

# The Discovery of Rapid Climate Change

**Only within the past decade have researchers warmed to the possibility of abrupt shifts in Earth's climate. Sometimes, it takes a while to see what one is not prepared to look for.**

Spencer Weart

**H**ow fast can our planet's climate change? Too slowly for humans to notice, according to the firm belief of most scientists through much of the 20th century. Any shift of weather patterns, even the Dust Bowl droughts that devastated the Great Plains in the 1930s, was seen as a temporary local excursion. To be sure, the entire world climate could change radically: The ice ages proved that. But common sense held that such transformations could only creep in over tens of thousands of years.

In the 1950s, a few scientists found evidence that some of the great climate shifts in the past had taken only a few thousand years. During the 1960s and 1970s, other lines of research made it plausible that the global climate could shift radically within a few hundred years. In the 1980s and 1990s, further studies reduced the scale to the span of a single century. Today, there is evidence that severe change can take less than a decade. A committee of the National Academy of Sciences (NAS) has called this reorientation in the thinking of scientists a veritable "paradigm shift." The new paradigm of abrupt global climate change, the committee reported in 2002, "has been well established by research over the last decade, but this new thinking is little known and scarcely appreciated in the wider community of natural and social scientists and policymakers."<sup>1</sup>

Much earlier in the 20th century, some specialists had evidence of abrupt climate change in front of their eyes. The evidence was meaningless to them. To appreciate change occurring within 10 years as significant, scientists first had to accept the possibility of change within 100 years. That, in turn, had to wait until they accepted the 1000-year time scale. The history of this evolution gives a good example of the stepwise fashion in which science commonly proceeds, contrary to the familiar heroic myths of discoveries springing forth in an instant. The history also suggests why, as the NAS committee worried, most people still fail to realize just how badly the world's climate might misbehave.

## Was a 1000-year climate change possible?

During the early decades of the 20th century, a very few meteorologists did speculate about possibilities for rapid change. The most striking scenario was offered in 1925 by

the respected climate expert C. E. P. Brooks, who suggested that a slight change of conditions might set off a self-sustaining shift between climate states. Suppose, he said, some random decrease of snow cover in northern latitudes exposed dark ground. Then the ground would absorb more sunlight, which would warm the air, which would melt still more snow—a vicious

feedback cycle. An abrupt and catastrophic rise of tens of degrees was conceivable, Brooks wrote, "perhaps in the course of a single season."<sup>2</sup> Run the cycle backward, and an ice age might suddenly descend.

Most other professional climatologists dismissed the idea as preposterous. The continental glaciers of an ice age, a kilometer thick, would surely require vast lengths of time to build up or melt away. Beyond that elementary reasoning lay a deeper rejection of all such speculations. It was the climatologists' trade to compile statistics on past weather in order to advise a farmer what crops to grow or tell an engineer what sort of floods were likely over the lifetime of a bridge. The climatologist's career thus rested on a conviction that the experience of the recent past reliably described future conditions. That belief was supported by a paucity of data, for hardly any accurate records of daily temperatures and the like went back more than half a century or so. The limitation scarcely worried climatologists, who assumed that significant changes took place only over thousands of years. In their textbooks, climate was introduced as the long-term average of weather over time, by definition, static over centuries.

The experts held a traditional belief that the natural world is self-regulating: If anything started to perturb a grand planetary system like the atmosphere, natural forces would automatically compensate. Scientists came up with various plausible self-regulating mechanisms. For example, if temperatures rose, then more water would evaporate from the seas; in response, clouds would thicken and reflect more sunlight, which would restore normal temperatures. The perception of self-regulation reflected a view of the world held deeply in almost every human culture: Stability was guaranteed, if not by Divine Providence, then by the suprahuman power of a benevolent "balance of nature."

Those beliefs were not disturbed by the few long-term climate records available at the time. The best of those data were compiled in the 1920s by an Arizona astronomer, Andrew Ellicott Douglass, who noted that the rings in trees were thinner in dry years. Analyzing old logs, Douglass reported a major century-long climate perturbation around the 17th century. But most other scientists doubted that tree rings (if they reflected climate at all) gave information about anything beyond random regional variations.

Signs of climate shifts were also visible in varves, a

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**Figure 1. Crew aboard the *Vema*,** a pioneering research vessel, extracted cores of deep seabed mud and clay in the 1960s to uncover changes in ocean conditions over time. Studies of tiny fossil shells in the cores showed that the oceans, for all their huge mass, were not as stable as most scientists had assumed. In various parts of the world, surface temperatures had changed several degrees in a few thousand years. If there had been any changes faster than that, the evidence was blurred by perturbations of the mud. (Courtesy Lamont-Doherty Earth Observatory.)



Swedish word for the layers laid down each year in the mud on the bottom of northern lakes. From bogs and outcrops where the beds of fossil lakes were exposed, or from cores of slick clay drilled out of living lakes, the layers were painstakingly counted and measured. Ancient pollen told what plants had lived in the region when the layers were laid down. Major changes in vegetation suggested that the last ice age had not ended with a uniformly steady warming, but with peculiar oscillations of temperature. Scandinavian data revealed a particularly striking shift around 12 000 years ago, when a warm period gave way to a spell of bitterly cold weather, dubbed the Younger Dryas, after *Dryas octopetala*, a hardy Arctic flower whose pollen signals frigid tundra. In 1955, the timing was pinned down by a radiocarbon-dating study, which revealed that the temperature change had been rapid; for climate scientists at midcentury, “rapid” meant a change that took place over as little as 1000 years.<sup>3</sup>

Ice-age changes over a thousand years or so in a restricted region, although surprising, seemed acceptable. The rate of advance and retreat of the great glaciers would be no faster than present-day mountain glaciers were seen to move. That perception was compatible with the so-called uniformitarian principle, a geological tenet that the forces that molded ice, rock, sea, and air did not vary over time. Through most of the 20th century, the uniformitarian principle was cherished by geologists as the very foundation of their science: How could one study anything scientifically unless the rules stayed the same? The idea had become central to their training and theories during a century of disputes, when scientists painfully gave up traditions that explained certain geological features by invoking Noah’s Flood or other supernatural interventions. In human experience, temperatures apparently did not rise or fall radically in less than millennia, so the uniformitarian principle declared that such changes had never happened in the past. Scientists found themselves insisting on this principle as they were confronted, time and again, by cranks and religious fundamentalists who publicly proclaimed ideas about apocalyptic global cataclysms.

Something resembling catastrophic climate jumps could in fact show up in varves. But the silt layers could

have been distorted in countless ways that had nothing to do with climate: a forest fire perhaps, or a shift of stream drainage. Scientists saw the jumps not as climate data to be analyzed, but as mere local noise. They did not worry about the fact that old radiocarbon dates were accurate only within a thousand years or so, so that the chronologies of different sites could not be matched well enough to point to any rapid and widespread change.

In 1956, studying variations in the shells of plankton that were embedded in cores of clay pulled from the deep seabed (see figure 1), radiocarbon expert Hans Suess discovered what was at the time the fastest change that anyone expected. Suess reported that the last glacial period had ended with a relatively rapid rise of temperature, about 1°C per thousand years.<sup>4</sup> It scarcely bothered him and his colleagues that no faster change could have been seen in most cores. In many places, the mud was constantly stirred by burrowing worms or by seafloor currents and slumping, which blurred any differences between layers. Yet the data curves did sharpen as cores were pulled from regions of rapid deposition and as radiocarbon dating improved. By 1960, a trio of scientists at what is now the Lamont-Doherty Observatory—Wallace Broecker, Maurice Ewing, and Bruce Heezen—were reporting a variety of evidence, from deep-sea and lake deposits, that a global climate shift of as much as 5–10°C had taken place in less than a thousand years.<sup>5</sup> Most of their colleagues found such a rise barely plausible.

### Making sense of rapid change

Evidence of a climate shift could only be accepted if it made sense—that is, if there existed some plausible theory of the climate system that could explain the shift. Broecker suspected that the cause might be a rapid turnover of North





**Figure 2. Wallace Broecker saw signs** of rapid shifts between two alternate climate states while assembling geological evidence for his doctoral thesis in the 1950s. But it was hard for scientists to believe such abrupt transitions were possible in the absence of any plausible mechanism. From the 1960s through the 1980s, Broecker drew together work by many people to convincingly describe one such mechanism. The entire circulation of the world's oceans could shut down or start up in the span of centuries, or less, and bring radical global climate change. Global warming might trigger such a shift. (Courtesy AIP Emilio Segre Visual Archives.)

Atlantic ocean waters, but that was just hand-waving speculation. More influential was a 1956 paper by Ewing and William Donn, who built an elaborate model for the coming and going of ice ages.<sup>6</sup> Like Brooks and others before them, Ewing and Donn began with the notion that a retreat of reflective snow and ice would bring more warming by sunlight. Their new idea was that the feedback mechanism had a hair trigger set off by ocean currents. As ice sheets melted and the sea level rose, warm water would spill into the Arctic Ocean and melt its ice cover, thus speeding up the warming. But once the Arctic Ocean was free of ice, they argued, so much moisture would evaporate that snow would fall heavily all around the Arctic, switching the feedback to cooling. Ewing and Donn thought it conceivable that the polar ocean might become ice-free and launch us into a new ice age within the next few hundred years.

Journalists alerted the public to the risk of a glacial advance within the foreseeable future. People were prepared to believe it, for they were already abandoning their old ideas about an imperturbable balance of nature. The headlong advances of population and industry were making themselves felt in ever more widespread pollution. More ominous still was the global radioactive fallout from nuclear weapons tests, alongside scientists' warnings that a nuclear war could wreck the entire planet. It was no longer inconceivable that some perturbation—even one produced from human industry—might alter the entire planet.

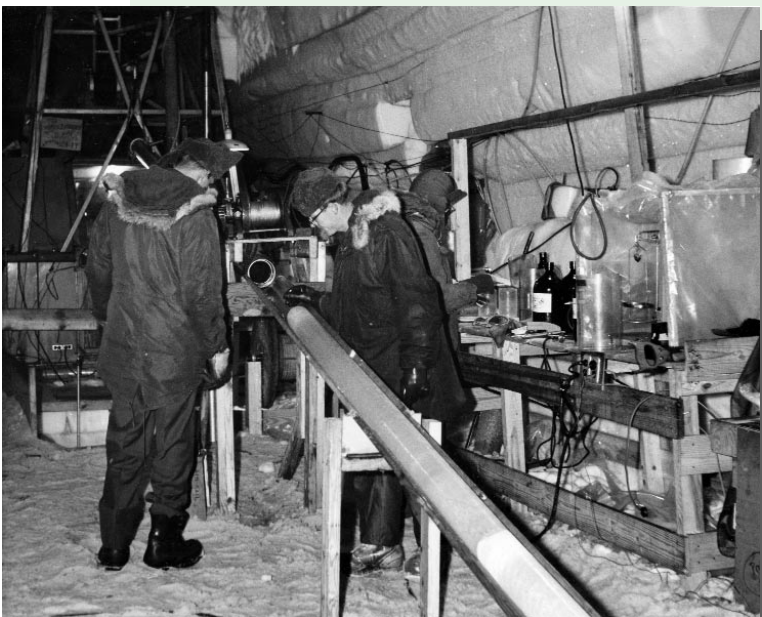
In fact, Ewing and Donn's theory was erroneous, as other scientists quickly pointed out. Nevertheless, it had served a useful function. For the first time, there was respectable scientific backing for a picture of rapid, even disastrous, climate change. Other scientists, even as they re-

jected the theory, were stimulated to broaden their thinking and to inspect data for new kinds of information.

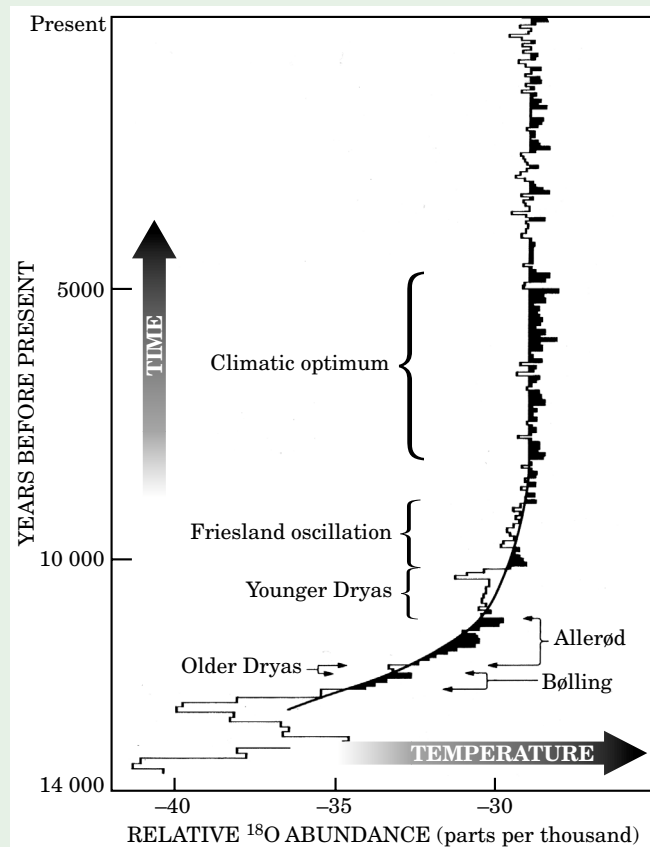
Further stimulation came from entirely different studies. In the late 1950s, a group led by Dave Fultz at the University of Chicago carried out tabletop "dishpan" experiments in which they used a rotating fluid to simulate the circulation of the atmosphere. They created a simulacrum complete with a miniature jet stream and cyclonic storms. But when they perturbed the rotating liquid with a pencil, they found that the circulation pattern could flip between distinct modes. If the actual atmospheric circulation did that, weather patterns in many regions would shift almost instantly. In the early 1960s, climatologist Mikhail Budyko in Leningrad got disturbing results on a still larger scale from some simple equations for Earth's energy budget. His calculations indicated that feedbacks involving snow cover could indeed bring extraordinary climate changes within a short time. Other geophysical models turned up more possibilities for rapid change.

The most influential idea for what might bring rapid change was developed from old speculations about the circulation of the North Atlantic Ocean. In 1966, Broecker (pictured in figure 2), taking a close look at deep-sea cores, reported evidence for an "abrupt transition between two stable modes of operation of the ocean-atmosphere system."<sup>7</sup> Nowadays, warm tropical water flows northward near the surface of the Atlantic; a large quantity, heavy with cold and salt, sinks near Iceland and returns southward in the deep. A change of temperature or salinity might shut down the circulation, cut off the northward transport of a huge amount of heat, and bring severe climate change. Simple numerical models involving the transport of fresh water by a changed pattern of winds showed that such a change could be self-sustaining.

At the University of Wisconsin-Madison, Reid Bryson scrutinized entirely different types of data. In the late 1950s, he had been struck by the wide variability of climates as recorded in the varying width of tree rings. He was also familiar with the dishpan experiments that showed how a circulation pattern might change almost instantaneously. To take a new, interdisciplinary look at climate, Bryson brought together a group that even included an anthropologist who studied the ancient Native American cultures of the Midwest. From radiocarbon-dated bones and pollen, they deduced that a prodigious drought had struck the region in the 1200s—the very period when flourishing towns of the Mound Builders had gone into decline. Compared to that drought, the Dust Bowl of the 1930s had been mild and temporary. By the mid-1960s,



**Figure 3. Cores drilled from the ice at Camp Century, Greenland, and processed on the spot in 1964 (see photo), revealed ancient climate changes in unprecedented detail. The ratio of oxygen-18 to oxygen-16 isotopes in the annual snow layers serves as a thermometer, as shown in the plot: Part per thousand variations to the right indicate warmer temperatures; those to the left, cooler ones. The large rise in temperature started about 14 000 years ago at the end of the last ice age. The plot also shows 1–2°C temperature leaps even within the one-century resolution of the data, but the authors of the 1971 report barely mentioned them in passing. Their concern was the cycles lasting a few centuries or more, which were remarkable enough. Since only a single site was sampled, none of the changes could confidently be called global, and the leaps could have been artifacts due to flow of the deep ice layers. (Photo by David Atwood, courtesy of US Army-ERDC-Cold Regions Research and Engineering Laboratory. Graph adapted from ref. 18.)**



Bryson was announcing that “climatic changes do not come about by slow, gradual change, but rather by apparently discrete ‘jumps’ from one atmospheric circulation regime to another.”<sup>78</sup> His group further reported pollen studies showing a rapid shift around 10 500 years ago; by “rapid” they meant a change in the mix of tree species within less than a century. Perhaps the Younger Dryas was not just a local Scandinavian anomaly.

Still, no major climate change was required to transform any particular forest. Many experts continued to believe it was sheer speculation to imagine that the climate of a region, let alone of the entire world, could change in less than a thousand years or so. But confirmation of changes at that rate, at least, was coming from a variety of studies. As the respected climatologist J. Murray Mitchell Jr explained in 1972, in place of the old view of “a grand, rhythmic cycle,” the new evidence showed a “much more rapid and irregular succession” in which Earth “can swing between glacial and interglacial conditions in a surprisingly short span of millennia (some would say centuries).”<sup>79</sup>

The most convincing evidence came from a long core of ice drilled at Camp Century, Greenland, by Willi Dansgaard’s Danish group, in cooperation with Americans led by Chester Langway Jr. The proportions of different oxygen isotopes in the layers of ice gave a fairly straightforward record of temperature. Mixed in with the expected

gradual cycles were what the group called “spectacular” shorter-term shifts, including the Younger Dryas oscillation. Some of the shifts seemed to have taken as little as a century or two (see figure 3).

During the early 1970s, most climate experts came to agree that interglacial periods tended to end more abruptly than had been supposed. Many concluded that the current warm period could end in a rapid cooling, possibly even within the next few hundred years. Bryson (pictured in figure 4), Stephen Schneider, and a few others took this new concern to the public. They insisted that the climate we had experienced in the past century or so, mild and equable, was not the only sort of climate the planet knew. For all anyone could say, the next decade might start a plunge into a cataclysmic freeze, drought, or other change unprecedented in recent memory, although not without precedent in the archaeological and geological record.

Cooling was not the only change that experts were starting to worry about. Since the late 1950s, attentive scientists had acknowledged the potential value of the old idea that human emissions of carbon dioxide gas (CO<sub>2</sub>) might lead to global warming. (See PHYSICS TODAY, January 1997, page 34.) Most experts assumed that if such a greenhouse-effect warming did occur, it would come as they expected for any climate change—gradually over the course of a few centuries. But some suggested swifter possibilities.

**Figure 4. Reid Bryson at the University of Wisconsin.**

In the 1960s, he reported evidence of severe climate changes within the time span of a century, such as prolonged droughts that had devastated Native American cultures in the 1200s. And he drew public attention to the question in the early 1970s, when unusual droughts were afflicting several parts of the world.

Bryson's chief concern was that the rapid increase of aerosols—industrial smoke plus dust from eroding farms and grasslands—would bring drastic cooling. Although that never happened, many took to heart his key message: Grievous climate change could descend with little warning as an unintended consequence of human activities. (1972 photo courtesy of Reid Bryson.)



In 1972, pursuing his calculations of ice-cover feedbacks, Budyko declared that, at the rate we were pumping CO<sub>2</sub> into the atmosphere, the ice covering the Arctic Ocean might melt entirely by 2050. And glacier experts were developing models that suggested how warming might cause the ice sheets of Antarctica to break up swiftly and shock the climate system. Bryson and others worked harder than ever to bring their concerns to the attention of the broader scientific community and the public.

Most scientists spoke more cautiously. When leading experts had to state a consensus opinion, as in a 1975 NAS report on climate research,<sup>10</sup> they reported that they saw nothing that would bring anything beyond relatively small changes that would take centuries or longer to develop. They did warn that there could be significant noise, the usual irregularities of weather patterns. And they admitted that they might have failed to recognize some mechanisms of change. If there was a threat, experts in the 1970s could not agree whether it was from global warming or cooling. The one thing that all scientists agreed on was that they were seriously ignorant about how the climate system worked. So the only step they recommended to policymakers was to pursue research more aggressively.

**Jumps within centuries—or less**

In the late 1970s and early 1980s, a variety of new data revealed surprising climate shifts. To take one example, a study of beetles that had been preserved in peat bogs since the end of the last glacial epoch turned up changes in the mix of species; those changes represented climate shifts of 3°C in well under 1000 years. Meanwhile, computer models produced plausible calculations for rapid climate shifts involving snow-cover feedbacks, a shutdown of North Atlantic circulation, or ice-sheet collapse.<sup>11</sup> During the 1980s, the list of plausible mechanisms grew. Perhaps a rise in global temperature would cause methane to bubble out of the vast expanses of boggy tundra. Because methane is a greenhouse gas that blocks heat radiation even more effectively than CO<sub>2</sub>, such a release would cause even more warming in a vicious feedback cycle. Or what about the clathrates—peculiar ices that lock up huge volumes of methane in the muck of seabeds? Perhaps those would disintegrate and release greenhouse gases.

Many scientists continued to look on such speculations as little more than science fiction. The evidence for rapid shifts, as it sometimes turned up in odd data sources like bog beetles, was never entirely convincing. Any single record could be subject to all kinds of accidental errors. The best example of a problem was in the best data on climate

shifts, the odd wiggles in measurements from the Camp Century core. Those data came from near the bottom of the hole. Skeptics argued that the ice layers there, squeezed tissue-thin, were folded and distorted as they flowed over the bedrock.

To get more reliable data, the ice drillers went to a second location, some 1400 kilometers distant from Camp Century. By 1981, after a decade of tenacious labor, they hit bedrock and extracted gleaming cylinders of ice 10 cm in diameter and more than two km deep; the deepest ice came from the last ice age, 14 000 years ago. The ratios of oxygen isotopes within the ice layers gave a temperature record showing what the researchers called “violent” changes. The most prominent of those, corresponding to the Younger Dryas oscillation, showed “a dramatic cooling of rather short duration, perhaps only a few hundred years.”<sup>12</sup>

Since the 1950s, jumps had persistently turned up in weather and climate models, whether built from rotating dishpans or from sets of equations run through computers. Scientists could have dismissed those models as too crude to say anything reliable—but the historical data showed that the notion of radical climate instability was not absurd after all. And scientists could have dismissed the jumps in the scattered data as artifacts, due to merely regional changes or simple errors—but the models showed that global jumps were physically plausible.

Nevertheless, experts were scarcely prepared for the shock that came from the Greenland ice plateau in 1993. Plans had been laid to drill at the summit of the ice cap, where irregularities due to the deep flow of ice would have been minimal. Early hopes for a new cooperative program joining Americans and Europeans broke down and each team drilled its own hole, some 3 km deep (see figure 5). Competition was transmuted into cooperation by a decision to put the two boreholes just far enough apart (30 km)



so that anything that showed up in both cores must represent a real climate effect, not an artifact due to bedrock conditions. The match turned out to be remarkably exact for most of the way down. The comparison between cores showed convincingly that climate could change more rapidly than almost any scientist had imagined. Swings of temperature that were believed in the 1950s to take tens of thousands of years, in the 1970s to take thousands of years, and in the 1980s to take hundreds of years, were now found to take only decades. Greenland had sometimes warmed a shocking 7°C within a span of less than 50 years. More recent studies have reported that, during the Younger Dryas transition, drastic shifts in the entire North Atlantic climate could be seen within five snow layers, that is, as little as five years!<sup>13</sup>

Studies of pollen and other indicators—at locations ranging from Ohio to Japan to Tierra del Fuego, and dated with greatly improved radiocarbon techniques—suggested that the Younger Dryas event affected climates around the world. The extent of the climate variations was controversial (and to some extent remains so). Likewise uncertain was whether such variations could occur not only in glacial times, but also in warm periods like the present. Computer modelers, now fully alerted to the delicate balance of salinity and temperature that drove the North Atlantic circulation, found that global warming might bring future changes in precipitation that could shut down the current heat transport. The 2001 report of the Intergovernmental Panel on Climate Change, pronouncing the official consensus of the world's governments and their climate experts, reported that a shutdown in the coming century was "unlikely" but "cannot be ruled out." If such a shutdown did occur, it would change climates all around the North Atlantic—a dangerous cooling brought on by global warming.<sup>14</sup>

Now that the ice had been broken, so to speak, most experts were prepared to consider that rapid climate change—huge and global change—could come at any time. "The abrupt changes of the past are not fully explained yet," wrote the NAS committee in its 2002 report, "and climate models typically underestimate the size, speed, and extent of those changes. Hence, . . . climate surprises are to be expected."<sup>15</sup> Despite the profound implications of this new viewpoint, hardly anyone rose to dispute it.<sup>15</sup>

Although people did not deny the facts head-on, many denied them more subtly by failing to revise their accustomed ways of thinking. "Geoscientists are just beginning to accept and adapt to the new paradigm of highly variable climate systems," wrote the NAS committee. And beyond geoscientists, "this new paradigm has not yet penetrated the impacts community"—the economists and other specialists who try to calculate the consequences of climate change.<sup>16</sup> Policymakers and the public lagged even farther behind in grasping what the new scientific view could mean. As a geologist once remarked, "To imagine that turmoil is in the past and somehow we are now in a more stable time seems to be a psychological need."<sup>17</sup>

### A gradual discovery process

How abrupt was the discovery of abrupt climate change? Many climate experts would put their finger on one moment: the day they read the 1993 report of the analysis of Greenland ice cores. Before that, almost nobody confidently believed that the climate could change massively within a decade or two; after the report, almost nobody felt sure that it could not. So wasn't the preceding half-century of research a waste of effort? If only scientists had enough foresight, couldn't they have waited until they

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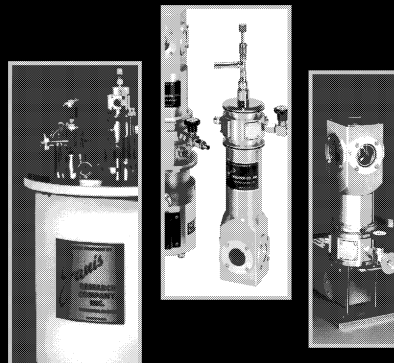
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**Figure 5.** Three kilometers of ice stored as a gleaming library of cylinders in the US National Ice Core Laboratory in Denver, Colorado. Analysis of the ice, drilled from the Greenland icecap during the 1990s, provided a compelling record of precipitous climate changes around the end of the last glacial epoch. The findings stimulated computer simulations of the atmosphere–ocean–ice system; those simulations suggested that such changes could befall us within the next few hundred years. (Photo by Kendrick Taylor, DRI, University of Nevada, Reno, courtesy of the National Oceanic and Atmospheric Administration Paleoclimatology Program/US Department of Commerce.)

were able to get good ice cores and settle the matter once and for all with a single unimpeachable study?

The actual history shows that even the best scientific data are never that definitive. People can see only what they find believable. Over the decades, many scientists who looked at tree rings, varves, ice layers, and such had held evidence of decade-scale climate shifts before their eyes. They easily dismissed it. There were plausible reasons to dismiss global calamity as nothing but a crackpot fantasy. Sometimes the scientists' assumptions were actually built into their procedures: When pollen specialists routinely analyzed their clay cores in 10-cm slices, they could not possibly see changes that took place within a centimeter's worth of layers. If the conventional beliefs had been the same in 1993 as in 1953—that significant climate change always takes many thousands of years—the short-term fluctuations in ice cores would have been passed over as meaningless noise.

First, scientists had to convince themselves, by shuttling back and forth between historical data and studies of possible mechanisms, that rapid shifts made sense, with the meaning of "rapid" gradually changing from millennia to centuries to decades. Without that gradual shift of understanding, the Greenland cores would never have been drilled. The funds required for those heroic projects became available only after scientists reported that climate could change in damaging ways on a time scale meaningful to governments. In an area as difficult as climate sci-

ence, in which all is complex and befogged, it takes a while to see what one is not prepared to look for.

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## References

1. National Academy of Sciences, Committee on Abrupt Climate Change, *Abrupt Climate Change: Inevitable Surprises*, National Academy Press, Washington, DC (2002), pp. 1, 16. Available online at <http://books.nap.edu/books/0309074347/html>.
2. C. E. P. Brooks, *Q. J. R. Meteorol. Soc.* **51**, 83 (1925).
3. See, for example, R. F. Flint, *Am. J. Sci.* **253**, 249 (1955).
4. H. E. Suess, *Science* **123**, 355 (1956).
5. W. S. Broecker, M. Ewing, B. C. Heezen, *Am. J. Sci.* **258**, 429 (1960).
6. M. Ewing, W. L. Donn, *Science* **123**, 1061 (1956).
7. W. S. Broecker, *Science* **151**, 299 (1966).
8. D. A. Barreis, R. A. Bryson, *Wis. Archaeologist* **46**, 204 (Dec. 1965).
9. J. M. Mitchell Jr, *Quaternary Res.* **2**, 436 (1972).
10. National Research Council, US Committee for the Global Atmospheric Research Program, *Understanding Climatic Change: A Program for Action*, National Academy of Sciences, Washington, DC, (1975), appendix A.
11. For beetle data, see G. R. Coope, *Philos. Trans. R. Soc. London B* **280**, 313 (1977); for albedo feedback theory, see M. I. Budyko, *EOS Trans. Am. Geophys. Union* **53**, 868 (1972); for a discussion on ocean circulation, see K. Bryan, M. J. Spelman, *J. Geophys. Res.* **90**, 11679 (1985); for ice-sheet theory, see H. Flohn, *Quaternary Res.* **4**, 385 (1974).
12. W. Dansgaard et al., *Science* **218**, 1273 (1982).
13. For a summary and popular account, see P. A. Mayewski, F. White, *The Ice Chronicles: The Quest to Understand Global Climate Change*, University Press of New England, Hanover, N.H. (2002).
14. Intergovernmental Panel on Climate Change, *Climate Change 2001—The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, J. T. Houghton et al., eds., Cambridge U. Press, New York (2001), p. 420. Available online at <http://www.ipcc.ch/pub/reports.htm>.
15. Current thinking is reviewed in R. B. Alley et al., *Science* **299**, 2005 (2003).
16. See ref. 1, p. 121.
17. E. Moores, quoted in J. McPhee, *Annals of the Former World*, Farrar, Straus and Giroux, New York (1998), p. 605.
18. W. Dansgaard et al., in *The Late Cenozoic Glacial Ages*, K. K. Turekian, ed., Yale U. Press, New Haven, Conn. (1971), chap. 3. ■