of suspended animation. (In Fairbanks, grass that is still green has been found in permafrost dating back to the middle of the last ice age.) In this way, much like a peat bog or, for that matter, a coal deposit, permafrost acts as a storage unit for accumulated carbon.

One of the risks of rising temperatures is that this storage process can start to run in reverse. Under the right conditions, organic material that has been frozen for millennia will break down, giving off carbon dioxide or methane, which is an even more powerful greenhouse gas. In parts of the Arctic, this is already happening. Researchers in Sweden, for example, have been measuring the methane output of a bog known as the Stordalen mire, near the town of Abisko, for almost thirty-five years. As the permafrost in the area has warmed, methane releases have increased, in some spots by up to sixty per cent. Thawing permafrost could make the active layer more hospitable to plants, which are a sink for carbon. Even this, though, probably wouldn't offset the release of greenhouse gases. No one knows exactly how much carbon is stored in the world's permafrost, but estimates run as high as four hundred and fifty billion metric tons.

"It's like ready-use mix—just a little heat, and it will start cooking," Romanovsky told me. It was the day after we had arrived in Deadhorse, and we were driving through a steady drizzle out to another monitoring site. "I think it's just a time bomb, just waiting for a little warmer conditions." Romanovsky was wearing a rain suit over his canvas work clothes. I put on a rain suit that he had brought along for me. He pulled a tarp out of the back of the truck.

Whenever he has had funding, Romanovsky has added new monitoring sites to his network. There are now sixty of them, and while we were on the North Slope he spent all day and also part of the night—it stayed light until nearly eleven—rushing from one to the next. At each site, the routine was more or less the same. First, Romanovsky would hook up his computer to the data logger, which had been recording permafrost temperatures on an hourly basis since the previous summer. (When it was raining, he would perform this step hunched under the tarp.) Then he would take out a metal probe shaped like a "T" and poke it into the ground at regular intervals, measuring the depth of the active layer. The probe was a metre long, which, it turned out, was no longer quite long enough. The summer had been so warm that almost everywhere the active layer had grown deeper, in some spots by just a few centimetres, in other spots by more than that; in places where the active layer was particularly deep, Romanovsky had had to work out a new way of measuring it using the probe and a wooden ruler. Eventually, he explained, the heat that had gone into increasing the depth of the active layer would work its way downward, bringing the permafrost that much closer to the thawing point. "Come back next year," he advised me.

On the last day I spent on the North Slope, a friend of Romanovsky's, Nicolai Panikov, a microbiologist at the Stevens Institute of Technology, in New Jersey, arrived. Panikov had come to collect cold-loving microörganisms known as psychrophiles. He was planning to study these organisms in order to determine whether they could have functioned in the sort of conditions that, it is believed, were once found on Mars. Panikov told me that he was quite convinced that Martian life existed—or, at least, had existed. Romanovsky expressed his opinion on this by rolling his eyes; nevertheless, he had agreed to help Panikov dig up some permafrost.

That day, I also flew with Romanovsky by helicopter to a small island in the Arctic Ocean, where he had set up yet another monitoring site. The island, just north of the seventieth parallel, was a bleak expanse of mud dotted with little clumps of yellowing vegetation. It was filled with ice wedges that were starting to melt, creating a network of polygonal depressions. The weather was cold and wet, so while Romanovsky hunched under his tarp I stayed in the helicopter and chatted with the pilot. He had lived in Alaska since 1967. "It's definitely gotten warmer since I've been here," he told me. "I have really noticed that."

When Romanovsky emerged, we took a walk around the island. Apparently, in the spring it had been a nesting site for birds, because everywhere we went there were bits of eggshell and piles of droppings. The island was only about ten feet above sea level, and at the edges it dropped off sharply into the water. Romanovsky pointed out a spot along the shore where the previous summer a series of ice wedges had been exposed. They had since melted, and the ground behind them had given way in a cascade of black mud. In a few years, he said, he expected more ice wedges would be exposed, and then these would melt, causing further erosion. Although the process was different in its mechanics from what was going on in Shishmaref, it had much the same cause and, according to Romanovsky, was likely to have the same result. “Another disappearing island,” he said, gesturing toward some freshly exposed bluffs. “It’s moving very, very fast.”

On September 18, 1997, the Des Groseilliers, a three-hundred-and-eighteen-foot-long icebreaker with a bright-red hull, set out from the town of Tuktoyaktuk, on the Beaufort Sea, and headed north under overcast skies. Normally, the Des Groseilliers, which is based in Québec City, is used by the Canadian Coast Guard, but for this particular journey it was carrying a group of American geophysicists, who were planning to jam it into an ice floe. The scientists were hoping to conduct a series of experiments as they and the ship and the ice floe all drifted, as one, around the Arctic Ocean. The expedition had taken several years to prepare for, and during the planning phase its organizers had carefully consulted the findings of a previous Arctic expedition, which took place back in 1975. Based on those findings, they had decided to look for a floe averaging nine feet thick. But when they reached the area where they planned to overwinter—at seventy-five degrees north latitude—they found that not only were there no floes nine feet thick but there were barely any that reached six feet. One of the scientists on board recalled the reaction on the Des Groseilliers this way: “It was like ‘Here we are, all dressed up and nowhere to go.’ We imagined calling the sponsors at the National Science Foundation and saying, ‘Well, you know, we can’t find any ice.’ ”

Sea ice in the Arctic comes in two varieties. There is seasonal ice, which forms in the winter and then melts in the summer, and perennial ice, which persists year-round. To the untrained eye, all sea ice looks pretty much the same, but by licking it you can get a good idea of how long a particular piece has been floating around. When ice begins to form in seawater, it forces out the salt, which has no place in the crystal structure. As the ice gets thicker, the rejected salt collects in tiny pockets of brine too highly concentrated to freeze. If you suck on a piece of first-year ice, it will taste salty. Eventually, if the ice survives, these pockets of brine drain out through fine, vein-like channels, and the ice becomes fresher. Multiyear ice is so fresh that if you melt it you can drink it.

The most precise measurements of Arctic sea ice have been made by NASA, using satellites equipped with microwave sensors. In 1979, the satellite data show, perennial sea ice covered 1.7 billion acres, or an area nearly the size of the continental United States. The ice’s extent varies from year to year, but since then the over-all trend has been strongly downward. The losses have been particularly great in the Beaufort and Chukchi Seas, and also considerable in the Siberian and Laptev Seas. During this same period, an atmospheric circulation pattern known as the Arctic Oscillation has mostly been in what climatologists call a “positive” mode. The positive Arctic Oscillation is marked by low pressure over the Arctic Ocean, and it tends to produce strong winds and higher temperatures in the far north. No one really knows whether the recent behavior of the Arctic Oscillation is independent of global warming or a product of it. By now, though, the perennial sea ice has shrunk by roughly two hundred and fifty million acres, an area the size of New York, Georgia, and Texas combined. According to mathematical models, even the extended period of a positive Arctic Oscillation can account for only part of this loss.

The researchers aboard the Des Groseilliers knew that the Arctic sea ice was retreating; that was, in fact, why they were there. At the time, however, there wasn’t much data on trends in sea-ice depth. (Since then, a limited amount of information on this topic—gathered, for rather different purposes, by nuclear submarines—has been declassified.) Eventually, the researchers decided to settle for the best ice floe they could find. They picked one that stretched over some thirty square miles and in some spots was six feet thick, in some spots three. Tents were set up on the floe to house experiments, and a safety protocol was established: anyone venturing out onto the ice had to travel with a buddy and a radio. (Many also carried a gun, in case of polar-bear problems.) Some of the scientists speculated that, since the ice was abnormally thin, it would grow during the expedition. The opposite turned out to be the case. The Des Groseilliers spent twelve months frozen into the floe, and, during that time, it drifted some three hundred miles north. Nevertheless, at the end of the year, the average thickness of the ice had declined, in some spots by as much as a third. By August, 1998, so many of the scientists had fallen through that a new requirement was added to the protocol: anyone who set foot off the ship had to wear a life jacket.

Donald Perovich has studied sea ice for thirty years, and on a rainy day last fall I went to visit him at his office in Hanover, New Hampshire. Perovich works for the Cold Regions Research and Engineering Laboratory, or CRREL (pronounced "crell"), a division of the U.S. Army established in 1961 in anticipation of a very cold war. (The assumption was that if the Soviets invaded they would probably do so from the north.) He is a tall man with black hair, very black eyebrows, and an earnest manner. His office is decorated with photographs from the Des Groseilliers expedition, for which he served as the lead scientist; there are shots of the ship, the tents, and, if you look closely enough, the bears. One grainy-looking photo shows someone dressed up as Santa Claus, celebrating Christmas out on the ice. "The most fun you could ever have" was how Perovich described the expedition to me.

Perovich's particular area of expertise, in the words of his CRREL biography, is "the interaction of solar radiation with sea ice." During the Des Groseilliers expedition, he spent most of his time monitoring conditions on the floe using a device known as a spectroradiometer. Facing toward the sun, a spectroradiometer measures incident light, and facing toward earth it measures reflected light. If you divide the latter by the former, you get a quantity known as albedo. (The term comes from the Latin word for "whiteness.") During April and May, when conditions on the floe were relatively stable, Perovich took measurements with his spectroradiometer once a week, and during June, July, and August, when they were changing more rapidly, he took measurements every other day. The arrangement allowed him to plot exactly how the albedo varied as the snow on top of the ice turned to slush, and then the slush became puddles, and, finally, some of the puddles melted through to the water below.

An ideal white surface, which reflected all the light that shone on it, would have an albedo of one, and an ideal black surface, which absorbed all the light, would have an albedo of zero. The albedo of the earth, in aggregate, is 0.3, meaning that a little less than a third of the sunlight that hits it gets reflected back out. Anything that changes the earth's albedo changes how much energy the planet absorbs, with potentially dramatic consequences. "I like it because it deals with simple concepts, but it's important," Perovich told me.

At one point, Perovich asked me to imagine that we were looking down at the earth from a spaceship above the North Pole. "It's springtime, and the ice is covered with snow, and it's really bright and white," he said. "It reflects over eighty per cent of the incident sunlight. The albedo's around 0.8, 0.9. Now, let's suppose that we melt that ice away and we're left with the ocean. The albedo of the ocean is less than 0.1; it's like 0.07.

"Not only is the albedo of the snow-covered ice high; it's the highest of anything we find on earth," he went on. "And not only is the albedo of water low; it's pretty much as low as anything you can find on earth. So what you're doing is you're replacing the best reflector with the worst reflector." The more open water that's exposed, the more solar energy goes into heating the ocean. The result is a positive feedback, similar to the one between thawing permafrost and carbon releases, only more direct. This so-called ice-albedo feedback is believed to be a major reason that the Arctic is warming so rapidly.

"As we melt that ice back, we can put more heat into the system, which means we can melt the ice back even more, which means we can put more heat into it, and, you see, it just kind of builds on itself," Perovich said. "It takes a small nudge to the climate system and amplifies it into a big change."

A few dozen miles to the east of CRREL, not far from the Maine-New Hampshire border, is a small park called the Madison Boulder Natural Area. The park's major—indeed, only—attraction is a block of granite the size of a two-story house. The Madison Boulder is thirty-seven feet wide and eighty-three feet long and weighs about ten million pounds. It was plucked out of the White Mountains and deposited in its current location eleven thousand years ago, and it illustrates how relatively minor changes to the climate system have, when amplified, yielded cataclysmic results.

Geologically speaking, we are now living in a warm period after an ice age. Over the past two million years, huge ice sheets have advanced across the Northern Hemisphere and retreated again more than twenty times. (Each major glaciation tended, for obvious reasons, to destroy the evidence of its predecessors.) The most recent advance, called the Wisconsin, began roughly a hundred and twenty thousand years ago, when ice began to creep outward from centers in Scandinavia, Siberia, and the highlands near Hudson Bay. By the time the sheets had reached their maximum southern extent, most of New England and New York and a good part of the upper Midwest were buried under ice nearly a mile thick. The ice sheets were so heavy that they depressed the crust of the earth, pushing it down into the mantle. (In some places, the process of recovery, known as isostatic rebound, is still going on.) As the ice retreated, it deposited, among other landmarks, the terminal moraine called Long Island.

It is now known, or at least almost universally accepted, that glacial cycles are initiated by slight, periodic variations in the earth's orbit. These orbital variations alter the distribution of sunlight at different latitudes during different seasons according to a complex pattern that takes a hundred thousand years to complete. But orbital variations in themselves aren't nearly sufficient to produce the sort of massive ice sheet that moved the Madison Boulder.

The crushing size of that ice sheet, the Laurentide, which stretched over some five million square miles, was the result of feedbacks, more or less analogous to those now being studied in the Arctic, only operating in reverse. As ice built up, albedo increased, leading to less heat absorption and the growth of yet more ice. At the same time, for reasons that are not entirely understood, as the ice sheets advanced $CO2$ levels declined: during each of the most recent glaciations, carbon-dioxide levels dropped almost precisely in synch with falling temperatures. During each warm period, when the ice retreated, $CO2$ levels rose again. Ice cores from Antarctica contain a record of the atmosphere stretching back more than four glacial cycles—minute samples of air get trapped in tiny bubbles—and researchers who have studied these cores have concluded that fully half the temperature difference between cold periods and warm ones can be attributed to changes in the concentrations of greenhouse gases. Antarctic ice cores also show that carbon-dioxide levels today are significantly higher than they have been at any other point in the last four hundred and twenty thousand years.

While I was at CRREL, Perovich took me to meet a colleague of his named John Weatherly. Posted on Weatherly's office door was a bumper sticker designed to be pasted—illicitly—on S.U.V.s. It said, "I'm Changing the Climate! Ask Me How!" For the last several years, Weatherly and Perovich have been working to translate the data gathered on the Des Groseilliers expedition into computer algorithms to be used in climate forecasting. Weatherly told me that some climate models—worldwide, there are about fifteen major ones in operation—predict that the perennial sea-ice cover in the Arctic will disappear entirely by the year 2080. At that point, although there would continue to be seasonal ice that forms in winter, in summer the Arctic Ocean would be completely ice-free. "That's not in our lifetime," he observed. "But it is in the lifetime of our kids."

Later, back in his office, Perovich and I talked about the long-term prospects for the Arctic. Perovich noted that the earth's climate system is so vast that it is not easily altered. "On the one hand, you think, It's the earth's climate system, it's big; it's robust. And, indeed, it has to be somewhat robust or else it would be changing all the time." On the other hand, the climate record shows that it would be a mistake to assume that change, when it comes, will come slowly. Perovich offered a comparison that he had heard from a glaciologist friend. The friend likened the climate system to a rowboat: "You can tip and then you'll just go back. You can tip it and just go back. And then you tip it and you get to the other stable state, which is upside down."

Perovich said that he also liked a regional analogy. "The way I've been thinking about it, riding my bike around here, is, You ride by all these pastures and they've got these big granite boulders in the middle of them. You've got a big boulder sitting there on this rolling hill. You can't just go by this boulder. You've got to try to push it. So you start rocking it, and you get a bunch of friends, and they start rocking it, and finally it starts moving. And then you realize, Maybe this wasn't the best idea. That's what we're doing as a society. This climate, if it starts rolling, we don't really know where it will stop."

As a cause for alarm, global warming could be said to be a nineteen-seventies idea; as pure science, however, it is much older than that. In 1859, a British physicist named John Tyndall, experimenting with a machine he had built—the world's first ratio spectrophotometer—set out to study the heat-trapping properties of various gases. Tyndall found that the most common elements in the air—oxygen and nitrogen—were transparent to both visible and infrared radiation. Gases like carbon dioxide, methane, and water vapor, by contrast, were not. Tyndall was quick to appreciate the implications of his discovery: the imperfectly transparent gases, he declared, were largely responsible for determining the earth's climate. He likened their impact to that of a dam built across a river: just as a dam "causes a local deepening of the stream, so our atmosphere, thrown as a barrier across the terrestrial rays, produces a local heightening of the temperature at the earth's surface."

The phenomenon that Tyndall identified is now referred to as the "natural greenhouse effect." It is not remotely controversial; indeed, it's an essential condition of life on earth as we know it. To understand how it works, it helps to imagine the planet without it. In that situation, the earth would constantly be receiving energy from the sun and, at the same time, constantly radiating energy back out to space. All hot bodies radiate, and the amount that they radiate is a function of their temperature. In order for the earth to be in equilibrium, the quantity of energy it sends into space must equal the quantity it is receiving. When, for whatever reason, equilibrium is disturbed, the planet will either warm up or cool down until the temperature is once again sufficient to make the two energy streams balance out.

If there were no greenhouse gases, energy radiating from the surface of the earth would flow away from it unimpeded. In that case, it would be comparatively easy to calculate how warm the planet would have to get to throw back into space the same amount of energy it absorbs from the sun. (This amount varies widely by location and time of year; averaged out, it comes to some two hundred and thirty-five watts per square metre, or roughly the energy of four household light bulbs.) The result of this calculation is a frigid zero degrees. To use Tyndall's Victorian language, if the heat-trapping gases were removed from the air for a single night "the warmth of our fields and gardens would pour itself unrequited into space, and the sun would rise upon an island held fast in the iron grip of frost."

Greenhouse gases alter the situation because of their peculiar absorptive properties. The sun's radiation arrives mostly in the form of visible light, which greenhouse gases allow to pass freely. The earth's radiation, meanwhile, is emitted mostly in the infrared part of the spectrum. Greenhouse gases absorb infrared radiation and then reëmit it—some out toward space and some back toward earth. This process of absorption and reëmission has the effect of limiting the outward flow of energy; as a result, the earth's surface and lower atmosphere have to be that much warmer before the planet can radiate out the necessary two hundred and thirty-five watts per square metre. The presence of greenhouse gases is what largely accounts for the fact that the average global temperature, instead of zero, is actually a far more comfortable fifty-seven degrees.

By the end of the nineteenth century, Tyndall's work on the natural greenhouse effect had been extended to what would today be called the "enhanced greenhouse effect." In 1894, the Swedish chemist Svante Arrhenius became convinced that humans were altering the earth's energy balance. Much as Tyndall had tried to imagine what the world would be like in the absence of greenhouse gases, Arrhenius tried to imagine what it would be like in the presence of more of them. Starting on Christmas Eve, he set out to calculate what would happen to the earth's temperature if CO_2 levels were doubled. Arrhenius described the calculations as some of the most tedious of his life. He routinely worked on them for fourteen hours a day, and was not finished for nearly a year. Finally, in December, 1895, he announced his results to the Royal Swedish Academy of Sciences.

Like the natural greenhouse effect, the enhanced greenhouse effect is—in theoretical terms, at least—uncontroversial. If greenhouse-gas levels in the atmosphere increase, all other things being equal, the earth's temperature will rise. The key uncertainties concern how this process will play out in practice, since in the real world all things rarely are equal. For several decades after Arrhenius completed his calculations, scientists were unsure to what extent mankind was even capable of affecting atmospheric carbon-dioxide levels; the general assumption was that the oceans would absorb just about everything humans could emit. Arrhenius himself predicted that it would take three thousand years of coal burning to double the CO_2 in the air, a prediction, it is now known, that was off by roughly twenty-eight centuries.

Swiss Camp is a research station set up in 1990 on a platform drilled into the Greenland ice sheet. Because the ice sheet is moving—ice flows like water, only more slowly—the camp is always in motion: in fifteen years, it has migrated by more than a mile, generally in a westerly direction. Every summer, the whole place gets flooded, and every winter its contents solidify. The cumulative effect of all this is that almost nothing at Swiss Camp functions anymore the way it was supposed to. To get into it, you have to clamber up a snowdrift and descend through a trapdoor in the roof, as if entering a ship's hold or a space module. The living quarters are no longer habitable, so now the scientists at the camp sleep outside, in tents. (The one assigned to me was the same sort used by Robert Scott on his ill-fated expedition to the South Pole.) By the time I arrived at the camp, late last May, someone had jackhammered out the center of the workspace but had left the desks encased in three-foot-high blocks of ice. Inside them I could dimly make out a tangle of wires, a bulging plastic bag, and an old dustpan.

Konrad Steffen, a professor of geography at the University of Colorado, is the director of Swiss Camp. A native of Zurich, Steffen is tall and lanky, with pale-blue eyes, blondish hair, and a blondish-gray beard. He fell in love with the Arctic when, as a graduate student in 1975, he spent a summer on Axel Heiberg Island, four hundred miles northwest of the north magnetic pole. A few years later, for his doctoral dissertation, he lived for two winters on the sea ice off Baffin Island. (Steffen told me that for his honeymoon he had wanted to take his wife to Spitsbergen, an island five hundred miles north of Norway, but she demurred, and they had ended up driving across the Sahara instead.)

When Steffen planned Swiss Camp—he built much of the place himself—it was not with global warming in mind. Rather, he was interested in meteorological conditions on what is known as the ice sheet's "equilibrium line." Along this line, winter snow and summer melt are supposed to be precisely in balance. But, in recent years, "equilibrium" has become an increasingly elusive quality. In the summer of 2002, the ice sheet melted to an unprecedented extent. Satellite images taken by NASA showed that snow had melted up to an elevation of sixty-five hundred feet. In some of these spots, ice-core records revealed, liquid water had not been seen for hundreds, perhaps thousands, of years. The following winter, there was an unusually low snowfall, and in the summer of 2003 the melt was so great that, around Swiss Camp, five feet of ice were lost.

When I arrived at the camp, the 2004 melt season was already under way. This, to Steffen, was a matter of both intense scientific interest and serious practical concern. A few days earlier, one of his graduate students, Russell Huff, and a postdoc, Nicolas Cullen, had driven out on snowmobiles to service some weather stations closer to the coast. The snow there was melting so fast that they had had to work until five in the morning, and then take a long detour back, to avoid getting caught in the quickly forming rivers. Steffen wanted to get everything that needed to be done completed ahead of schedule, in case everyone had to pack up and leave early. My first day at Swiss Camp he spent fixing an antenna that had fallen over in the previous year's melt. It was bristling with equipment, like a high-tech Christmas tree. Even on a relatively warm day on the ice sheet, which this was, it never gets more than a few degrees above freezing, and I was walking around in a huge parka, two pairs of pants plus long underwear, and two pairs of gloves. Steffen, meanwhile, was tinkering with the antenna with his bare hands. He has spent fourteen summers at Swiss Camp, and I asked him what he had learned during that time. He answered with another question.

"Are we disintegrating part of the Greenland ice sheet over the longer term?" he asked. He was sorting through a tangle of wires that to me all looked the same but must have had some sort of distinguishing characteristics. "What the regional models tell us is that we will get more melt at the coast. It will continue to melt. But warmer air can hold more water vapor, and at the top of the ice sheet you'll get more precipitation. So we'll add more snow there. We'll get an imbalance of having more accumulation at the top, and more melt at the bottom. The key question now is: What is the dominant one, the more melt or the increase?"

Greenland's ice sheet is the second-largest on earth. (Antarctica's is the largest.) In its present form, the Greenland ice sheet is, quite literally, a relic of the last glaciation. The top layers consist of snow that fell recently. Beneath these layers is snow that fell centuries and then millennia ago, until, at the very bottom, there is snow that fell a hundred and thirty thousand years ago. Under current climate conditions, the ice sheet probably would not form, and it is only its enormous size that has sustained it for this long. In the middle of the island, the ice is so thick—nearly two miles—that it creates a kind of perpetual winter. Snow falls in central Greenland year-round and it never melts, although, over time, the snow gets compacted into ice and is pressed out toward the coast. There, eventually, it either calves off into icebergs or flows away. In summertime, lakes of a spectacular iridescent blue form at the ice sheet's lower elevations; these empty into vast rivers that fan out toward the sea. Near Swiss Camp—elevation 3,770 feet—there is a huge depression where one such lake forms each July, but by that point no one is around to see it: it would be far too dangerous.

Much of what is known about the earth's climate over the last hundred thousand years comes from ice cores drilled in central Greenland, along a line known as the ice divide. Owing to differences between summer and winter snow, each layer in a Greenland core can be individually dated, much like the rings of a tree. Then, by analyzing the isotopic composition of the ice, it is possible to determine how cold it was at the time each layer was formed. (Although ice cores from Antarctica contain a much longer climate record, it is not as detailed.) Over the last decade, three Greenland cores have been drilled to a depth of ten thousand feet, and these cores have prompted a rethinking of how the climate operates. Where once the system was thought to change, as it were, only glacially, now it is known to be capable of sudden and unpredictable reversals. One such reversal, called the Younger Dryas, after a small Arctic plant—*Dryas octopetala*—that suddenly reappeared in Scandinavia, took place roughly twelve thousand eight hundred years ago. At that point, the earth, which had been warming rapidly, was plunged back into glacial conditions. It remained frigid for twelve centuries and then warmed again, even more abruptly. In Greenland, average annual temperatures shot up by nearly twenty degrees in a single decade.

As a continuous temperature record, the Greenland ice cores stop providing reliable information right around the start of the last glacial cycle. Climate records pieced together from other sources indicate that the last interglacial, which is known as the Eemian, was somewhat warmer than the present one, the Holocene. They also show that sea levels during that time were at least fifteen feet higher than they are today. One theory attributes this to a collapse of the West Antarctic Ice Sheet. A second holds that meltwater from Greenland was responsible. (When sea ice melts, it does not affect sea level, because the ice, which was floating, was already displacing an equivalent volume of water.) All told, the Greenland ice sheet holds enough water to raise sea levels worldwide by twenty-three feet. Scientists at NASA have calculated that throughout the nineteen-nineties the ice sheet, despite some thickening at the center, was shrinking by twelve cubic miles per year.

Jay Zwally is a NASA scientist who works on a satellite project known as ICESat. He is also a friend of Steffen's, and about ten years ago he got the idea of installing global-positioning-system receivers around Swiss Camp to study changes in the ice sheet's elevation. Zwally happened to be at the camp while I was there, and the second day of my visit we all got onto snowmobiles and headed out to a location known as JAR 1 (for Jakobshavn Ablation Region) to reinstall a G.P.S. receiver. The trip was about ten miles. Midway through it, Zwally told me that he had once seen spy-satellite photos of the region we were crossing, and that they had shown that underneath the snow it was full of crevasses. Later, when I asked Steffen about this, he told me that he had had the whole area surveyed with bottom-seeking radar, and no crevasses of any note had been found. I was never sure which one of them to believe.

Reinstalling Zwally's G.P.S. receiver entailed putting up a series of poles, a process that, in turn, required drilling holes thirty feet down into the ice. The drilling was done not mechanically but thermally, using a steam drill that consisted of a propane burner, a steel tank to hold snow, and a long rubber hose. Everyone—Steffen, Zwally, the graduate students, me—took a turn. This meant holding onto the hose while it melted its way down, an activity reminiscent of ice fishing. Seventy-five years ago, not far from JAR 1, Alfred Wegener, the German scientist who proposed the theory of continental drift, died while on a meteorological expedition. He was buried in the ice sheet, and there is a running joke at Swiss Camp about stumbling onto his body. "It's Wegener!" one of the graduate students exclaimed, as the drill worked its way downward. The first hole was finished relatively quickly, at which point everyone decided—prematurely, as it turned out—that it was time for a midday snack. Unless a hole stays filled with water, it starts to close up again, and can't be used. Apparently, there were fissures in the ice, because water kept draining out of the next few holes that were tried. The original plan had been for three holes, but, some six hours later, only two had been drilled, and it was decided that this would have to suffice.

Although Zwally had set out to look for changes in the ice sheet's elevation, what he ended up measuring was, potentially, even more significant. His G.P.S. data showed that the more the ice sheet melted the faster it started to move. Thus in the summer of 1996, the ice around Swiss Camp moved at a rate of thirteen inches per day, but in 2001 it had sped up to twenty inches per day. The reason for this acceleration, it is believed, is that meltwater from the surface makes its way down to the bedrock below, where it acts as a lubricant. (In the process, it enlarges cracks and forms huge ice tunnels, known as moulins.) Zwally's measurements also showed that, in the summer, the ice sheet rises by about six inches, indicating that it is floating on a cushion of water.

At the end of the last glaciation, the ice sheets that covered much of the Northern Hemisphere disappeared in a matter of a few thousand years—a surprisingly short time, considering how long it had taken them to build up. At one point, about fourteen thousand years ago, they were melting so fast that sea levels were rising at the rate of more than a foot a decade. Just how this happened is not entirely understood, but the acceleration of the Greenland ice sheet suggests yet another feedback mechanism: once an ice sheet begins to melt, it starts to flow faster, which means it also thins out faster, encouraging further melt. Not far from Swiss Camp, there is a huge river of ice known as the Jakobshavn Isbrae, which probably was the source of the iceberg that sank the Titanic. In 1992, the Jakobshavn Isbrae flowed at a rate of three and a half miles per year; by 2003, its velocity had increased to 7.8 miles per year. Similar findings were announced earlier this year by scientists measuring the flow of ice streams on the Antarctic Peninsula.

Over the last century, global sea levels have risen by about half a foot. The most recent report of the U.N.'s Intergovernmental Panel on Climate Change, issued in 2001, predicts that they will rise anywhere from four inches to three feet by the year 2100. This prediction includes almost no contribution from Greenland or Antarctica; it is based mostly on the physics of water, which, as it warms up, expands. Two climatologists at Pennsylvania State University, Richard Alley and Byron Parizek, recently issued new predictions that take into account the observed acceleration of the ice sheets; this effect in Greenland alone, they estimate, will cause up to two and half inches of additional sea-level rise over the coming century. James Hansen, the NASA official who directed one of the initial nineteen-seventies studies on the effects of carbon dioxide, has gone much further, arguing that if greenhouse-gas emissions are not controlled the total disintegration of the Greenland ice sheet could be set in motion in a matter of decades. Although the process would take hundreds, perhaps thousands, of years to fully play out, once begun it would become self-reinforcing, and hence virtually impossible to stop. In an article published earlier last year in the journal *Climatic Change*, Hansen, who is now the head of the Goddard Institute for Space Studies, wrote that he hoped he was wrong about the ice sheet, "but I doubt it."

As it happened, I was at Swiss Camp just as last summer's global-warming disaster movie, "The Day After Tomorrow," was opening in theatres. One night, Steffen's wife called on the camp's satellite phone to say that she had just taken the couple's two teen-age children to see it. Everyone had enjoyed the film, she reported, especially because of the family connection.

The fantastic conceit of "The Day After Tomorrow" is that global warming produces global freezing. At the start of the film, a chunk of Antarctic ice the size of Rhode Island suddenly melts. (Something very similar to this actually happened in March, 2002, when the Larsen B ice shelf collapsed.) Most of what follows—an instant ice age, cyclonic winds that descend from the upper atmosphere—is impossible as science but not as metaphor. The record preserved in the Greenland ice sheet shows that over the last hundred thousand years temperatures have often swung wildly—so often that it is our own relatively static experience of climate that has come to look exceptional. Nobody knows what caused the sudden climate shifts of the past; however, many climatologists suspect that they had something to do with changes in ocean-current patterns that are known as the thermohaline circulation.

"When you freeze sea ice, the salt is pushed out of the pores, so that the salty water actually drains," Steffen explained to me one day when we were standing out on the ice, trying to talk above the howl of the wind. "And salty water's actually heavier, so it starts to sink." Meanwhile, owing both to evaporation and to heat loss, water from the tropics becomes denser as it drifts toward the Arctic, so that near Greenland a tremendous volume of seawater is constantly sinking toward the ocean floor. As a result of this process, still more warm water is drawn from the tropics toward the poles, setting up what is often referred to as a "conveyor belt" that moves heat around the globe.

"This is the energy engine for the world climate," Steffen went on. "And it has one source: the water that sinks down. And if you just turn the knob here a little bit"—he made a motion of turning the water on in a bathtub—"we can expect significant temperature changes based on the redistribution of energy.” One way to turn the knob is to heat the oceans, which is already happening. Another is to pour more freshwater into the polar seas. This is also occurring. Not only is runoff from coastal Greenland increasing; the volume of river discharge into the Arctic Ocean has been rising. Oceanographers monitoring the North Atlantic have documented that in recent decades its waters have become significantly less salty. A total shutdown of the thermohaline circulation is considered extremely unlikely in the coming century. But, if the Greenland ice sheet started to disintegrate, the possibility of such a shutdown could not be ruled out. Wallace Broecker, a professor of geochemistry at Columbia University’s Lamont-Doherty Earth Observatory, has labelled the thermohaline circulation the “Achilles’ heel of the climate system.” Were it to halt, places like Britain, whose climate is heavily influenced by the Gulf Stream, could become much colder, even as the planet as a whole continued to warm up.

For the whole time I was at Swiss Camp, it was “polar day,” and so the sun never set. Dinner was generally served at 10 or 11 P.M., and afterward everyone sat around a makeshift table in the kitchen, talking and drinking coffee. (Because it is not—strictly speaking—necessary, alcohol was in short supply.) One night, I asked Steffen what he thought conditions at Swiss Camp would be like in the same season a decade hence. “In ten years, the signal should be much more distinct, because we will have added another ten years of greenhouse warming,” he said.

Zwally interjected, “I predict that ten years from now we won’t be coming this time of year. We won’t be able to come this late. To put it nicely, we are heading into deep doo-doo.”

Either by disposition or by training, Steffen was reluctant to make specific predictions, whether about Greenland or, more generally, about the Arctic. Often, he prefaced his remarks by noting that there could be a change in atmospheric-circulation patterns that would dampen the rate of temperature increase or even—temporarily at least—reverse it entirely. But he was emphatic that “climate change is a real thing.

“It’s not something dramatic now—that’s why people don’t really react,” he told me. “But if you can convey the message that it will be dramatic for our children and our children’s children—the risk is too big not to care.”

The time, he added, “is already five past midnight.”

On the last night that I spent at Swiss Camp, Steffen took the data he had downloaded off his weather station and, after running them through various programs on his laptop, produced the mean temperature at the camp for the previous year. It was the highest of any year since the camp was built.

That night, dinner was unusually late. On the return trip of another pole-drilling expedition, one of the snowmobiles had caught on fire, and had to be towed back to camp. When I finally went out to my tent to go to bed, I found that the snow underneath it had started to melt, and there was a large puddle in the middle of the floor. I got some paper towels and tried to mop it up, but the puddle was too big, and eventually I gave up.

No nation takes a keener interest in climate change, at least on a per-capita basis, than Iceland. More than ten per cent of the country is covered by glaciers, the largest of which, Vatnajökull, stretches over thirty-two hundred square miles. During the so-called Little Ice Age, the advance of the glaciers caused widespread misery; it has been estimated that in the mid-eighteenth century nearly a third of the country’s population died of starvation or associated ills. For Icelanders, many of whom can trace their genealogy back a thousand years, this is considered to be almost recent history.

Oddur Sigurdsson heads up a group called the Icelandic Glaciological Society. One day last fall, I went to visit him in his office, at the headquarters of Iceland's National Energy Authority, in Reykjavík. Little towheaded children kept wandering in to peer under his desk. Sigurdsson explained that Reykjavík's public schoolteachers were on strike, and his colleagues had had to bring their children to work.

The Icelandic Glaciological Society is composed entirely of volunteers. Every fall, after the summer-melt season has ended, they survey the size of the country's three hundred-odd glaciers and then file reports, which Sigurdsson collects in brightly colored binders. In the organization's early years—it was founded in 1930—the volunteers were mostly farmers; they took measurements by building cairns and pacing off the distance to the glacier's edge. These days, members come from all walks of life—one is a retired plastic surgeon—and they take more exacting surveys, using tape measures and iron poles. Some glaciers have been in the same family, so to speak, for generations. Sigurdsson became head of the society in 1987, at which point one volunteer told him that he thought he would like to relinquish his post.

"He was about ninety when I realized how old he was," Sigurdsson recalled. "His father had done this at that place before and then his nephew took over for him." Another volunteer has been monitoring his glacier, a section of Vatnajökull, since 1948. "He's eighty," Sigurdsson said. "And if I have some questions that go beyond his age I just go and ask his mother. She's a hundred and seven."

In contrast to glaciers in North America, which have been shrinking steadily since the nineteen-sixties, Iceland's glaciers grew through the nineteen-seventies and eighties. Then, in the mid-nineteen-nineties, they, too, began to decline, at first slowly and then much more rapidly. Sigurdsson pulled out a notebook of glaciological reports, filled out on yellow forms, and turned to the section on a glacier called Sólheimajökull, a tongue-shaped spit of ice that sticks out from a much larger glacier, called My´rdalsjökull. In 1996, Sólheimajökull crept back by ten feet. In 1997, it receded by another thirty-three feet, and in 1998 by ninety-eight feet. Every year since then, it has retreated even more. In 2003, it shrank by three hundred and two feet and in 2004 by two hundred and eighty-five feet. All told, Sólheimajökull—the name means "sun-home glacier" and refers to a nearby farm—is now eleven hundred feet shorter than it was just a decade ago. Sigurdsson pulled out another notebook, which was filled with slides. He picked out some recent ones of Sólheimajökull. The glacier ended in a wide river. An enormous rock, which Sólheimajökull had deposited when it began its retreat, stuck out from the water, like the hull of an abandoned ship.

"You can tell by this glacier what the climate is doing," Sigurdsson said. "It is more sensitive than the most sensitive meteorological measurement." He introduced me to a colleague of his, Kristjana Eythórsdóttir, who, as it turned out, was the granddaughter of the founder of the Icelandic Glaciological Society. Eythórsdóttir keeps tabs on a glacier named Leidarjökull, which is a four-hour trek from the nearest road. I asked her how it was doing. "Oh, it's getting smaller and smaller, just like all the others," she said. Sigurdsson told me that climate models predicted that by the end of the next century Iceland would be virtually ice-free. "We will have small ice caps on the highest mountains, but the mass of the glaciers will have gone," he said. It is believed that there have been glaciers on Iceland for the last few million years. "Probably longer," Sigurdsson said.

In October, 2000, in a middle school in Barrow, Alaska, officials from the eight Arctic nations—the U.S., Russia, Canada, Denmark, Norway, Sweden, Finland, and Iceland—met to talk about global warming. The group announced plans for a three-part, two-million-dollar study of climate change in the region. This past fall, the first two parts of the study—a massive technical document and a hundred-and-forty-page summary—were presented at a symposium in Reykjavík.

The day after I went to talk to Sigurdsson, I attended the symposium's plenary session. In addition to nearly three hundred scientists, it drew a sizable contingent of native Arctic residents—reindeer herders, subsistence hunters, and representatives of groups like the Inuvialuit Game Council. In among the shirts and ties, I spotted two men dressed in the brightly colored tunics of the Sami and several others wearing sealskin vests. As the session went on, the subject kept changing—from hydrology and biodiversity to fisheries and on to forests. The message, however, stayed the same. Almost wherever you looked, temperatures in the Arctic were rising, and at a rate that surprised even those who had expected to find clear signs of climate change. Robert Corell, an American oceanographer and a former assistant director at the National Science Foundation, coördinated the study. In his opening remarks, he ran through its findings—shrinking sea ice, receding glaciers, thawing permafrost—and summed them up as follows: "The Arctic climate is warming rapidly now, with an emphasis on now." Particularly alarming, Corell said, were the most recent data from Greenland, which showed the ice sheet melting much faster "than we thought possible even a decade ago."

Global warming is routinely described as a matter of scientific debate—a theory whose validity has yet to be demonstrated. This characterization, or at least a variant of it, is offered most significantly by the Bush Administration, which maintains that there is still insufficient scientific understanding to justify mandatory action. The symposium's opening session lasted for more than nine hours. During that time, many speakers stressed the uncertainties that remain about global warming and its effects—on the thermohaline circulation, on the distribution of vegetation, on the survival of cold-loving species, on the frequency of forest fires. But this sort of questioning, which is so basic to scientific discourse, never extended to the relationship between carbon dioxide and rising temperatures. The study's executive summary stated, unequivocally, that human beings had become the "dominant factor" influencing the climate. During an afternoon coffee break, I caught up with Corell. "Let's say that there's three hundred people in this room," he told me. "I don't think you'll find five who would say that global warming is just a natural process."

The third part of the Arctic-climate study, which was still unfinished at the time of the symposium, was the so-called "policy document." This was supposed to outline practical steps to be taken in response to the scientific findings, including—presumably—reducing greenhouse-gas emissions. The policy document remained unfinished because American negotiators had rejected much of the language proposed by the seven other Arctic nations. (A few weeks later, the U.S. agreed to a vaguely worded statement calling for "effective"—but not obligatory—actions to combat the problem.) This recalcitrance left those Americans who had travelled to Reykjavík in an awkward position. A few tried—halfheartedly—to defend the Administration's stand to me; most, including many government employees, were critical of it. At one point, Corell observed that the loss of sea ice since the late nineteen-seventies was equal to "the size of Texas and Arizona combined. That analogy was made for obvious reasons."

That evening, at the hotel bar, I talked to an Inuit hunter named John Keogak, who lives on Banks Island, in Canada's Northwest Territories, some five hundred miles north of the Arctic Circle. He told me that he and his fellow-hunters had started to notice that the climate was changing in the mid-eighties. A few years ago, for the first time, people began to see robins, a bird for which the Inuit in his region have no word.

"We just thought, Oh, gee, it's warming up a little bit," he recalled. "It was good at the start—warmer winters, you know—but now everything is going so fast. The things that we saw coming in the early nineties, they've just multiplied.

"Of the people involved in global warming, I think we're on top of the list of who would be most affected," Keogak went on. "Our way of life, our traditions, maybe our families. Our children may not have a future. I mean, all young people, put it that way. It's just not happening in the Arctic. It's going to happen all over the world. The whole world is going too fast."

The symposium in Reykjavík lasted for four days. One morning, when the presentations on the agenda included “Char as a Model for Assessing Climate Change Impacts on Arctic Fishery Resources,” I decided to rent a car and take a drive. In recent years, Reykjavík has been expanding almost on a daily basis, and the old port city is now surrounded by rings of identical, European-looking suburbs. Ten minutes from the car-rental place, these began to give out, and I found myself in a desolate landscape in which there were no trees or bushes or really even soil. The ground—fields of lava from some defunct, or perhaps just dormant, volcanoes—resembled macadam that had recently been bulldozed. I stopped to get a cup of coffee in the town of Hveragerdi, where roses are raised in greenhouses heated with steam that pours directly out of the earth. Farther on, I crossed into farm country; the landscape was still treeless, but now there was grass, and sheep eating it. Finally, I reached the sign for Sólheimajökull, the glacier whose retreat Oddur Sigurdsson had described to me. I turned off onto a dirt road. It ran alongside a brown river, between two crazily shaped ridges. After a few miles, the road ended, and the only option was to continue on foot.

By the time I got to the lookout over Sólheimajökull, it was raining. In the gloomy light, the glacier looked forlorn. Much of it was gray—covered in a film of dark grit. In its retreat, it had left behind ridged piles of silt. These were jet black and barren—not even the tough local grasses had had a chance to take root on them. I looked for the enormous boulder I had seen in the photos in Sigurdsson’s office. It was such a long way from the edge of the glacier that for a moment I wondered if perhaps it had been carried along by the current. A raw wind came up, and I started to head down. Then I thought about what Sigurdsson had told me. If I returned in another decade, the glacier would probably no longer even be visible from the ridge where I was standing. I climbed back up to take a second look. ◆

(*This is the first part of a three-part article.)*