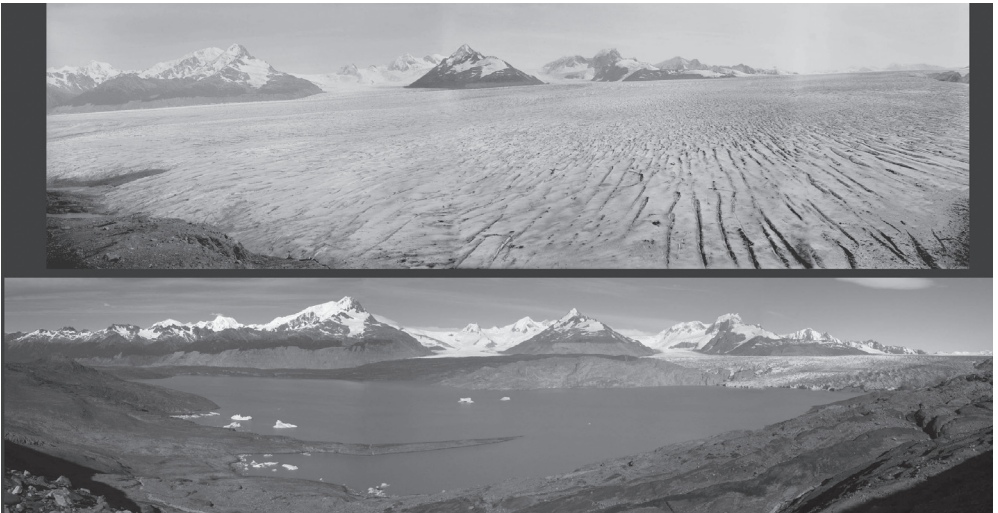


PART TWO

CLIMATE

*The Lockstep Relationship Between
Carbon Dioxide and Temperature*



(Overleaf)

Above: Original photograph taken in 1928 of the Upsala Glacier in Argentina

Below: The same scene today

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CHAPTER 5

The Drillers

DRIVING ALONG the south side of Cape Cod, on Route 28 from South Yarmouth to Chatham, where the cape abruptly curves north, you might notice, coming out of Harwich, a little antiques shop set back from the road, nestled between a country barber shop and a bait-and-tackle store. If you went in, you wouldn't find much at first glance to distinguish it or its proprietor, Chester Langway, from many other such establishments in the vicinity. There's a miscellany of the usual oddities—pots and pans, an old dentist's chair minus the drilling apparatus, glass and ceramics, and a depiction of Daniel Webster, New England's political leader in the first half of the nineteenth century, in which Langway takes special pride. If you get into a chat with Langway, a vigorous man in his mid-seventies who gets around in a little Ford pickup, he'll explain in his telltale New England accent—the wide vowels, the errant or missing *rs* at the end of words—how Webster used to frequent a raw bar in Boston, still a going concern, where he'd order four or five dozen oysters along with a fifth of bourbon to wash them down. He'll tell you he's thinking of donating the picture of Webster to the bar. Yet even if you linger a while, it isn't likely you'll find any clues to what Langway himself did before retiring to the cape, unless, at the very back of the store, you happen upon some soapstone carvings made by Inuits, whom Langway, indifferent to the “politically correct” conventions of the day, still calls Eskimos. Though the little figures are surely the most original items in the store, Langway evidently isn't too eager to sell them. They're the one memento of his unique contribution, in an unusual career, to what one historian has aptly called “an extraordinary revolution in paleoclimatology.”¹

Fifty years ago, Langway's life took a singular turn. After serving several years in the military, he had just earned bachelor's and master's degrees in geology at Boston University when, in 1956, he was hired by one Henri Bader to work as a research scientist at the U.S. Army Corps of Engineers' Snow, Ice, and Permafrost Research Establishment (SIPRE) in Wilmette, Illinois, a suburb just north of Chicago. Bader, considered by Langway and others to be the father of ice core research in the United States,² was a native of Switzerland who had obtained his doctorate at the prestigious ETH (the Confessional Technical High School) in Zurich, the country's equivalent of MIT, and had worked at Switzerland's top ice laboratory in Davos, the Alpine town now best known as the spot where the industrial world's elites meet for annual confabs and as the fictional setting of Thomas Mann's *The Magic Mountain*. Bader, like Mann, sensed in the 1930s that things were going badly awry in Europe and began to cast about for some other continent to work on. His wanderings took him first to Moscow, then to various places in Latin America, where he found employment intermittently as a manager of mining operations. Finally, after World War II, he landed a professorship at Rutgers University in New Jersey, and then, still more improbably, the position of chief scientist with the U.S. Army's ice program. When he recruited Langway, he was getting ready to do some exploratory drillings into the ice sheets of Greenland and Antarctica.

Those sheets, covering more than 10 percent of the earth's land surface and containing nearly four fifths of its fresh water, represented—together with the ocean's depths and outer space—the planet's last physical frontier from a scientific point of view. In 1930, the great German meteorologist and geophysicist Alfred Wegener, the discoverer of continental drift, had died on a meteorological expedition in central Greenland. On that journey, one of his assistants, Ernst Sorge, noticed, upon digging a pit in the ice, that annual layers of accumulation could be discerned, as if they were tree rings. That discovery opened enticing possibilities. While there had been attempts, as Langway would later observe, to drill mechanically into Swiss glaciers as early as the 1840s to do thickness measurements, and later into the ice sheets, “never until now,” in the mid-1950s, “had the snow-ice mantle of high polar ice sheets been completely penetrated.”³ There had been exploratory drilling in Alaska and Greenland in 1949, 1950, and 1951, in which Bader was involved, but the equipment kept breaking and jamming, and nobody got farther than about 100 meters into the ice. Nobody had ever

attempted to read the world's paleoclimate by drilling long cores and examining the layers Sorge had discovered.

At the time Bader hired Langway, an international program of polar research was being organized, which would come to be known as the International Geophysical Year of 1957–58. Bader clearly recognized the potential in Sorge's discovery. "Two thirds of the area of the Greenland ice sheet and practically all of the Antarctic ice sheet are permanently dry," he wrote in a report on the polar ice and snow to be studied. "All precipitation is in the form of snow. Summer melt is rare, and usually affects a surface layer only a few centimeters thick [but marking the boundaries between annual layers]. Thus every snowfall, including everything that fell with it, is, so to say, separately and safely filed for future reference by being buried under later snowfalls."⁴ To obtain those files, one had to drill down using a rock drill adapted to remove ice chips by means of a compressed air system or, later, a thermoelectric drill that would melt its way through the ice. Four cores were drilled under Bader's supervision in 1956 and 1957, two in Greenland and two in Antarctica, and the results were promising—though Bader thought at the time that they had already reached, at a depth of little more than 300 meters, the maximum length at which recovery of cores would still be feasible. Fortunately for the scientific understanding of climate, that guess turned out to be too pessimistic by a factor of ten.

Within decades, 3-kilometer-long cores would be drilled, a remarkable achievement that depended on the development of new drilling technology and analytic techniques. One of the first things to be puzzled out was the nature of the little gas bubbles found on the way down into the ice, for they contained clues to the earth's distant past. Why were the bubbles there? Basically, as new snow falls, air from the ambient atmosphere is trapped between ice crystals at the surface. As the snow is buried and starts turning to old snow, known as firn, the trapped air forms bubbles, which become quite spherical as the firn is compressed into ice—in Greenland's ice sheets, this characteristically happens at a depth of 57 to 70 meters. Ice drillers would discover, as they extracted cores deeper down, 900 to 1,300 meters from the surface, that as the ice "relaxed" at the surface, expanding as it warmed, the bubbles would reappear and snap, like ice cubes in a cool summer drink. Still farther down, at around 1,300 meters in Greenland, the air diffuses into the ice to form what scientists call a clathrate—molecules of one kind are completely trapped in the crystal lattice of another substance.

Langway's first important job for Bader was to determine the pressures of the bubbles, which required him to use a novel apparatus and exact procedures. He was successful, winning Bader's respect and affection. In 1961, SIPRE was folded into a new army lab being set up in Hanover, New Hampshire, the Cold Regions Research and Engineering Laboratory (CRREL). In due course, Langway was appointed chief of the snow and ice branch, having in the meantime finished his doctoral studies at the University of Michigan. At CRREL, with great efficiency and acumen, he would organize collaborations between U.S. and European scientists, which, by the end of the decade, would produce some startling revelations about the earth's prehistoric climates. One was the discovery of what scientists would call abrupt, rapid, or even catastrophic climate change. Even more important, there would be what Langway and the Swiss physicist Hans Oeschger called "the astonishing revelation that the carbon dioxide/air ratio varied contemporaneously with the climatic conditions experienced during glacial/interglacial shifts."⁵ What the scientists discovered was that, when the earth moved into and out of its three or four most recent ice ages, as global mean temperatures rose and dropped, carbon dioxide levels climbed and fell too, in lockstep.

As a matter of pure theory, it's been understood since the mid-nineteenth century that trapping of the sun's radiant energy by the earth's atmosphere—strictly speaking, trapping of radiation that would otherwise radiate from earth back into space—is what boosts temperatures on this planet enough to support advanced life.⁶ And for more than a hundred years, the common belief has been that this greenhouse effect, as it's popularly, if slightly inaccurately known, would be strengthened by combustion of fossil fuels, because of the added carbon dioxide pumped into the atmosphere.⁷ But only in the last few decades have those notions been proven as hard empirical fact, as scientists like Ramanathan directly measured flows of energy into and out of the atmosphere, others gauged present-day changes in greenhouse gas levels, and—most tellingly of all—a growing number of exceptionally enterprising individuals began to extract the history of the world's climate from a wide variety of sources.

Throughout earth's history in the narrow sense, the very recent period for which written records exist, climate trends could be gleaned from sources like the all-India monsoon record going back to the nineteenth

century, and records from China of droughts, floods, and cold snaps going back to the first century A.D. (two millennia before the present or “B.P.,” to use the language favored by professional paleoclimatologists). The Hudson’s Bay Company required its captains and agents to record daily weather, including first snows and thaws, throughout the eighteenth and nineteenth centuries. A record going still further back comes from Spanish “rogation” ceremonies performed to bring rain or to end a deluge.⁸

Seeking clues to more ancient climates, students of the more recent prehistoric centuries have relied primarily on tree rings, from both living and preserved trunks. By matching the patterns in living trees with overlapping patterns in dead trees found in places like the embankments of the Rhine River and its tributaries, scientists can obtain information about rainfall and temperatures going back as much as 12,000 years. (The trick is to find situations where either temperature or rainfall is believed to have stayed fairly constant, so that the rings accurately indicate changes only in the other parameter.) Just as ingeniously, scientists learned to extract cores from lake beds and distinguish annual accumulations of sediment, and take various kinds of readings from what was found in each layer. In some regions, for example, pollen records showing how wildflowers had migrated in response to changing climate could be constructed for tens of thousands of years. Similar information could be obtained from animal middens, excrement containing residues of organic matter the creatures had ingested under different circumstances. From all such data sets covering the last 1,000 years, both the written histories and the physical indicators, a sharp rise in the world’s temperatures in recent decades has been well documented.⁹

Even more dramatic, however, have been the discoveries made by those drilling into ocean beds and into polar ice. Their insights, especially those published in just the last two decades, have transformed our understanding of the earth’s last half million years. From the character of the ice accumulated in Greenland and Antarctica and from the gases trapped in each layer, it’s become evident that the earth’s climate is not merely unstable, but violently unstable. Changes previously believed to have unfolded over thousands or tens of thousands of years were found to have taken place in less than a hundred, sometimes in less than ten. An intimate relationship between temperature and greenhouse gas levels, long assumed, has been demonstrated beyond doubt.

The story of these epochal discoveries is one of adventurous and imaginative individuals turning all manner of very new technology to the study of very old climates. Without the breakthroughs made during the 1930s in atomic chemistry, and without instruments developed in World War II, these pioneering scientists could not have done their work. Nor, most likely, could the job of exploring the world's most frigid regions have been accomplished without the mad tensions and pressures of the Cold War, which gave rise to opportunities that a handful of farsighted knowledge seekers were quick to seize.

The story is perhaps best begun before Langway entered the scene, in 1947, when a young Danish geophysicist, Willi Dansgaard, was assigned to help take geomagnetic readings at a weather station in northwest Greenland. There, Dansgaard and his young wife were "bitten with Greenland for life... its forces, its bounty, its cruelty, and above all its beauty," as he would later put it.¹⁰ During a follow-on stint with Denmark's weather service, Dansgaard began to feel that earth's climate was a lot more interesting than its magnetism, an important foundation stone for what would be an unusual career.

When Dansgaard returned in 1951 to the University of Copenhagen's Biophysical Laboratory, where he had earned his academic degrees, he was put to work on instrumentation. His first job was to install a brand-new mass spectrometer. Basically, a mass spectrograph or spectrometer spews out a stream of charged matter across a magnetic field, so that the material can be weighed and identified according to the extent it is deflected in the field. The instrument had been invented by Francis William Aston at Cambridge University in 1918–19, and it immediately played a key role in the development of atomic theory, the branch of physics called quantum mechanics. One use of the mass spectrometer, on a very large scale, was in the Manhattan Project, to separate fissile uranium 235 for atomic bombs from the much more prevalent nonfissile U-238 isotope.¹¹ (Isotopes are variants of an element that are chemically identical but have different numbers of neutrons and therefore different atomic weights and numbers.) At the Copenhagen lab, the application in mind was the production and use of stable isotopes (isotopes that do not decay radioactively) for medical and biological research.

Because Dansgaard had been exposed to aspects of meteorology, unusual climates, and nuclear science, he happened to learn that rain-

water contains lighter and heavier components: two variants of regular H_2O , the dominant one containing the O^{16} isotope of oxygen and a much rarer one containing the heavier O^{18} ; and so-called heavy water, HDO , in which one of the hydrogen atoms is the heavier isotope called deuterium.¹² This nugget of information led to a startling discovery of great import. During a huge rainstorm in northern Europe during the weekend of June 21, 1952, Dansgaard wondered whether the isotopic composition of the precipitation might change from one shower to the next. To find out, he put funnels in beer bottles out on his lawn to collect water. He was the right man wondering at the right time, for “it turned out to be an unusually well developed front system,” as he later recalled.¹³ “When the rain began in western Jutland, it had not stopped raining in Wales 1000 kilometers to the west. I have not seen anything like it, at no time before or after. The miracle consisted in my starting the collection accidentally under these unusually favorable conditions.”

Upon analyzing the water samples at the Copenhagen lab, using the mass spectrometer he had helped install and improve, Dansgaard discovered that the isotopic composition of the rainwater did in fact change, and that it changed in a regular way as the storm progressed. Specifically, because the heavier water molecules are less likely to evaporate from a surface but more likely to condense from a cloud, the higher and colder a cloud is, the less likely it is to contain the heavier waters. To look at the situation dynamically, the first rainfall will leave a cloud depleted in H_2O^{18} and HDO because of their greater propensity to condense. As the cloud rises and cools, still more of the heavier waters condense out, and so on. The bottom line—disarmingly simple—is that the temperature of a cloud from which rainwater falls can be inferred from the isotopic composition of the rainwater.

Having learned that, Dansgaard, a very determined perfectionist, according to lifelong associates, took the next logical step: to find out whether this relationship held true for rainwater falling in different parts of the world from clouds of widely varying temperatures. Through the good offices of the Danish East India Company, Dansgaard obtained enough water samples to convince himself and others that rain falling in temperate and polar regions had lower concentrations of the heavier isotopes than rain falling in the tropics. In getting the samples he needed to document this finding, he owed a good deal to the clubby character of Danish science, politics, and business. Copenhagen was a

small world in which all the elites mixed comfortably and casually, and everybody interesting or important knew everybody else.

Through such connections, the lucky Dansgaard would now benefit from an even bigger favor. In the late 1950s, the World Meteorological Organization in Rome and the International Atomic Energy Agency in Vienna launched a Global Precipitation Network to gather samples from all over the world on a regular basis. The main objective was to track radiation from bomb tests or nuclear power plant accidents, which concerned the WMO as the world's designated monitor of the earth and the IAEA as its monitor of nuclear standards and safeguards.¹⁴ Through diplomatic and science agency contacts in Copenhagen, Dansgaard was able to get access to the samples. The key intermediary was a high official at the Danish Atomic Energy Commission who, during the war, had made a name for himself channeling treasury department funds to the Danish Resistance and getting food to Nazi concentration camp inmates. Analysis of the samples enabled Dansgaard to definitively establish, on a global basis, the direct correspondence of cloud temperatures and isotope ratios. The result was his landmark paper, "Stable Isotopes in Precipitation," which the journal *Tellus* published in 1964, and which continues to be cited frequently in scholarly references.¹⁵

What made that paper so immensely important was its connection to another insight Dansgaard had already had a decade earlier. Because of his experience in Greenland and his musing about what had happened to the polar ice cap in past geologic ages, it had occurred to him that isotope ratios might be the key to learning the temperature of the world's atmosphere in epochs gone by.¹⁶ "I was immediately sure it was a good idea," he would later say, "maybe the only really good one I ever got."¹⁷ It was in fact a brilliant idea, and for the rest of his working life, with growing crews of oarsmen at his beck and call, Dansgaard would pursue it with the obsessiveness of a Viking raider.

Two years after the *Tellus* paper appeared, Dansgaard obtained a coveted professorship at the University of Copenhagen, on the basis of the doctoral dissertation he had completed in 1961. It summed up results from a sailing expedition he had made to Greenland in 1958 to collect samples from icebergs, to further test his ideas about oxygen isotopes and temperatures. In 1964, when he had another opportunity to visit Greenland with fellow scientists—this time to take samples for an at-

tempt to date ice by means of the radioactive decay process in silicon 32—he found something astonishing, an enormously elaborate U.S. base at Camp Century, 220 kilometers east of Thule in the far northwest corner of Greenland. Thule itself was a major NATO air base, with thousands of military personnel, jet fighters, and the C-707 transport planes used to refuel B-52 strategic bombers in the air, Langway recalls. The subsidiary base at Camp Century, pretty literally carved out of the ice, was one of the more bizarre by-products of the Cold War, but one that proved crucial to the fast-evolving sciences of glaciology and paleoclimatology.

It was operated by CRREL, the lab in Hanover where Langway was doing basic environmental and ice research, but which was mainly dedicated to the development of equipment and techniques for military operations in frigid conditions. That mission had taken on new life with the Cold War, first of all because of a general feeling among American generals that the Red Army knew a lot more than they did about fighting on ice and permafrost. But more specifically, the generals were eyeing Greenland as a particularly favorable location for U.S. systems to provide early warning of a Soviet missile attack, and possibly even as a site for forward deployment of U.S. ballistic missiles. Under these circumstances, Denmark's colonization of Greenland was an advantage for Danish scientists seeking to piggyback research projects on U.S. military operations. Technically, the United States could not do anything in Greenland without the permission of the Danish government,¹⁸ and, while relations between the two countries were very friendly, proposed U.S. military activities in Greenland were potentially controversial in Europe, and therefore required not just pro forma permission but strict oversight from the Danish authorities.

Dansgaard and his colleagues found at Camp Century a whole town built under the ice, with a main street, mess halls, post exchange ("PX") stores, and recreational facilities. People, goods, and equipment were ferried around by gigantic custom-built D8 tractors and trains: the tractors, with 1.5-meter-wide treads, pulled eight wagons with 3-meter-diameter balloonlike tires. The base was powered by its own nuclear reactor, and the remains of a sub-ice iron railway lay in tunnels, eventually to be bent out of shape by shifting ice floes.

Later Dansgaard would be told and would believe, perhaps too credulously (Langway thinks), that Camp Century had been built as part of a highly classified project called Ice Worm to explore the idea of

installing U.S. ballistic missiles on mobile launchers in the ice tunnels. If there's anything to that, it would cast the events leading up to the Cuban missile crisis, and the deal that ended the crisis by trading U.S. missiles in Turkey for the Soviet missiles in Cuba, in a new light. However that may be, at the time, Dansgaard and his fellow Danes came away with an impression of their American friends as having rather too many dollars and perhaps too few of what Agatha Christie's detective Hercule Poirot famously called those little gray cells.

What interested Dansgaard most at Camp Century was a core drilling derrick installed in a trench under the snow. Though he couldn't divine exactly why or for what purpose it had been built, he thought immediately of how ideally suited it would be for taking ice samples to do oxygen isotope analysis. He learned that the drill had been designed and built by CRREL's B. Lyle Hansen, the first major inventor of deep-ice coring equipment. The Americans would use that drill two years later in 1966, to go all the way down through the ice to bedrock at Camp Century and take the first very long core. Dansgaard's Copenhagen lab would provide crucial help with the stable isotope analysis from that core and its successors to determine atmospheric temperatures that had prevailed over Greenland for tens of thousands of years.

From conversations with the veterans of the early ice coring expeditions, it's not easy to fathom what the pioneers had in mind when they first began to poke around in the polar ice sheets in the 1950s and 1960s. Looking back now, it almost seems that ice science was like the proverbial mountain that had to be climbed simply because it was there. Large military transports were available for ferrying equipment to remote ice sheets, while smaller planes could take scientists to outposts and rescue them if they got into trouble. Newly developed vehicles like the huge Caterpillar wagon trains at Camp Century could move people around on the ground.

The most important piece of equipment in the new science of ice coring was of course the drill itself. Hansen's first models included a thermally heated auger and a pretty straightforward electromechanical drill derived from ones developed for oil exploration and extraction. The latter consisted of drilling blades at the end of a rotating steel cylinder, with a compressed-air system bringing shavings to the surface.¹⁹ It soon became apparent that the early models had to be improved and optimized in a number of ways for practical removal of

cores, especially as bore holes went longer and deeper. Techniques had to be devised for removing core segments while drilling continued, fast enough to make the whole drilling operation economically practical and humanly tolerable. The drill had to cut as fast as possible, but not so fast it overheated and got stuck deep in a hole, bringing operations to a halt—sometimes irreversibly. As the drill descended, the space above it had to be filled with a fluid to equalize pressure in the hole and prevent it from freezing over the drill. As time went on, special operations such as drilling through relatively warm ice or in remote mountain glaciers required development of much more compact and energy-efficient drills. One such type, a thermal drill, has a heating element at the tip rather than at the blades, so that the drill simply melts its way through the ice, with a system to remove the meltwater to the top.

As it dawned on scientists that ice cores might go a lot deeper and would be much more valuable as they went much farther back in time than had been guessed initially, it became crucial to drill in just the right spot. This meant finding locations where there was good reason to think the ice had stayed frozen and undisturbed for tens or hundreds of thousands of years, and where little or no ice drifting had occurred, so that the cores extracted would be truly sequential, year by year. Naturally the goal was to go all the way to bedrock, so careful radar surveys from planes were necessary to determine whether and where that might be possible.

Development of advanced instrumentation also was required. When the first relatively shallow holes were bored, dating ice did not seem especially challenging, as layers close to the surface were distinguishable to the eye. But when the cores went deeper, where annual layers were no longer visible, figuring out where one year ended and the next began required an array of highly sophisticated instruments. One such device was the mass spectrometer, which sometimes could be used not only to gauge changes in temperature from year to year but also to detect seasonal variations with each year's water isotopes. Langway played a key role in establishing the feasibility of distinguishing one year from another, within certain ranges, by using the spectrometer to detect seasonal differences in oxygen isotope levels.

A novel instrument invented and employed in the 1970s was the Coulter counter. It relies on lasers to detect dust particles in melted water from samples that are pumped through capillary tubes. Since the

air over Greenland is usually driest and dustiest in the spring, when particles blow in from as far away as the Himalayan highlands, the Coulter counter can precisely discern each summer's point of maximum warmth and dryness.

Another instrument, relatively simple in principle and designed to work automatically, continuously, and fast, measures the acidity of ice. The core is split, two electrodes are dragged along the flat surface, and spikes in electrical conductivity between the electrodes indicate the presence of higher acidity, particularly sulfuric acid from volcanic eruptions. This device, invented by a Dane, Claus Hammer, enables scientists to detect fallout from historically dated volcanic eruptions in the immediate past millennium and to calibrate other dating techniques to match those records. (Discovery of the volcanic residues, which were found to have caused global cooling when fallout was in the air, provided support for "nuclear winter" scenarios that were developed in the 1980s. Models indicated that an all-out nuclear war, besides killing hundreds of millions of people instantly, would also produce a devastating global chill.)

Even with all the new technology and infrastructure, and a political environment that favored ice core research, somebody had to have the idea that interesting things could be learned from drilling into ice to really get that research going. In the United States, Bader was the catalyst, and Langway, his protégé, was quick to identify the other most highly qualified pioneers. It was he who would broker a marriage between the little community of U.S. glaciologists and top European experts reared in the Scandinavian and Alpine traditions of ice study.

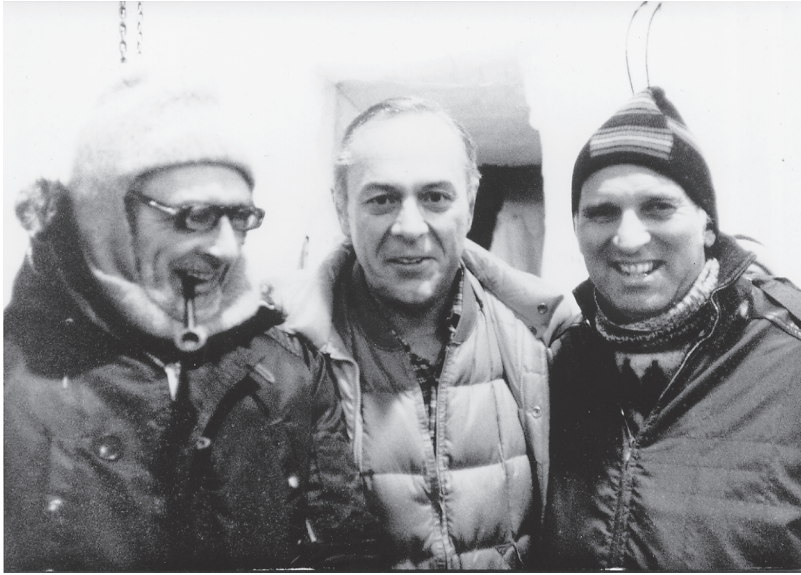
As the work from the 1957–58 geophysical year was digested, recalls Langway, "other interested scientists were struck that the cores revealed crucial information about the history of climate." The stage was set for the first really long core to be extracted. Langway found himself in charge of the analysis that would be done on the ice from the next big coring effort, which would be carried out by the United States, this time at Camp Century, again with a drill developed and perfected by the ingenious engineer Hansen. As the core was being extracted, Langway set about finding the very best people to analyze the ice. "Chester had a deep understanding of what was important—really key—and wanted the best possible science," recalls Sigfus Johnsen, an Icelandic disciple of Dansgaard whose drills eventually supplanted Hansen's.²⁰ One of Langway's major recruits was Dansgaard, who contacted him in 1966

after spotting the Camp Century drilling rig and then, at Langway's invitation, flew over to the United States to negotiate a working arrangement. Dansgaard took charge of the stable isotope analysis for the Langway–Hansen Camp Century core, and Langway came to appreciate him as a person “dead set” on getting a job done, and having “the scientific prowess to make a program fly.”

Just as important was a Swiss recruit named Hans Oeschger, whom Langway met at a conference in Austria in 1962. His attention was caught by Oeschger's efforts to do carbon 14 dating in very small samples, samples in which the expected quantities of carbon 14 would be minuscule. Langway flew straight to Bern to get better acquainted. In due course, it became apparent that trying to estimate an ice sample's age from the radioactive decay of the carbon 14 isotope wouldn't work very well: the isotope made up too minute a fraction of the carbon dioxide trapped in tiny bubbles to yield meaningful readings. And any carbon dating would be confined only to the most recent 50,000 years or so, because almost all the carbon 14 in a given sample decays in less time than that. But what really mattered, despite these disappointments, was Oeschger's skill at measuring tiny quantities of carbon dioxide.

As a graduate student in the 1950s, Oeschger had invented and built a novel instrument called the proportional counter to detect and measure ultralow levels of radioactivity; unlike a Geiger counter, it was capable of identifying the type of radiation prompting a signal. Completed in 1955, it came to be known as the Oeschger counter, and was for many years a leading instrument in radiocarbon laboratories.²¹ In 1959, using the device, Oeschger and two scientific collaborators were the first to radiocarbon date Pacific Ocean deep water, which helped set the stage for the systematic study of oceanic circulation patterns. Working with Langway in the 1960s and 1970s, Oeschger learned how carbon dioxide gets trapped in ice, how to extract it, and how to select ice samples with air bubbles retaining the composition they had when they were formed.

Langway, Oeschger, and Dansgaard made a powerful trio, with Langway interested in the physical and chemical properties of ice, Oeschger in carbon dioxide and radioactive isotope concentrations, and Dansgaard in the stable isotopes' temperature variations. In the next decades they produced what is arguably the most compelling and provocative evidence of large-scale and rapid climate change obtained from any source.



Dansgaard, Langway, and Oeschger (left to right). Source: American Institute of Physics, Emilio Segré Visual Archives / Gift of Chester C. Langway Jr.

In 1961 Hansen took his drill to Camp Century, and by 1966, using a variety of drills, a 1.5-kilometer-long core had been obtained, revealing about 125,000 years of atmospheric and environmental history. Dansgaard's isotope analysis showed pronounced warming and cooling periods in times for which there are historical records, corresponding to well-documented episodes such as the Little Ice Age of medieval times and a short warming trend that culminated in the 1930s. Farther back, very sharp coolings and warmings were detected, corresponding to glaciation and deglaciation, notably the Allerød/Bolling event that terminated the last ice age. When Dansgaard and others presented their preliminary results at an international symposium in 1968, it caused "quite a stir," Dansgaard reported,²² and resulted in his being invited on the spot to give a talk later that year at the Nobel Prize symposium in Uppsala, Sweden. The following year, Dansgaard and colleagues published their definitive summation, "One Thousand Centuries of Climate Records from Camp Century on the Greenland Ice Sheet," in *Science* magazine, the top U.S. journal.²³

Building quickly on that success, Hansen took his equipment down to Antarctica and started to drill with a vengeance at the Byrd station, reaching bedrock 2,164 meters—more than 2 kilometers—down in 1969. Oxygen isotope analysis in that core produced pictures of the last ice age and the following deglaciation that were dramatically consistent with Camp Century's. Just as important, the ice at the Byrd station turned out to be much more pure than that obtained from the Camp Century core, which was found to be too contaminated with carbonates to yield reliable measures of carbon dioxide levels by means of Oeschger's techniques.

Subsequently the drillers returned to Greenland to take a core at Dye 3, the site of a big U.S. radar installation that was part of the famed DEW line early warning system.²⁴ This was part of what they called the Greenland Ice Sheet Program, or GISP, a U.S.–Danish–Swiss collaboration. Conveniently, the drillers were able to work underneath the framework of a giant radar building, installing their equipment in its shelter. (The structure was jacked up each year, as the underlying ice became compressed and snow drifted under the frame.) For analysis, the core was split down the middle and studied independently at the U.S. Army's Hanover lab and in Copenhagen. That core provided an opportunity to test a new thermal drill devised by Hansen, to strengthen collaborative procedures, and to improve analytic techniques. It was the first of twenty relatively short cores to be extracted from various Greenland sites over a ten-year period as part of the GISP.

This first Dye 3 core was only about 400 meters long and was taken, it seems, largely as a matter of convenience. The site in southern Greenland really did not satisfy the key conditions for a good core: no surface melting (because it could result in soluble gases contaminating the atmospheric traces left in each year's ice bubbles), little or no disturbance to deep stratification from ice flows, and good snow accumulation with little melting.²⁵ So the drillers prepared to extract a long core from a more selectively chosen site in central Greenland, called Summit. Meanwhile, however, the U.S. science authorities began to quibble about the high expense of going to a new site, and meanwhile, Hansen had run into difficulties with a new drill in Antarctica.

Dansgaard's younger colleague Sigfus Johnsen stepped into the breach with a new design. Some salient features of his Istuk drill (a contraction of the Danish word for ice and the Greenlandic word for spear or

awl) were its much greater compactness, a tilting mechanism for easier core removal and maintenance, a novel method of directly extracting ice shavings rather than dissolving them as drilling proceeded, and a microchip built into the drill head to keep operators apprised of key parameters like speed, inclination, pressure, temperature, battery charge, and the mechanical resistance encountered by the cutting mechanisms. Johnsen also developed techniques to speed preparation of samples, a crucial economic consideration as drills went deeper, and to automate some sample analysis. By this time, recalls Langway, the Danes could process 256 samples in a night and be ready the following evening to process another day's yield—a record that's never been beat.

In 1977, the U.S. authorities agreed to join the Danes in a collaborative deep core back at Dye 3, chosen for logistical convenience and economy, despite the site's obvious drawbacks, using Johnsen's Istuk drill. They struck bedrock on August 11, 1981, a little more than 2 kilometers below the surface. Like the Camp Century core, the Dye 3 sample provided a strong hint that the periodicity of ice age glaciation and deglaciation was strongly associated with the Milankovitch cycles—the subtle variations in the Earth's relationship to the Sun (described at the end of chapter 2). And Dye 3 confirmed Camp Century's discovery of sharp oscillations in temperature roughly every 1,500 years—an observation that seemed almost too weird to credit when first made. With the cycles now showing up not just in one core but two, and subjected to close scrutiny by international teams, they began to get a lot of attention, and not just from glaciologists.

The general pattern in these dramatic oscillations, which came to be better known as Dansgaard–Oeschger cycles, was for them to begin with a very abrupt warming, on the order of 10 degrees Celsius on average, and to end with a much more gradual cooling. The warmings, which Dansgaard referred to in print²⁶ as “spectacular changes” in temperature, took place in as little as a century. Altogether, 24 such cycles were seen in the camp Century and Dye 3 cores, in parallel with one another.

The Dansgaard–Oeschger cycles, like the ice ages themselves, remain something of a mystery. Coming up with a completely convincing explanation of them is to this day one of the grand challenges in paleoclimatology. The most widely accepted account is one developed largely by the climatologist William Ruddiman, Oeschger, and Wallace Broecker, a geochemist at Columbia University's Lamont-Doherty Earth Observatory, whose ideas will be discussed at greater length in

chapter 7.²⁷ It rests on presumed changes in ocean circulation, a notion that Ruddiman may have been the first to enunciate,²⁸ and which Broecker championed. It distinguishes between two types of millennial cycle, the usual Dansgaard–Oeschger events and a category of more drastic but rare cycles known as Heinrich–Bond events.

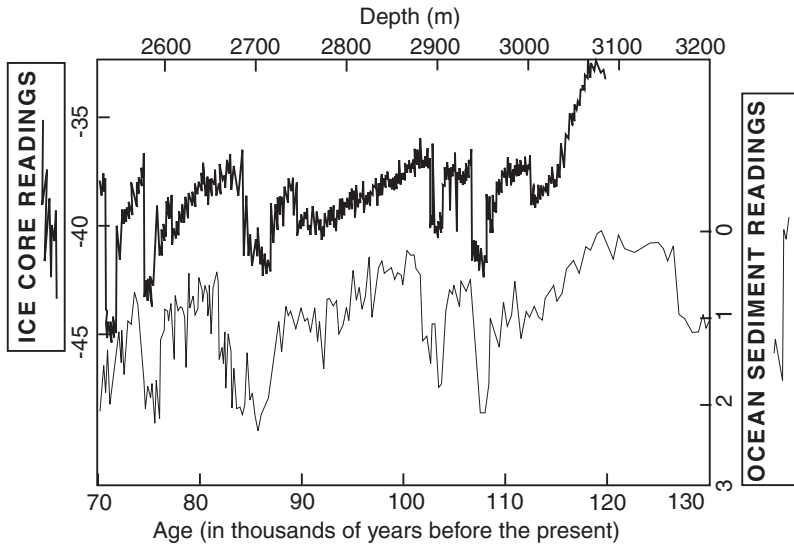
The German scientist Hartmut Heinrich was a specialist on debris that had collected at the base of glaciers during the last 100,000 years, to be “rafted” out to sea in icebergs and finally deposited on the seabed far from its origins, in a series of layers. Gerald Bond, a colleague of Broecker’s at Lamont, had made observations and reached conclusions from ocean bed cores that provided a key ingredient of the provisional explanation for the Dansgaard–Oeschger cycles. Though merely a hypothesis, the theory is so suggestive and disconcerting that it bears some attention. Bond noticed a pattern within the Dansgaard–Oeschger oscillations: several in succession would get colder and colder at their most extreme, and then—just before a really abrupt warming—a lot of iceberg-rafted debris would show up in ocean sediments. Bond, Oeschger, and Broecker hypothesized that as the Dansgaard–Oeschger cycles got colder, Hudson Bay would fill up entirely with ice, but when the ice reached a certain depth, it would act as a thermal blanket. Heat from the earth’s interior would eventually melt the bottom of the ice sheet, and suddenly the whole sheet would give way, slide out into the North Atlantic, and break up, carrying accumulated debris out into the more southerly waters. But as the icebergs melted, an infusion of fresh water would prevent the normally salty surface waters of the North Atlantic from sinking, interrupt the normal flow of warm southerly waters into the North Atlantic, and lead to a gradual cooling. If that infusion of water took place only in the far north, the result would be a normal Dansgaard–Oeschger cycle, but if it was more widespread and affected waters in intermediate latitudes as well, there would be a more pervasive and severe “Heinrich” event.

A wide variety of oceanic evidence indicates that the regular Dansgaard–Oeschger cycles would make themselves strongly felt throughout most of the Northern Hemisphere, down to the equator and sometimes across it. The double-impact Heinrich events would affect the whole globe more perceptibly. “Comparison of the Greenland and Antarctic cores showed,” science historian Spencer Weart has observed,²⁹ that at least some of “the climate changes were truly global, coming at essentially the same time in hemispheres.”

Before Camp Century and Dye 3, sediments bored out of ocean floors had provided the most insight into earth's climatic prehistory. During a 1947 Swedish expedition, scientists developed a way to extract a column of sediment from a bore hole in the ocean floor without disturbing the sequence of accumulated sediments, and in the next decade, radiocarbon dating was used to calibrate the rate of sedimentation.³⁰ By the mid-1960s, several drilling expeditions around the world had produced results going back several hundred thousand years, showing a correspondence with the Milankovitch cycles and indicating that the world must have gone through dozens of glaciations and deglaciations—not just four, as nineteenth-century geologists had come to believe. It was becoming apparent that the modern era in which human civilization had emerged, the Holocene, was a blessedly benign anomaly in the much larger scheme of things.

Once the results from Camp Century and Dye 3 were in, however, it was generally recognized that ice cores now provided the most authoritative record of past climates. For all the qualms about the Dye 3 site, two long cores were much better than just one, and the consistency of the two records was striking. The rather sensational findings set off what a writer for *The New Yorker* magazine aptly called an “ice rush,”³¹ with the ironic consequence that the spirit of international cooperation that had prevailed up until then quickly broke down. Now that coring was recognized as a really serious business, the U.S. National Science Foundation began to “micromanage” it, says Langway, and that seems to have undermined the crossnational relations that had evolved over two decades. Dansgaard and Johnsen got the impression that the U.S. authorities felt the Danes had been enjoying a “free ride,” though it was Johnsen’s “ice spear” that had produced Dye 3 and Dansgaard’s Copenhagen lab that had developed the key analytic techniques and performed much of the actual analysis. (Dansgaard had a reputation for being cantankerous and difficult to work with. But he had done analytic work on all the major Greenland cores so far “without ever charging a penny for it,” notes Langway.) Perhaps, taking a longer view, the collapse of the fruitful U.S.–European collaboration was just an early signal—weirdly analogous to other early warning signs from the Greenland sheets—of the larger deterioration in U.S.–European relations that began with the Cold War’s thawing and end.

The U.S. and European teams went their separate ways after Dye 3, each drilling a new long core at Summit sites in north-central Green-



Consistent readings from Greenland ice and Atlantic ocean sediments

Source: Dansgaard, *Frozen Annals*, fig. 14.8

land in the 1980s and 1990s, separated by about 30 kilometers (one called GRIP, or Greenland Ice core Project, the other GISP 2). Those cores were better situated than Dye 3, and from a scientific point of view, there was something to be said for doing two long cores completely independently. So when the results came in and were processed in the early years of this century, they gave still greater credibility to the earlier discoveries and provided more detailed data on ice age onset and termination, as well as on the Dansgaard–Oeschger and Heinrich–Bond cycles. The results also raised a host of new issues about what was going on globally and how events in the far north squared with what was going on in the south—in Antarctica especially, but also in the equatorial regions. Even in the nearsighted perspective of historical time, the cores showed some nice consistencies with well-documented events: GISP 2, for example, gave a snapshot of fluctuations in which important events could be discerned, like a European period of torrential rains and famine from 1308 to 1318 and a period of North Sea storminess from 1343 to 1362, known as “the great drowning.”³²

Particularly dramatic was the correspondence between temperature readings from Europe’s NorthGRIP core and those from ocean borings

done off the coast of Portugal (see graph). In 1976, a comprehensive study of ocean sediment samples definitively established temperature fluctuations corresponding to the Milankovitch periods of 23,000, 41,000, and 100,000 years.³³ As ocean sediment and ice samples continued to yield closely consistent findings, it became unmistakably clear that ice ages—many more than just the four postulated in the nineteenth century—had occurred at the 100,000-year Milankovitch beat, with remarkably small changes in solar radiation mysteriously producing huge and disconcerting changes in the earth's climate.

Yet even as the story of polar ice research approached a kind of crescendo and climax, the United States allowed its leadership to slip, first technologically, with the replacement of Hansen's drilling rigs by Johnsen's, then scientifically, as the Europeans worked more exclusively with one another, and increasingly with Russian drillers and scientists as well. In the last decade of the twentieth century, the initiative increasingly was taken by drillers working the South Pole sheets, notably groups of collaborating French and Russians, who during the Cold War had been looking on jealously from the sidelines as ice-based paleoclimatology got exciting. The Russians began to poke around their Antarctic station in Vostok, though initially they couldn't seem to get their equipment to function. A French team based at Grenoble started to work closely with the Russians. Its scientific leader, Claude Lorius, was known as a personable man eager to collaborate with everybody, but without seeming to have—at least initially—anything unique to put on the table. Eventually, though, in something like a tortoise-and-hare tale, the Franco-Russian group drilled a very long core at Vostok and produced a compelling picture of earth's climate during the last 430,000 years.

When Oeschger first was turning his attention to the carbon dioxide trapped in ice, as noted, it had turned out that radiocarbon dating was really not practical for long-term ice dating. Then, after enormous work extracting and measuring the carbon dioxide content in the first long Greenland cores, many of the results proved almost worthless when it was discovered that much of the ice had been contaminated by dust containing carbonates. Nevertheless, in the course of studying those cores, Oeschger and his collaborators gradually perfected the art of carbon analysis, and during the 1980s and 1990s they established a close correspondence between temperature and carbon fluctuations.

Just as importantly, Oeschger firmly established how much carbon dioxide was in the atmosphere before the industrial revolution began, so that increases in carbon dioxide levels could be charted for the last 250 years.

As early as 1980, Oeschger and colleagues published an analysis in the journal *Radiocarbon* of the carbon dioxide in air bubbles in the Byrd and Camp Century cores,³⁴ and found that concentrations were significantly lower during the last glaciation than afterward, possibly as much as 50 percent lower. A paper published by the Swiss team in the top British journal *Nature* in 1982, based on an analysis of three cores, found that increases in atmospheric carbon dioxide from the last ice age to the current Holocene era ranged by factors of 1.2 to 1.4.³⁵ A 1988 Swiss paper considering “pitfalls” in carbon dioxide study concluded, from further analysis of the long Byrd core, that glacial carbon dioxide levels were about 30 percent lower than the Holocene, preindustrial levels.³⁶ Specifically, the glacial carbon dioxide concentration fluctuated between 180 and 200 parts per million (ppm), while the preindustrial Holocene level was around 280 ppm.

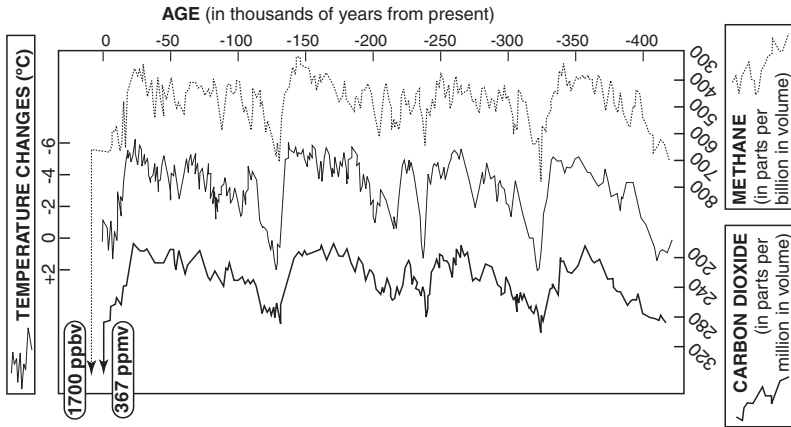
“The discovery of natural oscillations in greenhouse gases from fossil air trapped in polar ice ranks as one of the most important advances in the field of climate and earth science,” wrote the noted geologist Thomas M. Cronin at the time,³⁷ hailing the Swiss and French achievement. Determination of the preindustrial carbon dioxide level, crucial to evaluating global warming in the industrial era, also was a feat of no small import. Since 1957–58, at the behest of Roger Revelle and Hans Suess at the Scripps Institution of Oceanography in La Jolla, California, direct measurements of carbon dioxide concentrations in the atmosphere were made atop Mount Mauna Loa in Hawaii. This ongoing record of steadily rising concentrations, done by their colleague C. D. Keeling, has come to be Exhibit A in the debate over global warming and the canonical presumptive proof that human activity must be affecting global climate. But the record had an annoying shortcoming in that it started out in midstream, long after the industrial revolution began in eighteenth-century Britain.

Oeschger proposed now to connect the dots. Relying on the best data they had obtained on carbon concentrations in ice cores, Oeschger and his colleagues estimated in 1985 that the atmospheric carbon dioxide concentration in the year 1750 was about 280 ppm, and had increased in the meantime by 22.5 percent, to 345 ppm in 1984.³⁸ Twenty years

later, in 2004, the level of carbon dioxide in the atmosphere was 377 ppm, 35 percent higher than in 1750.

From determination of the variations in carbon dioxide levels and the determination of the preindustrial level, it was a short step to finding exact correspondences between carbon dioxide levels and global temperatures. In October 1987, *Nature* published three papers from the Franco-Russian group drilling at Vostok. It is the coldest station on earth, 1,400 kilometers from the nearest coast, with a mean yearly temperature of minus 70 °C. The three 1987 reports delivered what the magazine's expert commentator, Eric T. Sundquist of the U.S. Geological Survey, called "remarkably close association between CO₂ and climate variation, extending through the last interglacial period," proving beyond doubt "that the global climate system and carbon cycle are intensely interactive." At the same time, he said, though both the deuterium isotopes and carbon dioxide records squared fairly well with the 40,000- and 200,000-year Milankovitch cycles, the connections were not simple, and there were some puzzling discrepancies between these records and others.³⁹

Additional drilling at Vostok soon showed that the world's present greenhouse gas levels are unprecedented for the last 420,000 years and that carbon and temperature levels are inextricably linked in a lockstep relationship. On June 3, 1999, *Nature* published an article based on the Vostok cores producing what its expert reviewer, the Bern climatologist Bernhard Stauffer, called a "cornucopia of ice core results."⁴⁰ Drilling had started in 1990, with U.S. scientists joining the Franco-Russian team, and reached bedrock in 1998 at 3.6 kilometers. The article summarizing the results, compiled mainly by the Grenoble group, contained what is surely one of the most striking charts in the history of climate research, and perhaps the most striking of all. It shows that if changes in greenhouse gases and temperature variations are plotted against time, the correspondence is so close that the two sets of data could almost have been plotted on the same lines. The right axis—which might reasonably be dubbed the Dansgaard axis—records stable isotope levels; the left axis—the Oeschger axis, if you will—records levels of carbon dioxide and methane. The four peaks and troughs so vividly seen represent four transitions from glacial warm epochs, starting at 335,000 years B.P., 245,000, 145,000, and 18,800. The roughly 100,000-year periodicity, along with the shorter and subtler cycles, correlates well with the Milankovitch cycles, sup-



The Lockstep Relationship of Greenhouse Gases and Temperature

Source: Lorius

porting the idea that “changes of the orbital parameters of the earth (eccentricity, obliquity, and precession of axis) cause variations in the intensity and distribution of solar radiation, which in turn trigger natural climate changes,” as Stauffer put it.

It remains unclear why the correspondences between carbon dioxide and temperature levels in the 420-millennium record are so exact, and what causal sequences are at work. If surprisingly subtle changes in solar irradiation are prompting sharp temperature changes, are the changes in carbon dioxide levels merely effects of the temperature changes? Or do the temperature changes somehow induce changes in carbon dioxide levels, which in turn amplify the temperature changes, in a chain reaction? And what if the causal chain is reversed, with carbon dioxide changes being the initiating events? Will we then continue to see the same lockstep relationship between carbon dioxide and temperature levels?

That the answers to such questions are not known is no ground for complacency. If scientists could say precisely how greenhouse gases and temperatures have interacted in past eras, then, looking ahead, perhaps they could say with confidence that as greenhouse gas levels rise sharply in the next century, drastic consequences can be excluded. But in fact, all they know is that in the past, sharp declines in greenhouse gas levels were associated with cataclysmic events, and that in the future, equally

sharp increases in greenhouse gas levels will occur unless the world goes about its business rather differently.

The Vostok core represented, in a sense, the climax in a 50-year saga. In recognition of the path-breaking work begun by Bader and Langway and culminating in Lorius's Vostok core, Dansgaard, Oeschger, and Lorius were honored in 1996 with the Tyler Prize—the most prestigious award in the field of environmental science.⁴¹ But Vostok is not the end of the story. An even longer Antarctic core, drilled at the so-called Dome C site, has in the meantime pushed the climate record back 740,000 years. Scientists studying the Dome C core noticed striking similarities between the transition that occurred 430,000 years ago (“Termination V”), which was unusually long, and the interglacial transition we are in now, prompting them to speculate that “without human intervention, a climate similar to the present one would extend well into the future.”⁴² It would seem, accordingly, that we do not have greenhouse gases to thank for the fact that we are not already entering another ice age—a train of thought that has sometimes tempted global warming skeptics.

What is especially disturbing about the Vostok and Dome C reports, even taking into consideration all the uncertainties about leads and lags and causes and effects,⁴³ is the scale of the greenhouse gas changes, compared to what's happening at present. The changes in carbon dioxide levels of 80 to 90 ppm between glacial and interglacial epochs are of the same order as the increase in carbon dioxide registered *so far* since the beginning of the modern industrial era. As this century progresses, unless concerted remedial action is taken, contemporary increases in greenhouse gases will soon far exceed the increases or decreases that accompanied the world into and out of the four most recent ice ages. By the same token, the temperature changes between glacial and interglacial periods—about 9 degrees Fahrenheit or 5 degrees Celsius—are similar in scale (though opposite in sign) to the changes that could occur in this century if carbon dioxide levels double.

Estimates of how much temperatures could change are derived from highly sophisticated computer models. But the startling discoveries of the ice drillers and analysts have presented climate modelers with a big challenge, and the jury is out on whether they will be able to meet it. As Dansgaard says on the last page of his memoir, *Frozen Annals*,

combining all the various feedbacks between ocean and atmosphere into a convincing model able to predict future climate is a task of “overwhelming complexity.” And while huge resources and tremendous brainpower are being brought to bear on that task, “one cannot even be sure that the climate is predictable at all.”⁴⁴ That said, computer modeling is a science that also has made revolutionary strides in the last generation, and it may yet rise to the challenges posed by the ice research community.