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Rapid Climate Change

By the 20th century scientists, rejecting old tales of world catastrophe, were convinced that global climate could change only gradually over many tens of thousands of years. But in the 1950s a few scientists found evidence that some changes in the past had taken only a few thousand years. During the 1960s and 1970s other data, supported by new theories and new attitudes about human influences, reduced the time a change might require to hundreds of years. Many doubted that such a rapid shift could have befallen the planet as a whole. The 1980s and 1990s brought proof (chiefly from studies of ancient ice) that the global climate could indeed shift radically within a century—perhaps even within a decade. And there seemed to be feedback loops that could make warming self-sustaining. Into the 21st century, researchers turned up more and more potential physical and biological feedback mechanisms, interacting with one another in a devilishly complex and possibly unstable system. If greenhouse gas emissions continued to rise, scientists could not rule out passing”tipping points” for an irreversible and catastrophic climate change.

This essay covers large one-way jumps of climate. For short-term cyclical changes, see the essay on “The Variable Sun.” For the main discussion of rapid changes in ice sheets, see the essay on “Ice Sheets, Rising Seas, Floods.” For biological feedbacks see the essay on “Biosphere: How Life Alters Climate.

SUBSECTIONS: ASSUMING INSTABILITY - CHANGES OVER MILLENNIA? (1950S) - HINTS OF INSTABILITY - CHANGES WITHIN A CENTURY? (EARLY 1970S) - MECHANISMS FOR ABRUPT CHANGE - SURPRISES FROM THE ICE (1980S) - ABRUPT GLOBAL CHANGE (1990S) - THE FRAGILE ATLANTIC CIRCULATION - MORE MECHANISMS FOR CATASTROPHE - A PARADIGM SHIFT

“A small forcing can cause a small [climate] change or a huge one...” —*National Academy of Sciences, 2002*[1]

Climate, if it changes at all, evolves so slowly that the difference cannot be seen in a human lifetime. That was the opinion of most people, and nearly all scientists, through the first half of the 20th century. To be sure, there were regional excursions, such as long spells of drought in one place or another. But people expected that after a few years “the weather” would automatically drift back to its “normal” state, the conditions they were used to. The planet’s atmosphere was surely so vast and stable that outside forces, ranging from human activity to volcanic eruptions, could have no more than a local and temporary effect.

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[1] National Academy of Sciences (2002), p. 7.

Looking to times long past, scientists recognized that massive ice sheets had once covered a good part of the Northern Hemisphere. The Ice Age was tens of thousands of years in the past, however, and it had been an aberration. During most of the geological record, the Earth had been bathed in uniform warmth—such was the fixed opinion of geologists. As one meteorologist complained as late as 1991, geology textbooks just copied down from their predecessors the venerable tradition that the age of the dinosaurs (and nearly all other past ages) had enjoyed an "equable climate."[1] The glacial epoch itself seemed to have been a relatively stable condition that lasted millions of years. It was a surprise when evidence turned up during the 19th century that the recent glacial epoch had been made up of several cycles of advance and retreat of ice sheets —not a uniform Ice Age but a series of ice ages.

Some geologists denied the whole idea, arguing that every glaciation had been regional, a mere local variation while "the mean climate of the world has been fairly constant."[2] But most accepted the evidence that the Earth's northern latitudes, at least, had repeatedly cooled and warmed as a whole. The global climate could change rapidly—that is, over the course of only a few tens of thousands of years. Probably the ice could come again. That gave no cause to worry, for it surely lay many thousands of years in the future.

Assuming Stability

A very few meteorologists speculated about possibilities for more rapid change, perhaps even the sudden onset of an ice age. The Earth's climate system might be in an unstable equilibrium, W.J. Humphreys warned in 1932. Although another ice age might not happen for millions of years, "we are not wholly safe from such a world catastrophe."[3] The respected climate expert C.E.P. Brooks offered the worst scenario. He 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, "perhaps in the course of a single season."[4] Run the cycle backward, and an ice age might suddenly descend.

Most scientists dismissed Brooks's speculations as preposterous. Talk of sudden change was liable to remind them of notions popularized by religious fundamentalists, who had confronted the scientific community in open conflict for generations. Believers in the literal truth of the Bible insisted that the Earth was only a few thousand years old, and defended their faith by claiming that ice sheets could form and disintegrate in mere decades. Hadn't mammoths been discovered as intact mummies with grass in their stomachs, evidently frozen in a shockingly

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[1] Crowley and North (1991), pp. 234-35; steady climate was still a "paradigm" in various geosciences into the 1980s, according to Schimel and Sulzman (1995).

[2] Gregory (1908), p. 340.

[3] Humphreys (1932).

[4] Brooks (1925), pp. 90-91.

abrupt change of climate? Scientists scorned such notions. Among other arguments, they pointed out that ice sheets kilometers thick must require at least several thousand years to build up or melt away. The physics of ice, at least, was simple and undeniable.

The conviction that climate changed only slowly was not affected by the detailed climate records that oceanographers recovered, with increasing frequency from the 1920s through the 1950s, from layers of silt and clay pulled up from the ocean floor. Analysis showed no changes in less than several thousand years. The scientists failed to notice that most cores drilled from the seabed could not in fact record a rapid change. For in many places the mud was constantly stirred by burrowing worms, or by sea floor currents and slumping, which blurred any abrupt differences between layers.

Lakes and peat bogs retained a more detailed record. Most telling were studies in the 1930s and 1940s of Scandinavian lakes and bogs, using ancient pollen to find what plants had lived in the region when the layers of clay ("varves") were laid down. Major changes in the mix of plants suggested that the last ice age had not ended with a uniformly steady warming, but with some peculiar oscillations of temperature.[1] The most prominent oscillation—already noticed in glacial moraines in Scandinavia around the turn of the century—had begun with a rise in temperature, named the Allerød warm period. This was followed by a spell of bitterly cold weather, first identified in the 1930s using Swedish data. It was dubbed the "Younger Dryas" period after *Dryas octopetala,* a graceful but hardy Arctic flower whose pollen gave witness to frigid tundra. (The glacial period that preceded the Allerød was the "Older Dryas.") The Younger Dryas cold spell was followed by a more gradual warming, ending at temperatures slightly higher than the present. In 1955 the timing was pinned down in a study that used a new technique for dating, measuring the radioactive isotope carbon-14 ("radiocarbon"). The study revealed that the chief oscillation of temperatures had come around 12,000 years ago. The changes had been rapid—where "rapid," for climate scientists at mid-century, meant a change that progressed over as little as one or two thousand years. Most scientists believed such a shift had to be a local circumstance, not a world-wide phenomenon. There were no data to drive them to any other conclusion, for it was impossible to correlate sequences of varves (or anything else) between different continents.

Even swifter changes could show up in the varves in the clay of lake beds laid down each year by the spring runoff. But there were countless ways that the spring floods and even the vegetation recorded in the layers could have changed in ways that had nothing to do with climate—a shift of stream drainages, a forest fire, the arrival of a tribe of farmers who cleared the land. Abrupt changes in varves, peat beds, and other geological records were easily attributed to such

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[1] Work of Knud Jessen, Johannes Iversen (both Danes) and others, reviewed in Manten (1966).

circumstances. Scientists could win a reputation by unraveling causes of kinks in the data, but for climatology it all looked like nothing but local "noise."[1]

Thus it was easy to dismiss the large climate swings that an Arizona astronomer, Andrew Ellicott Douglass, reported from his studies of tree rings recovered from ancient buildings and Sequoias. Other scientists supposed these were at most regional occurrences. Even regional climate changes scarcely seemed to affect the trees that most scientists looked at (the American Southwest was exceptional in its radically varying climate and precariously surviving trees). It didn't help that Douglass tried to correlate his weather patterns with sunspots, an approach most meteorologists thought hopelessly speculative.

If researchers had found simultaneous changes at widely different locations, they might have detected a broad climate shift. Carbon-14 dating remained fraught with uncertainties, however, and matching up the chronologies of different places was difficult and controversial. Moreover, even a massive and global climate change could bring rains in one locale, cold in another, and little shift at all of vegetation in a third. So each study remained isolated from the others.[2]

In any case it appeared that the rate of advance and retreat of the great ice sheets, at its fastest, had been no faster than present-day mountain glaciers were seen to move.[3] That was compatible with "the uniformitarian principle." This geological tenet held that the fundamental forces that molded ice, rock, sea, and air did not vary over time. Some further insisted that nothing could change otherwise than the way things are seen to change in the present. Geologists cherished the uniformitarian principle as the very foundation of their science, for how could you study anything scientifically unless the rules stayed the same? The idea had become central to their training and theories during a century of disputes. Scientists had painfully given up traditions that explained certain geological features by Noah's Flood or other one-time supernatural interventions. Although many of the theories of catastrophic geological change were argued on fully scientific grounds, by the end of the nineteenth century scientists had come to lump all such theories with religious dogmatism. The passionate debates between "uniformitarian" and "catastrophist" viewpoints had only partly brought science into conflict with religion, however. Many pious scientists and rational preachers could agree that everything happened by gradual natural processes in a world governed by a reliable God-given order.[4]

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[1] Classic work included that of Johannes Iversen on the arrival of agriculture in Denmark and Leonard Wilson on forest fire and other rapid glacial-era changes in Wisconsin.

[2] For discussion on the above points I am grateful to Ken Brown, Daniel A. Livingstone and other respondents from the QUATERNARY and PALEOCLIM listservs.

[3] Carbon-14 dating of trees overridden by the North American ice sheet showed the front had advanced and retreated by up to a kilometer a year between 13,600 and 12,200 years ago. Flint (1955).

[4] Palmer (1999); also Huggett (1990), pp. 119-21 and passim.

Historically, temperatures apparently had not risen or fallen radically in less than millennia, so the uniformitarian principle declared that such changes could not have happened in the past. The principle thus went hand-in-glove with a prevailing "gradualist" approach to all things geological. Alongside physical arguments that the great masses of ice, rock and water could not change quickly, paleontologists subscribed to a neo-Darwinian model of the evolution of species which argued that here too change must be continuous and gradual. All that seemed to apply to climate. Textbooks pointed out, for example, that there were plausible reasons to believe that tropical rainforests had scarcely changed over millions of years, so the climates that sustained the orchids and parrots must have been equally stable. There was no reason to worry about the fact that old carbon-14 dates were accurate only within about a thousand years plus or minus, so that a faster change could hardly have been detected. As for unmistakable fluctuations like the Younger Dryas, presumably those were restricted to the vicinity of the North Atlantic or an even narrower area (few studies had been done anywhere else).

Changes Over Millennia? (1950s)

In 1956 the carbon-14 expert Hans Suess, studying the shells of plankton embedded in cores of clay pulled from the seabed by Columbia University's Lamont Geological Observatory, discovered a change at the fastest speed that anyone expected. Suess reported that the last glacial period had ended with a "relatively rapid" rise of temperature—about 1°C (roughly 2°F) per thousand years.[1] The rise looked even more abrupt when David Ericson and collaborators inspected the way fossil foraminifera shells varied from layer to layer in the Lamont cores. They reported a "rather sudden change from more or less stable glacial conditions" about 11,000 years ago, a change from fully glacial conditions to modern warmth within as little as a thousand years. They acknowledged this was "opposed to the usual view of a gradual change."[2] Indeed Cesare Emiliani, who often disagreed with Lamont scientists, published an argument that the temperature rise of some 8°C had been the expected gradual kind, stretching over some 8,000 years.[3]

More was at stake than simple dating. A graduate student in the Lamont group, Wallace Broecker, put a bold idea in his doctoral thesis. Looking at Ericson's work and other data, Broecker saw severe changes around the world all dated to about the same time—"a far different picture of glacial oscillations than the usual sinusoidal pattern." Like Brooks, he suggested that "two stable states exist, the glacial state and the interglacial state, and that the system changes quite rapidly from one to the other." This was only one passage in a thick doctoral thesis that few people read, and to those few it must have sounded much like Brooks's speculations on cataclysmic changes, long since dismissed by scientists as altogether implausible. They were right to be cautious, for later studies found that the coincidence of changes that Broecker saw at

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[1] Suess (1956), p. 357; other scientists called this an "abrupt increase:" Ewing and Donn (1956a), p. 1061.

[2] Ericson et al. (1955); Ericson et al. (1956), quotes p. 388.

[3] Emiliani (1957).

different locations was an artifact of inaccurate dating. (This was not the last time he would glean a valuable idea from foggy data.)[1]

After considerable debate, Emiliani won his point. The rapid shift that Ericson had reported was not really to be found in the data. Like some other sudden changes reported in natural records, it reflected peculiarities in the method of analyzing samples, not the real world itself. Yet mistakes can be valuable, if they set someone like Broecker to thinking about overlooked possibilities. Sometimes the mistake even turns out to reflect a valid understanding, when, as Broecker later remarked, "...you go back around and actually the discovery itself was valid, even though the thing that led to it was wrong."[2] By 1960, three Lamont scientists—Broecker, Maurice Ewing, and Bruce Heezen—were reporting a variety of evidence, from deep-sea and lake deposits, that a radical global climate shift of as much as 5-10°C had in fact taken place in less than a thousand years.[3] While it would necessarily take many thousands of years to melt the great ice sheets, they had realized that meanwhile the atmosphere and the ocean surface waters, which were less massive, could be fluctuating on their own. Broecker speculated that the climate shifts might reflect some kind of rapid turnover of North Atlantic ocean waters—a natural place for an oceanographer to look.

A few scientists responded with more specific models. Most important was a widely noted paper by Ewing and William Donn, who were "stimulated by the observation that the change in climate which occurred at the close of the [most recent] glacial period was extremely abrupt." Their model proposed ways that feedbacks involving Arctic ice could promote change on a surprisingly rapid scale.[4] Following up, J.D. Ives drew on his detailed field studies of Labrador to assert that the topography there could support what he called "instantaneous glacierization of a large area." By "instantaneous" he meant an advance of ice sheets over the course of a mere few thousand years, which was roughly ten times faster than most scientists had imagined.[5] However, the Ewing-Donn theory turned out to have fatal errors, and most scientists continued to doubt that such swift changes were possible.

Further information came from studies of fossil pollen recovered from layers of peat laid down in bogs. The scientists who undertook such work had not set out to study the speed of climate change. Their inquiry was mostly a routine, plodding counting of hundreds of specks under the microscope, assembling data on vegetation shifts to catalog the way ice sheets came and went. But the carbon-14 dates offered surprises for an attentive eye. For example, a 1961 study

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[1] Broecker (1957), p. V-9; see Broecker and Kunzig (2008), pp. 28-29. A revision of Brooks's 1926 book on *Climate through the Ages* had been published in 1949, Brooks (1949), and it was popular enough to be reprinted in 1970.

[2] Broecker, interview by Weart, Nov. 1977, AIP.

[3] Broecker et al. (1960a).

[4] "Stimulated:" Broecker et al. (1960a), p. 442; Ewing with Heezen had collected some of the crucial cores and noticed the rapid change, Ewing and Donn (1956a).

[5] Ives (1957), quote p. 87; see also Ives (1958); Ives (1962).

mentioned in passing that at one location in Wisconsin, the transition from glacial-period pines to oak trees had taken at most 200 years.[1]

Earth scientists had to be careful in describing such results, for rapid change remained a touchy question. During the 1950s, Immanuel Velikovsky and others had excited the public with popular books describing abrupt and marvelous upheavals in the Earth's history. Frozen mammoths were brought forth again as proof that the world's climate could change catastrophically overnight (although every arctic hiker knows how swiftly a freeze can come even in summer, or how a misstep in a shifting riverbed could bury the careless in permafrost). Experts grew weary of explaining to students and newspaper reporters that the scenarios were sheer fantasy. The battle against Velikovsky and his ilk only reinforced geologists' insistence on the uniformitarian principle, which they took as a denial of any change radically unlike changes seen in the present. Ideas of catastrophic change were also tainted by the way zealots used the ideas, persistently and increasingly, as they sought "scientific" proof for their fundamentalist interpretation of passages in the Bible. (Typical was the complaint of a paleontologist who prefaced his 1992 book with a disclaimer: "in view of the misuse that my words have been put to in the past, I wish to say that nothing in this book should be taken out of context and thought in any way to support the views of the 'creationists'...")[2] There seemed to be no good evidence, nor plausible physical cause, for any swift global upset.

Hints of Instability

Hints that the climate system could change abruptly came unexpectedly from fields far from traditional climatology. In the late 1950s, a group in Chicago carried out tabletop "dishpan" experiments using a rotating fluid to simulate the circulation of the atmosphere. They found that a circulation pattern could flip between distinct modes. If the actual atmospheric circulation did that, weather patterns in many regions would change almost instantly. On a still larger scale, in the early 1960s a few scientists created crude but robust mathematical models that suggested that global climate really could change to an enormous extent in a relatively short time, thanks to feedbacks in the amount of snow cover and the like.[3]

Probably it was no coincidence that this new readiness of scientists to consider rapid and disastrous global change spread in the early 1960s. That was exactly when the world public was becoming anxious over the possibility of sudden global catastrophe. Alongside the fantasies of Velikovsky and warnings from increasingly prominent Bible fundamentalists, there were sober possibilities of disaster brought on by nuclear war, not to mention threats to the entire planet from chemical pollution and other human industrial ills.

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[1] West (1961); the abruptness of the transition was noted later by Lamb (1977), p. 80.

[2] Ager (1993), p. xi.

[3] Budyko (1962); Wilson (1964).

Now that theoretical ideas and the general trend of opinion alike made it easier for climate scientists to envision sharp change, they were increasingly able to notice it in their data. Broecker in particular, looking at deep-sea cores, in 1966 pointed to an “abrupt transition between two stable modes of operation of the ocean-atmosphere system,” especially a “sharp unidirectional change” around 11,000 years ago.[1] It proved possible to build simple fluid-flow models that showed how a switch in the pattern of ocean currents could promote such a change. Improved deep-sea records, going back hundreds of millennia, brought additional information. By comparing the irregular curves from a number of cores, Broecker noticed that the general pattern of glacial cycles was not a simple symmetric wave. It looked more like a sawtooth where “gradual glacial buildups over periods averaging 90,000 years in length are terminated by deglaciations completed in less than one tenth this time.”[2]

The view was supported by data gathered independently at the University of Wisconsin-Madison, where Reid Bryson was already interested in rapid climate changes. In the late 1950s, supported by an Air Force contract to study weather anomalies, he had been struck by the wide variability of climates as recorded in the varying width of tree rings. And he was familiar with the Chicago “dishpan” experiments that showed how a circulation pattern might change almost instantaneously. Bryson brought together a group to take a new, interdisciplinary look at climate, including even an anthropologist who studied the ancient native American cultures of the Midwest. From bones and pollen they deduced that a disastrous drought had struck the region in the 1200s—the very period when the flourishing towns of the Mound Builders had gone into decline. It was already known that around that time a great drought had ravaged the Anasazi culture in the Southwest (the evidence was constricted tree rings in ancient logs from their dwellings). Compared with this drought of the 1200s, the ruinous Dust Bowl of the 1930s had been mild and temporary. A variety of historical evidence hinted that the climate shift had been world-wide. And there seemed to have been distinct starting and ending points. By the mid 1960s, Bryson concluded that “climatic changes do not come about by slow, gradual change, but rather by apparently discrete ‘jumps’ from one [atmospheric] circulation regime to another.”[3]

Next the Wisconsin team reviewed carbon-14 dates of pollen from around the end of the last ice age. In 1968, they reported evidence for a rapid shift around 10,500 years ago, and by “rapid” they meant a change in the mix of tree species within less than a century (they quoted a “half-life” as short as 55 years). Perhaps the Younger Dryas was not just a local Scandinavian anomaly.

Bryson and his collaborators were developing a systematic technique for translating their counts of different kinds of pollens into a record of rainfall and temperature. It was a technique “built on

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[1] Broecker (1966), pp. 299, 301.

[2] Broecker and van Donk (1970).

[3] Bryson, personal communications, 2002. Anthropologist: David Barreis. Barreis and Bryson (1965), p. 204; see Bryson and Barreis (1968), chs. 2, 3; Bryson (1968). The causes of the collapse of the great urban center Cahokia and other elements of the Mississippian culture remain controversial today, with climate change a strong contender.

a foundation of debatable assumptions," as one reviewer observed, yet still "a major step forward." They produced for the American Midwest the most accurate, detailed, and comprehensive climate record available anywhere.[1] Looking at hundreds of carbon-14 dates spanning the past dozen millennia—dates that improvements had made accurate enough to give a reasonable correlation among widely dispersed sites—they believed they could confirm Bryson's disturbing conclusion. Climate change generally did not come smoothly, but in a steplike pattern; periods of "quasi-stable" climate ended in swift transitions.[2] In a 1974 followup, they spoke more boldly of stable periods interrupted by catastrophic "discontinuities," when "dramatic climate change occurred in a century or two at most."[3] The "at most" was a confession that the power of pollen studies was limited. For even if the climate changed overnight, it could take a century or more for the mix of trees in a forest to evolve until it accurately reflected the new conditions.

To be sure, it did not take a global climate change to transform any particular forest. Strictly local events could do that. There was no way to correlate climate changes in different parts of the world down to the exact century, since carbon-14 measurements still had a wide range of error and other dating techniques were worse. This limitation of the data did not worry most experts, for they felt it was sheer speculation to propose any physical mechanism that could change the entire world's climate in less than a thousand years or so.

Yet confirmation of changes at that rate, at least, was coming from a variety of other work. An example was George Kukla's study of snail shells and pollen in layers of loess (wind-blown dust) in Czechoslovakia—another study that was designed to investigate gradual shifts, but in which a close look at the data revealed unexpectedly abrupt transitions.[4] The emerging picture of severe instability was reinforced by studies of cores drilled from the Greenland and Antarctic ice caps, and by deep-sea cores that covered much longer times. Evidently the hundred-thousand-year glacial cycles did follow a sawtooth pattern: each cycle showed a slow descent into a long-lasting cold state that ended with a mysteriously abrupt rise of temperature. As Emiliani put it in 1974, "We used to think intervals as warm as the present lasted 100,000 years or so. Instead, they appear to be short, infrequent episodes."[5] Another respected climatologist explained that the old view of "a grand, rhythmic cycle" must be replaced by a "much more rapid and irregular succession," in which the Earth "can swing between glacial and interglacial conditions in a surprisingly short span of millennia (some would say centuries)."[6]

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[1] Webb and Bryson (1972); reviewer: Bradley (1985), pp. 322-329, quote p. 327; for a general review of "transfer functions" for deducing temperature, see Sachs et al. (1977).

[2] Bryson et al. (1970), p. 72.

[3] Discontinuities: Wendland and Bryson (1974); a century or two: Bryson (1974).

[4] Kukla and Kocí (1972), p. 383.

[5] Quoted in Alexander (1974), p. 94.

[6] Mitchell (1972), pp. 437-38.

Within these larger transitions, even quicker secondary oscillations showed up in various data, such as carbon-14 studies of ancient glacier moraines and lake levels.[1] Above all there was the Younger Dryas. Evidence from shells in a few excellent deep-sea cores showed a geographically widespread temperature oscillation. Many scientists found this evidence of little interest, however. Sea-floor slumping or various chemical and biological effects could easily have confused the data.[2] Up through the early 1970s, few of the scientists who studied ancient climates paid much attention to putative short-term changes. Their energies continued to focus on pinning down the grand multi-millennial rhythm of the ice ages and the famous puzzle of its causes.

Changes within a Century? (Early 1970s)

It was the pursuit of these long cycles, more than any expectation of finding abrupt changes, that attracted scientists to a high-altitude frozen plateau. A Danish group headed by Willi Dansgaard drilled a long core of ice at Camp Century, Greenland in cooperation with Americans led by Chester Langway, Jr. The proportions of different oxygen isotopes in the layers of ice gave a fairly direct record of temperature. But mixed in with the expected gradual cycles, the group was surprised to notice what they called "spectacular" shorter-term shifts—including, once again, an oscillation around 12,000 years ago. Some of the shifts seemed to have taken as little as a century or two. Nobody could be sure of that, however, for the odd wiggles in the data might represent not a world climate shift, but only local accidents in the ice.[3]

A group of glacial-epoch experts, meeting at Brown University in 1972, reached something close to a consensus. Reviewing the Camp Century ice cores, new foraminifera studies by Emiliani, and other field evidence, the scientists agreed that interglacial periods tended to be short, not more than ten thousand years, and to end more abruptly than had been supposed. The present interglacial had already lasted ten thousand years. In view of the cooling reported in the Arctic since the 1940s, they suspected our interglacial might be approaching its end. The majority

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[1] One author, speculating about the coming of a new ice age, pointed to "evidence of (at least) five rapid hemispheric coolings of about 5°C... each event spread over not more than about a century," Flohn (1974), quote p. 385; one line of evidence was carbon-14 studies of tree stumps in glacial deposits: Denton and Karlén (1973). But their fluctuations lasted several centuries, and the authors predicted not a new ice age but a shift to a mild climate.

[2] Broecker and van Donk (1970); Ruddiman & McIntyre too found evidence in deep-sea cores of faunal change (including one core where the warming was interrupted by a cold spell). They called the change "abrupt" although they thought it was spread over a few thousand years: Ruddiman and McIntyre (1973), p. 129; a few years later they realized the spread was due to bioturbation, and the changes were actually "very abrupt." See their review of relevant studies from 1941 to 1977, Ruddiman and McIntyre (1981a), pp. 146-50.

[3] Dansgaard et al. (1971); "spectacular": Dansgaard et al. (1972), p. 396; Dansgaard et al. (1973). The Camp Century and later work is discussed in Dansgaard (2004) and in interviews on GISP tape-recorded 1992-1994, records of Study of Multi-Institutional Collaborations, AIP. See for Camp Century Doel et al. (2016) and for the Cold-War context also Martin-Nielsen (2013).

concluded that the current warm period might possibly end in rapid cooling within the next few hundred years—”a first order environmental hazard.”[1]

Bryson, Stephen Schneider, and a few others took the 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, but not without precedent in the archeological and geological record. While Bryson warned that the increasing pollution of the atmosphere would shade the Earth and bring rapid cooling, this was not the only possibility. The growing realization that small perturbations could trigger sudden climate change also impressed scientists who were growing concerned about the rising level of the greenhouse gas carbon dioxide (CO_2). Perhaps that might bring serious global warming and other weather changes within as little as a century or two.

As abrupt changes became more credible, scientists noticed them in still more kinds of evidence. One example was the shells of beetles, which are abundant in peat bogs, and so remarkably durable that they can be identified even 50,000 years back. Beetles swiftly invade or abandon a region as conditions shift, so the species you find give a sensitive measure of the climate. Russell Coope, studying bog beetles in England, turned up rapid fluctuations from cold to warm and back again, a matter of perhaps 3°C, around 13,000 years ago. It all happened within a thousand years at most, he reported (if the change had been even faster his data could not have shown it).[2] This singular approach got a skeptical response from other scientists who pursued the well-established study of pollens, for they were accustomed to seeing more gradual transformations of forests and grasslands. They easily dismissed the fluctuations in Coope’s records as local peculiarities of English beetles.

The Camp Century cores, too, might tell little about change on a global scale. The data might be sensitive to changes of ice cover in the seas near Greenland, or to a local shift of the ice cap’s glacial flow. Other evidence, especially oxygen isotopes in shells from deep-sea cores that reflected conditions in the entire North Atlantic, showed changes only over several thousand years.

Nevertheless, as pieces of evidence accumulated, a growing number of scientists found it plausible that the climate over large regions, if not the entire world, had sometimes changed markedly in a thousand years or even less. Perhaps one reason was that the early 1970s meanwhile saw further development of global energy-balance models in which a few simple equations produced radical instability. In particular, Mikhail Budyko in Leningrad pursued calculations about feedbacks involving ice cover, and suggested that at the rate we were pumping CO_2 into the atmosphere, the ice covering the Arctic Ocean in summer might melt entirely by

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[1] Kukla and Matthews (1972).

[2] Coope (1977); already in 1970 a cooling within a thousand years or so was seen, although not remarked upon, Coope et al. (1971).

2050. Conversely, a buildup of snow and ice might reflect enough sunlight to flip the Earth into a glaciated state.[1] These ideas prompted George Kukla and his wife Helena to inspect satellite photos of Arctic snow cover, and they found surprisingly large variations from year to year. If the large buildup seen in 1971 were repeated for only another seven years, the snow and ice would reflect as much sunlight as during a glacial period. "The potential for fast changes of climate," they warned, "evidently does exist on the Earth."[2]

Meanwhile glacier experts developed ingenious models that suggested that global warming might provoke the ice sheets of Antarctica to break up swiftly, shocking the climate system with a huge surge of ice water.[3] Bryson and other scientists worked harder than ever to bring their concerns to the attention of the scientific community and the public. As Broecker put it, any decade now a severe "climatic surprise" could hit the world.[4]

Most scientists spoke more cautiously. When leading experts had to state a consensus opinion they were circumspect, as in a 1975 National Academy of Sciences report about plans for international cooperation in atmospheric research. Evaluating past statistics, the panel concluded that predictable influences on climate made for only relatively small changes. These changes, they said, would take centuries or longer to develop. Any big jerks that might matter for current human affairs were likely to be just "noise," the usual irregularities of climate. The panel agreed that there was a significant "likelihood of a major deterioration of global climate in the years ahead," but they could not say how rapidly that might happen. Scientists argued over whether the greatest global risk was cooling by atmospheric pollution or greenhouse effect warming. (Some journalists were writing lurid stories about the prospect of a catastrophic global cooling, but among scientists this was never more than a speculation offered by a minority.) No doubt the present warm interglacial period would end eventually, but that might be thousands of years away. About the only thing the scientists fully agreed on was that they were largely ignorant.[5]

As a landscape that looks smooth from a distance may display jagged gullies when seen through binoculars, so sharper and sharper changes appeared as measuring techniques got better. An example was an analysis that Emiliani published in 1975 of some deep-sea cores from the Gulf of Mexico. Thanks to unusually clear and distinct layers of silt, he found evidence of a remarkable event around 11,600 years ago: a rise of sea level at a rate of meters per decade.[6] Another compelling example was a 1981 study of a few sediment cores that had accumulated

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[1] Budyko (1972).

[2] Kukla and Kukla (1974), quote p. 713; this was brought to the public, e.g. in Time (1974a).

[3] E.g., Flohn (1974), with reference to work by Lorenz, Budyko, and Sellers on instability; Dansgaard et al. (1972), p. 396, speculating on cooling.

[4] Broecker (1975).

[5] GARP (1975), from App. A (pp. 186-90) by J. Imbrie, W.S. Broecker, J.M. Mitchell, Jr., J.E. Kutzbach. Speculation: see study by Peterson et al. (2008).

[6] Emiliani et al. (1975), for criticism, see *Science* **193** (24 Sept. 1976): 1268.

very rapidly, giving excellent time resolution. They showed a startling cooling around 11-12,000 years ago—as much as 7-10°C in less than a thousand years—before the warming resumed. One expert warned that temperatures in the past had sometimes jumped 5°C in as little as 50 years.[1]

Mechanisms for Abrupt Change

Was there really any mechanism that could have caused such leaps of temperature? The known cosmic causes, for example a modulation of sunlight, seemed unlikely to be strong enough to push truly rapid world-wide changes. An expert noted that most of his colleagues "take the European late-glacial chronology as standard for the whole world, in the belief that climatic changes must have been broadly synchronous because they were cosmically caused."[2] A close look at the best evidence, however, found only events affecting the North Atlantic region (where most of the experts did their work). A local trigger for the Younger Dryas, in particular, was suggested by the fossil shorelines of a gigantic lake of fresh water that had been dammed up behind the North American ice sheet. Evidence suggested that as the sheet melted back, an ice dam had suddenly broken up and released the entire lake to flood down the St. Lawrence River. By adding fresh water to the North Atlantic, that could have shut down the circulation in which warm water from the tropics moves north, then sinks as it grows denser from cold and salinity—an enormous transfer of heat that would later be called a global "conveyor belt" (see below, section "The Fragile Atlantic Circulation") .[3]

(The cause of the Younger Dryas would be disputed into the 21st century. The most widely accepted explanation remained a flood of glacial meltwater that stopped the North Atlantic

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[1] Ruddiman and McIntyre (1981a); another example: century-scale changes in carbon-dated peat bog pollen, including a clear oscillation 11,000-9,000 years ago, Woillard and Mook (1982); in 50 years: Flohn (1979).

[2] Mercer (1969), p. 227.

[3] Diversion of glacial meltwater from the Mississippi to the St. Lawrence was suggested by Kennett and Shackleton (1975) and Johnson and McClure (1976); Rooth (1982) suggested this disrupted the North Atlantic circulation. Ruddiman and McIntyre (1981a), p. 204, dismissed this; in 1985 Broecker suspected the meltwater pulse was the entire cause of the Younger Dryas, but later he suggested it was only the trigger that set the timing for a switch between "thermohaline" circulation modes, Broecker et al. (1989) (whose "synthesis of palaeoclimatic observations invigorated the community over the next decade," according to Le Treut et al. (2007), p. 106); Broecker et al. (1990). See "Ocean currents" essay. A computer model by Bryan (1986) supported this, but another model found that a cold North Atlantic surface sufficed to bring a Younger Dryas-like climate, Rind et al. (1986). Teller et al. (2002) review the evidence for a Lake Agassiz outburst as the trigger; McManus et al. (2004) showed there was a sharp decline in ocean circulation. For the history see also Broecker (2010). In 2010 geologists found evidence for a Dryas trigger in a massive release of glacial meltwater, as Broecker had predicted, but by way of the Mackenzie River system of northern Canada rather than the St. Lawrence, Murton et al. (2010).

circulation. But other ideas, each with a few supporters, could not be definitively excluded. Had an eruption of icebergs, following the sudden disintegration of Arctic Ocean ice sheets, cooled the entire North Atlantic Ocean? Or did a huge asteroid or comet strike set it off? Other mechanisms that scientists thought up were more global in scope. Had a catastrophic disintegration of Antarctic ice sheets sent forth masses of ice to cool all of Earth's oceans? Or perhaps a cluster of volcanic eruptions had affected the whole Northern Hemisphere? Or had changes in the North Atlantic been initiated in the tropics or in the North Pacific Ocean (huge regions often overlooked by the ice-core specialists), for example by some grand reorganization of the atmospheric circulation?[1] Then again, the changes might be purely chaotic—autonomous and unpredictable stutterings between different quasi-stable modes of the planet's climate system?)

There were all too many feedback forces that might turn any slow local temperature change into an abrupt global one. The old traditional candidates had included changes in ice and snow cover, in ocean currents, or in the pattern of wind circulation and storms. During the 1980s, additional speculations lengthened the list. Perhaps a rise in global temperature would cause microbial life to burgeon in the vast expanses of peat bogs and tundra, emitting more "swamp gas"? That was methane (CH_4), a greenhouse gas that traps heat radiation even more effectively than CO_2, so it could cause more warming still in a vicious feedback circle. Or what about clathrates—peculiar ices that locked up huge volumes of methane in the muck of cold seabeds—perhaps these would disintegrate and release greenhouse gases?

It was getting easier for scientists to consider such colossal transformations, for uniformitarian thinking was under attack. By the early 1980s, some geologists were stressing the importance of rare events like the enormous glacial meltwater floods that had created the peculiar Oregon "scablands". In biology, Stephen Jay Gould and a few others were arguing that some species had evolved in "punctuated" bursts.[2] Other scientists were offering plausible scenarios of cosmic catastrophes that might happen only once in tens of millions of years. Had a stunning climate change, following the fall of a giant asteroid, exterminated the dinosaurs in a single frozen year? Could something like that befall us?

Many scientists continued to look on such speculations as little better than science fiction. The evidence of abrupt shifts that turned up in occasional studies may seem strong in retrospect, but at the time it was not particularly convincing. Any single record could be subject to all kinds of accidental errors. The best example was in the best data on climate shifts, the wiggles in

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[1] Mercer (1969) considered breakup of an Arctic Ocean ice sheet; this is cited as a likely explanation by Ruddiman and McIntyre (1981a), pp. 204ff.; see Ruddiman and McIntyre (1981b). Wikipedia.org has a good article on "The Younger Dryas impact hypothesis," see Firestone et al. (2007), Kennett et al. (2015). Eruptions: Flohn (1974); tropics: see Steffensen et al. (2008); Pacific Ocean: Walczak et al. (2020).

[2] Gould (2002), pp. 1006-21 gives one version of the history, with his characteristically polemical approach.

measurements from the Camp Century core. These data came from near the bottom of the hole, where the ice layers were squeezed tissue-thin and probably folded and distorted as they flowed over the bedrock.

Broecker later remarked that the relatively smooth temperature record of oxygen isotopes in deep-sea sediments “tended to lull scientists into concluding that the Earth’s climate responds gradually when pushed.” Many continued to believe that the oceans could only vary gradually over thousands of years, with their massive thermal inertia that must moderate any climate changes. These scientists did not realize that the top few meters of ocean exchange heat only slowly with the rest, so the thin surface layer could indeed heat up quickly. And they failed to notice that at most places in the deep sea, sediments accumulate at only a few centimeters per thousand years. Churning by burrowing worms and other creatures within the mud (“bioturbation”) smears the layers, blurring any record of change.[1] Ice did not have these problems. Thus further progress would depend on getting more and better ice cores.

Surprises from the Ice (1980s)

Ice drilling was becoming a little world of its own, inhabited by people of many nations (Dansgaard’s “Danish” team spoke eight different languages). Their divergent interests made for long and occasionally painful negotiations. But the trouble of cooperation was worth it for bringing in a variety of expertise, plus (what was also essential) a variety of agencies that might grant funds.[2] Drilling teams hunted ancient ice in places barely possible to reach—eventually they penetrated not only the polar ice caps, but mountain ice fields from Peru to Tibet—and the teams had to somehow get there with tons of equipment and supplies. The outcome was a series of engineering triumphs, which could turn into maddening fiascos when a costly drill head got irretrievably stuck a mile down. Engineers went back to their drawing-boards, team leaders contrived to get more funds, and the work slowly pushed on. *There is a supplementary site on the History of Greenland Ice Drilling, with some documentation of the U.S. “GISP” projects of the 1980s.*

The first breakthrough came after the ice drillers went to a second Greenland location, a military radar station named “Dye 3" some 1,400 kilometers distant from Camp Century. By 1981, after a decade of tenacious labor and the invention of an ingenious new drill, they had extracted gleaming cylinders of ice ten centimeters in diameter and in total more than two kilometers long. Dansgaard’s group cut out 67,000 samples, and in each sample analyzed the ratios of oxygen

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[1] Also, the sluggish response of the massive polar icecaps to change smoothed the oxygen-isotope record. Broecker (1987b); for these issues in general, see Palmer (1999); Huggett (1990).

[2] For Greenland drilling, see interviews on GISP tape-recorded 1992-1994, records of Study of Multi-Institutional Collaborations, AIP; Martin-Nielsen (2013); Mayewski and White (2002); Alley (2000); Dansgaard (2004). For this and especially Lonnie Thompson’s high-altitude work see Bowen (2005).

isotopes. The temperature record showed what they called “violent” changes—which corresponded closely to the jumps at Camp Century. Moreover, the most prominent of the changes in their record corresponded to the Younger Dryas oscillation seen in pollen shifts all over Europe. It showed up in the ice as a swift warming interrupted by “a dramatic cooling of rather short duration, perhaps only a few hundred years.”[1]

A particularly good correlation came from a group under Hans Oeschger. An ice drilling pioneer, Oeschger was now measuring oxygen isotopes in glacial-era lake deposits near his home in Bern, Switzerland. That was far from Greenland, but his group found “drastic climatic changes” that neatly matched the ice record. The severe cold spells became known as “Dansgaard-Oeschger events.” They seemed to be restricted to the North Atlantic and Europe.[2]

As ice drillers improved their techniques, making ever better measurements along their layered cores, they found a variety of large steps not only in temperature but also in the CO_2 concentration.[3] This was a great surprise to everyone. Since the gas circulates through the atmosphere in a matter of months, the steps seemed to reflect world-wide changes. Other scientists promptly pointed out that the observations might be a mere artifact—the amount of gas absorbed might change with the local temperature in Greenland because of the physical chemistry of ice. Yet clearly *something* had made spectacular jumps. A variety of other evidence for very abrupt climate changes was accumulating, and some began to entertain the notion of such change on a global scale.

Most of these scientists, after presenting their data, could not resist adding a few suggestive words about possible causes. Dansgaard’s group was typical in speculating about “shifts between two different quasi-stationary modes of atmospheric circulation.”[4] That was the most common idea about how climate might change rapidly, harking back to the “dishpan” experiments of the 1950s. It implied transient variations of wind patterns within broad limits, and mostly concerned how weather might change in a particular region. The new thinking about grand global shifts urged a broader view. It was hard to see how the atmosphere could settle into an entirely new state unless something drastic happened in the oceans. For it is sea water, not air, that holds most of the heat energy and most of the moisture and CO_2 of the climate system. The question of century-scale shifts, now a main topic in climatology, came to rest on the desks of ocean scientists.

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[1] Dye 3: Dansgaard et al. (1982), “violent,” “dramatic” (also “drastic”), p. 1273; see also Oeschger et al. (1984); Camp Century CO_2: Neftel et al. (1982); note that they do not discuss a jump that is evident in their data.

[2] Siegenthaler et al. (1984), “drastic” p. 149. They found nothing similar in North American records; Barnola et al. (1987) found nothing like it in their Antarctic ice core, but admitted their methods would not detect very rapid changes.

[3] A century-scale shift closely correlated with temperature change was found by Oeschger et al. (1984); see also Dansgaard et al. (1984); decade-scale shifts are visible in the data, although not specially remarked upon, in Hammer et al. (1986).

[4] Dansgaard et al. (1982), p. 1275.

Their response was prompt. Experts mooted various hypotheses about how changes in the surface waters might affect CO_2 levels. There were complex links among temperature, sea water chemistry, biological activity, and the chemical nutrients that currents brought to the surface. Oceanographers also increasingly found it plausible that the pattern of North Atlantic Ocean circulation could change on a short timescale, as Broecker had proposed to explain the Younger Dryas. Since the circulating waters carry tremendous quantities of heat northward from the tropics, if the circulation ground to a halt, temperatures in many regions of the Northern Hemisphere would immediately plunge.

Broecker began to warn that the ocean-atmosphere climate system did not necessarily respond smoothly when it was pushed—it might jerk. In 1987, he wrote that scientists had been "lulled into complacency." People were increasingly taking their cue from elaborate supercomputer simulations of the general circulation of the atmosphere. They failed to realize that these models, in the very way they were constructed, allowed only gradual changes. The authors of an "unstable" model with odd jumps would rework it until it yielded smooth results. Broecker strongly suspected that "changes in climate come in leaps rather than gradually"—posing a drastic threat to human society and the natural world. As computer modelers labored to incorporate interactions between air and sea, their new simulations hinted that he was right.[1]

Abrupt Global Change (1990s)

Early in the 1990s, further revelations startled climate scientists. The quantity, variety, and accuracy of measurements of ancient climates were increasing at a breakneck pace—compared with the data available in the 1970s, orders of magnitude more were now in hand. The first shock came from the very summit of the Greenland ice plateau, a white wasteland so high that altitude sickness was a problem. From this location all ice flowed outward, so glacier experts hoped that even at the bottom, three kilometers (two miles) down, the layers would be relatively undisturbed by movement. Early hopes for a new cooperative program joining Americans and Europeans had broken down, and each team drilled its own hole. An ingenious decision transmuted competition into cooperation. The two holes were drilled just far enough apart (30 kilometers) so that anything that showed up in both cores must represent a real climate effect, not an accident due to bedrock conditions. The match turned out to be remarkably exact for most of the way down. A comparison of variations in the cores showed convincingly that climate could change more rapidly than almost any scientist had imagined.[2]

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[1] "The basic architecture of the models denies the possibility of key interactions that occur in the real system. The reason is that we do not yet know how to incorporate such interactions into the models." Broecker (1987a), pp. 123, 126; new models: Bryan and Spelman (1985); Manabe and Stouffer (1988).

[2] GISP interviews, records of Study of Multi-Institutional Collaborations, AIP. Firsthand accounts are Mayewski and White (2002); Alley (2000). For more on ice drilling, see Joel Genuth's Greenland Ice Sheet Project (GISP) on this Website and the GISP Website http://www.ngdc.noaa.gov/paleo/icecore/greenland/gisp/gisp.html.

Swings of temperature that in the 1950s scientists had believed would take tens of thousands of years, in the 1970s thousands of years, and in the 1980s hundreds of years, were now found to take only decades. Ice core analysis by Dansgaard's group, confirmed by the Americans' parallel hole, showed rapid oscillations of temperature repeatedly at irregular intervals throughout the last glacial period. Greenland had sometimes warmed a shocking 7°C within a span of less than 50 years. For one group of American scientists on the ice in Greenland, the "moment of truth" struck on a single day in midsummer 1992 as they analyzed a cylinder of ice, recently emerged from the drill hole, that came from the last years of the Younger Dryas. They saw an obvious change in the ice, visible within three snow layers, that is, scarcely three years! The team analyzing the ice was first excited, then sobered—their view of how climate could change had shifted irrevocably. The European team reported seeing a similar step within at most five years (later studies found a big temperature jump within a *single* year). "The general circulation [of the atmosphere] in the Northern Hemisphere must have shifted dramatically," Dansgaard's group eventually concluded.[1]

Or might the bulk of the change, some 9°C within a decade, have been a local event restricted to the vicinity of central Greenland? The first hints of the answer came from oceanographers, who had been hunting out seabed zones where bioturbation by burrowing worms did not smear any record of rapid change. In some places the sediments accumulated very rapidly, while in others, the sea water lacked enough oxygen to sustain life. The first results, from the Norwegian Sea in 1992, confirmed that the abrupt changes seen in Greenland ice cores were not confined to Greenland alone. Meanwhile changes in dustiness were noted in the ice itself, suggesting at least a continental scope for the change. Subsequent work on seabed cores from the California coast to the Arabian Sea, and on chemical changes recorded in cave stalagmites from Switzerland to China, confirmed that the swings found in the Greenland ice had been felt throughout the Northern Hemisphere. The reach of the Younger Dryas temperature step was confirmed by a rapid rise in the level of methane in the ice. The gas must have come from far distant emissions, perhaps out of warmed wetlands in the tropics.[2]

Meanwhile, in the late 1980s and early 1990s, improved carbon-14 techniques gave the first accurate dates for sediments containing pollen and other carbon-bearing materials at locations ranging from Japan to Tierra del Fuego. Good dates finally allowed correlation of many geological records with the Greenland ice. The results suggested that the Younger Dryas events had affected climates, one way or another, around the world. The extent and nature of the perturbation was controversial. (It was not until around 2010 that scientists firmly established that the Younger Dryas cooling in particular had been restricted to the Northern Hemisphere, with the

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[1] Dansgaard et al. (1989); increasingly abrupt changes were seen on further study, Johnsen et al. (1992); Grootes et al. (1993); jumps of Greenland snow accumulation "possibly in one to three years" were reported by Alley et al. (1993), see also Mayewski (1993); five-year steps: Taylor et al. (1997), changes of 2-4°C at Greenland within a single year: Steffensen et al. (2008) . Good histories are Alley (2000) and Cox, (2005), ch. 8.

[2] First ocean results: Karpuz et al. (1992), Lehman and Keigwin (1992). Changes in ice: Severinghaus et al. (1998), Severinghaus and Brook (1999).

Southern Hemisphere continuing to warm up.) But scientists were increasingly persuaded that abrupt climate shifts could have global scope, even if they affected different places differently—colder here and warmer there, wetter here and drier there.[1]

Could such drastic variations happen not only during glacial times, but also in warm interglacial periods like the present? That was the most interesting question in 1992, as the European drillers penetrated clear through the last glacial epoch to the preceding "Eemian" period, more than 100,000 years back—a time similar to the current one or perhaps slightly warmer (the world would in fact reach Eemian temperatures by the early 2020s). Ominously, Dansgaard and his colleagues saw that rapid oscillations had been common during the last interglacial warm period: enormous spikes of cooling, like a 14-degree cold snap that had struck in the span of a decade and lasted 70 years. The instability was unlike anything the ice record showed for our current interglacial period. The "recent climate stability," Dansgaard warned, "may be the exception rather than the rule," raising the question whether our climate "will remain stable in spite of the growing atmospheric pollution." Published in *Nature* in 1993, this would become one of the most widely cited of all climate papers. The ice core data, as *Science* magazine reported, "shattered" the standard picture of benign, equable interglacials.[2]

Comparison of the two groups' cores gave divergent results, however. Evidently Dansgaard's measurements, made near the bottom of the core, were distorted by ice flow that stirred together layers from warm and cold periods. Again scientists had benefitted from drilling parallel cores. But this time the lesson, valuable if unwelcome, was that they must do more work.[3]

Yet in terms of how scientists thought about the present climate system, one might say that the ice had been broken. Evidence of swift and severe shifts at the height of the last ice age had also been found recently in deep-sea cores, and scientists hesitated to dismiss these discontinuities as some kind of accidental noise. People recalled that the present climate system was certainly subject to abrupt and harrowing droughts, like the one revealed by Bryson's group that had devastated native North American cultures. Persuasive new geological evidence blamed extreme prolonged droughts for the downfall of ancient Mayan and Mesopotamian civilizations as well.[4]

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[1] For further references 1987-94 (including also Alaska, Ohio, New Zealand, etc.) see Broecker (1995b), pp. 306-08; for later developments, National Academy of Sciences (2002) and Lynch-Stieglitz (2004), also Cox, (2005), ch. 8. Northern only: e.g., Kaplan et al. (2010), Bereiter et al. (2018). Some historical details are in Broecker (2010), ch. 4.

[2] Dansgaard et al. (1993); Kerr (1993). Among the ten most-cited climate papers during the early 21st century: Robert McSweeney, "Analysis: The Most 'Cited' Climate Change Papers," CarbonBrief.org July 8, 2015, online at https://www.carbonbrief.org/analysis-the-most-cited-climate-change-papers

[3] Alley et al. (1995); Chappellaz et al. (1997), comparing with Vostok cores.

[4] Deep-sea cores: Heinrich (1988); Bond et al. (1992), on Heinrich and Bond see also notes in the essay on Ocean Currents and Climate. Maya: Hodell et al. (1995); Mesopotamia: Weiss et al. (1993); for global climate shifts throughout the postglacial period, see also

Antarctic cores could not help. Little snow falls there, and the layers of ice were too thin and squashed together to reveal rapid variations. Certainly no climate variation of Younger Dryas magnitude had been seen recently. So there was reason to hope that our present climate was relatively stable, at least for the moment. The Europeans and Americans nevertheless agreed that through most of the last 100,000 years the global climate had oscillated "on a scale that human cultural and industrial activities have not yet faced." More broadly, a landmark 2001 study published a temperature record for the entire past 65 million years, and it was far from smooth. "It now appears," the authors concluded, "that extreme aberrations in global climate can arise through a number of mechanisms."[1]

The Fragile Atlantic Circulation

Scientists will doubt even the best set of data if they have no theory to explain it, but at least one plausible explanation was at hand. A flip-flop of the entire North Atlantic Ocean's circulation pattern might have been involved in the Dansgaard-Oeschger events. People came up with various proposals for things that might have triggered a switch, in particular the collapse of an Arctic ice sheet sending a flotilla of icebergs through the Hudson Strait.

That was not easy to swallow. As one scientist remarked, many of his colleagues "do not believe that the small, energy-starved polar 'tail' can wag the large, energy-rich tropical 'dog'." But the evidence of iceberg surges was strong, and computer models suggested that such a surge could indeed have caused a drastic global circulation shift. Oceanographers began to work out how the tropical oceans could take part in a sudden global change. The tropical Pacific and Atlantic ocean and wind systems seemed to have feedbacks that, once perturbed, might reorganize the entire system of clouds, rainfall and currents. For example, a "permanent El Niño" might move the Earth back to a state not seen since several million years ago, when so much ice had been melted that the sea level stood roughly 25 meters above the present level.[2]

Did the same type of instability exist today? There was suggestive evidence that abrupt flips of the North Atlantic circulation had in fact happened in previous times of warmth.[3] "There is surely a possibility," Broecker wrote, "that the ongoing buildup of greenhouse gases might trigger yet another of these ocean reorganizations." The media picked up the dramatic image of Europe returning to the frigid conditions of the Younger Dryas. Global warming could bring on a new Ice Age almost instantly! Increasing attention went to what was coming to be named the Atlantic

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deMenocal et al. (2000).

[1] Divergence in cores: Taylor et al. (1993), Grootes et al. (1993). 2004 work: NGRIP (North Greenland Ice Core Project members, K.K. Andersen et al.) (2004); see report by Cuffey (2004) and also Cox (2005), ch. 8. Hammer et al. (1997), Preface, "not yet faced," p. 26,315. Cenozoic aberrations: Zachos et al. (2001).

[2] Wag the dog: Alley (1998). Icebergs: Menviel et al. (2014), Henry et al. (2016). El Niños: Cane and Evans (2000); Federov et al. (2006).

[3] Barber et al. (1999).

Meridional Overturning Circulation (AMOC)—part of the global "conveyor belt," as Broecker called it, that brought heat to the North Atlantic on the surface and back southward underneath (and onward to the Southern Ocean and Pacific). When an international panel of experts made their best guess on the matter in 2001, they concluded that a shutdown of the Atlantic circulation in the coming century was "unlikely" but "cannot be ruled out." If the shutdown did come, Broecker warned, it could mean "widespread starvation" within decades. In the next few years, scientists reported that the Atlantic waters were indeed growing less salty, thanks to fresh water from increased rainfall and the melting of ice. Still more troubling was a 2005 announcement that the amount of heat carried southward by the Atlantic circulation had decreased by as much as 30% since the 1950s.[1]

However, the observational record was skimpy. Further measurements showed that the system was so variable from year to year that it would take prolonged and dedicated observations to separate long-term changes from normal, temporary fluctuations. In any case a replay of the catastrophic Younger Dryas glacial scenario was not likely under the very different conditions of the present. Computer modelers redoubled their attention to the question, and their simulations showed only gradual, centuries-long changes in the global ocean circulation. In the best tradition of scientific self-correction, Broecker admitted that he had overestimated the danger of a shutdown of ocean circulation. In 2004 he publicly cautioned against the "exaggerated scenarios" that had recently appeared in a Hollywood summer spectacle. By 2008 many experts believed that the Atlantic circulation was very unlikely to collapse in the 21st century, and not likely to collapse later, "although," some admitted, "the possibility cannot be entirely excluded."[2]

As Broecker had pointed out, the computer models were *built* to give stable solutions. One pair of modelers admitted this frankly: "Anecdotal evidence suggests that many modeling groups (including our own) have encountered problems with an unstable AMOC, to the extent that it collapsed in their present-day model climate. These problems are seen as a model deficiency that in most cases would not be published but repaired by changes to the model..." The models, in short, might be unrealistically stable.

It was also worrying that modelers were unable to simulate the abrupt Younger Dryas shifts without arbitrary interventions. Indeed, observed long-term climate variation in general was much

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[1] Broecker et al. (1992); quotes: Broecker (1997), p. 1588; IPCC (2001a), p. 420; Atlantic freshening: Hansen et al. (2001); Dickson et al. (2002); Curry et al.(2003); Curry and Mauritzen (2005); slowed circulation: Bryden et al. (2005). In addition, the decline of Arctic Ocean sea ice cover led to increased warmth, and therefore buoyancy, of water that flowed into the North Atlanti, Sévellec et al. (2017) .

[2] "Exaggerated:" Broecker (2004); see Weaver and Hillaire-Marcel (2004); system variable: Cunningham et al. (2007) and Kanzow et al. (2007). One study found temperature discrepancies from computer models up to "two orders of magnitude for tropical variability at millennial timescales," Laepple and Huybers (2014); "unlikely... cannot be excluded," Clark et al. (2008), p. 9.

greater than appeared in computer simulations. Modelers could never include all the complex feedbacks that might conceivably cause a sudden shift. As one group that studied the Younger Dryas remarked, “the geological understanding of past abrupt climate changes is only preliminary. This does not bode well for predicting future, abrupt climate changes.”[1]

Among all the widely diverging models, a few did sometimes show abrupt ocean circulation shifts that brought rapid and severe climate change outside of glacial times. In the real world, a 2014 study of the last interglacial period, the best geological analog to the present warm state, discovered abrupt century-scale interruptions in the North Atlantic circulation. By 2020 oceanographers had managed to find unperturbed seabed sediments that allowed them to see changes on a scale of decades rather than centuries. They were surprised to see big, chaotic changes during past epochs scarcely warmer than the present. “The ocean circulation system,” they warned, “may be much less stable than previously thought.”[2]

To get a better handle on the matter, an array of sensors was deployed across the mid Atlantic beginning in 2004. In 2014 with a decade of data in hand, scientists reported a substantial slowdown of the Atlantic circulation, perhaps reaching 7% per year. But they cautioned it might be just a random natural fluctuation that could soon reverse. Meanwhile a new analysis of scraps of data going back to 1957 revealed a possible slowdown by 10% in the latter 20th century, and a study of sediments reported the circulation had been “anomalously weak” since the mid 19th century as compared with earlier millennia. A group that dove into details of advanced models found that quite rapid changes in ocean circulation might turn up even for a moderate global warming of less than 2°. And a team studying past temperatures reported evidence that “the AMOC weakness after 1975 is an unprecedented event in the past millennium.” Most experts, however, were unwilling to draw firm conclusions amid the noise of vast masses of water sloshing back and forth, still largely unobserved in many parts of the globe. They expected it would take decades more of monitoring before they could say whether the recent slowdown might be just a phase of an ordinary natural cycle, or even a purely random fluctuation.[3]

Around 2015 an unusually cold region appeared in the North Atlantic waters south of Greenland. This was a locale that oceanographers thought was crucial to the sinking of cold water that drove the entire global conveyer belt. The anomaly, persisting in later years as the only part of the globe

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[1] “Anecdotal evidence:” Hofmann and Rahmstorf (2009). Models unable: Liu et al. (2009); “Does not bode well:” Lowell et al. (2005).

[2] Last interglacial: Galaasen et al. (2014). Some models found that changes in the ocean circulation “are able to produce abrupt climate changes on decadal to centennial time scales:” Randall et al. (2007), p. 641. “Much less stable:” Stocker (2020) commenting on Galaasen et al. (2020).

[3] Slowdown: Smeed et al. (2014); see Schiermeier (2014). New analysis: Kanzow et al. (2010); “anomalously weak:” Thornalley et al. (2018). A slowdown after 1995 was reported by Mishonov et al. (2024). Computer model: Drijfhouta et al. (2015); unprecedented: Rahmstorf et al. (2015). Natural cycle: see Jackson et al. (2016), Latif et al. (2022).

that was not warming, had in fact already popped up in some computer models that predicted a slowdown of the AMOC. The "cold blob" was probably related to the torrents of fresh water that were now flooding off the melting Greenland icecap (a process that computer modelers had hitherto overlooked). Meanwhile some computer models pointed farther East, where continued warming might trigger an instability in the currents circulating in the seas between Labrador and Iceland. Oceanographers could only speculate about the effects of all this on the AMOC, and worried about passing a "critical threshold" for a shutdown. Pulses of freshwater from melting Arctic Ocean ice and Greenland glaciers were meanwhile shifting winds and currents around the North Atlantic in complex ways, perhaps causing the severe heats waves and droughts that Europe was experiencing.

Around 2023 new studies drew attention to the other end of the globe. A modeling team suggested that fresh water pouring from the melting ice of Antarctica would inhibit the overturning in regions of the Southern Ocean. In these regions trillions of tons of briny surface waters plunge into the abyss, an important component of the entire global conveyor belt. Observations of the overturning in one region did find a spasmodic slowing in recent decades. This was another case of oceanographers, traditionally focused on the North Atlantic, realizing that the Southern Hemisphere was no less important. The modelers warned that if global temperatures got too high, the oceans would become less effective in retarding the warming by carrying surface heat and CO_2 into the deeps. Or perhaps something else altogether would happen among the many obscure ocean processes.[1]

In its 2021 report the IPCC had found only "medium confidence" among experts that there would be no collapse before 2100. That was hardly reassuring, and confidence continued to drop. Two years later an expert already called the IPCC's evaluation "outdated," based as it was on models that at root were designed to be stable. A study that combined modeling with recent ocean observations claimed to detect "fingerprints" showing that the AMOC could already be near a "critical transition point" for collapse. And a pair of researchers using unconventional statistical methods announced they had 95% confidence that "a transition of the AMOC is most likely to occur around 2025-2095."

Most alarming of all was a study in the grandest tradition of climate science: a heroic six-month supercomputer run using the colossal state-of-the-art Community Earth System Model. When the team injected a prodigious torrent of freshwater, for the first time a full-scale model showed the circulation on a "tipping course" to a shutdown. The simulated circulation slowed, gradually but

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[1] "Cold blob," also "warming hole:" Caesar et al. (2018). Fresh water: Hansen et al. (2016); Liu et al. (2017). Chris Mooney, "Why some scientists are worried about a surprisingly cold 'blob' in the North Atlantic Ocean," *Washington Post* (Sept. 24, 2015), online at https://www.washingtonpost.com/news/energy-environment/wp/2015/09/24/why-some-scientists-are-worried-about-a-cold-blob-in-the-north-atlantic-ocean/. Drijfhouta et al. (2015), Sgubin et al. (2017), Armstrong McKay et al. (2022). "Critical threshold:" Oltmanns et al. (2018). Freshwater pulses precede heat waves: Oltmanns et al. (2024). Southern Ocean: Li et al. (2023), Gunn et al. (2023); see Russell (2023).

then suddenly, slamming to a dead halt in the space of half a century or so. The model calculated specific, and horrific, consequences. Sea ice would spread across the Atlantic as far south as Ireland every winter; temperatures in parts of Europe downwind from the frozen seas would drop by 5° to 15°C, resembling some climate shocks seen in the distant past. “No realistic adaptation measures,” the team pointed out, “can deal with such rapid temperature changes.” The rest of the globe would also be affected. The transition, to be sure, would not come as an instantaneous science-fiction scenario. But they suspected that, given enough meltwater, it could start at any time.

Adding another hazard, in 2015 a group of experts had gone out on a limb by arguing that if the AMOC did collapse, warmer sea water would undermine the ice masses that held the Greenland and Antarctic ice sheets in place. In a scenario that other experts thought speculative, but not demonstrably wrong, the result would be feedbacks that could raise sea level a meter or more within decades, along with other disastrous impacts. Other studies suggested additional forces that might bring ice sheet collapse. The climate community began to notice a more general threat: not only were there various processes that could provoke rapid climate change, but the processes might interact, reinforcing one another in a tangle of vicious feedbacks.[1]

More Mechanisms for Catastrophe

In the early 1990s, geologists had found that titanic emissions of greenhouse gases were a likely cause of a spectacular warming that happened 56 million years ago (the “Paleocene-Eocene Thermal Maximum,” PETM). At any rate *something* back then had radically changed climate, with a CO_2 level much higher than at present, global heating, and an abrupt change of the deep ocean circulation. The shock to ecosystems brought extinctions and reorganizations so massive that geologists called it the start of a new geological era. The leading suspect was the clathrate ices frozen in layers spread through sea floor muds. Clathrates might hold more methane and other carbon compounds than all the world’s coal and oil. Studies suggested that warming of the oceans could cause a clathrate deposit to disintegrate in a landslide-like chain reaction, venting a great belch of methane and CO_2 into the atmosphere.

During the PETM the rise in temperature had proceeded gradually over tens of thousands of years, “rapid” only to a geologist. But the emissions had come stepwise, each step spanning perhaps a few centuries. Sea floor outbursts also showed up at other points in the distant past. Whatever had

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[1] IPCC (2021a), Technical Summary Box TS.3. “Outdated:” Stefan Rahmstorf, “New Study Suggests the Atlantic Overturning Circulation AMOC ‘Is on Tipping Course’,” RealClimate.org (Feb. 9, 2024), online at https://www.realclimate.org/index.php/archives/2024/02/new-study-suggests-the-atlantic-overturning-circulation-amoc-is-on-tipping-course. Critical transition point: Boers (2021); around 2025-2095: Ditlevsen and Ditlevsen (2023). Six-month run: van Westen et al. (2024). Group of experts: Hansen et al. (2016), published in draft as Hansen et al. (2015). Interactions: see note below (Wunderling etc.) {n.76}

happened then, it seemed possible that global warming might provoke clathrates to vent gases into the atmosphere at a rate fast enough to bring serious additional warming within a human lifetime—a feedback loop that one scientist called “the clathrate gun.” The idea sounded like science fiction (indeed science fiction writers used it), spurring widespread controversy and research.

There were other ideas for what caused the PETM (a comet? A reorganization of the global ocean circulation?). In 2004 a group proposed that an eruption of magma into carbon-rich strata under the Atlantic had caused “an explosive release of methane.” In 2007 another group offered evidence that the main cause of the disaster was colossal volcanic emissions of CO_2—although there seemed to have been a “massive release of seabed methane” as well. Prolonged arguments settled by 2020 on a burst of volcanism that brought up deeply buried carbon, and perhaps initiated additional carbon emissions from... somewhere. Whatever the exact mechanism, the event indicated (as one group put it in 2021), “the existence of ‘tipping points’ in the Earth system, which can trigger release of additional carbon reservoirs and drive Earth’s climate into a hotter state.”[1]

For the sea floor “clathrate gun” in particular, however, further research inspired by the threat turned out to be reassuring. For one thing, it should take thousands of years for heat to diffuse into the deep sediments where the bulk of clathrates lurked. The idea that greenhouse gas emissions might cause cataclysmic seabed outbursts looked like speculation about a distant future. Even that worry faded after an oil well blew out deep under the Gulf of Mexico in 2010. Along with a devastating oil spill, a great plume of methane bubbled up. All the gas dissolved into the seawater and was oxidized by bacteria before it could reach the atmosphere. Presumably the same would happen to gas released from clathrates. Concern persisted, however, for the geology of the clathrate deposits held many mysteries. For example, surveys turned up regions on the sea floor with swarms of giant craters as much as a kilometer across. Had blowouts during past climate crises released methane in amounts massive enough to reach the atmosphere?

There was another huge and possibly unstable reservoir of clathrates, along with other forms of carbon: the world’s permafrost, often hundreds of feet deep. Some experts suspected that the

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[1] Appenzeller (1991); Kennett and Stott (1991), updated with evidence from other epochs (“mounting geologic evidence for past pervasive, massive CH_4 releases from the marine sediment reservoir”) by Kennett et al. (2000); high CO_2 and hot tropical oceans: Zachos et al. (2003); other theories, Higgins and Schrag (2006); volcanism: Svensen et al. (2004), Storey et al. (2007), confirmed by Foster et al. (2017), Jones et al. (2019); according toGernon et al. (2022), much of the carbon was brought up from the deep mantle. “Gun:” Kennett et al. (2003); Koch et al. (1992); Dickens et al. (1995); Norris and Röhl (1999); Katz et al. (1999); Nunes and Norris (2006); an overview is Kunzig (2004). Science fiction: e.g., in passing in the award-winning Robinson (1994). Harvey and Huang (1995) estimated clathrates could bring at worst a 10-25% increase in warming. Outbursts: Dickens (2003); “massive release:” Gehler et al. (2015); see Gutjahr et al. (2017) and Frieling et al. (2019) (with evidence for ocean methane release). “Tipping points:” Kender et al. (2021).

release of this carbon had played a role in the abrupt warming that ended the Younger Dryas, and perhaps also in the PETM and other climate catastrophes farther in the past. A closer look was only partly reassuring. An isotope analysis of the methane shifts during the Younger Dryas found the shifts mostly involved young carbon, probably from wetlands, rather than fossil carbon from deep in ancient tundra—but a massive release from wetlands could be bad enough.[1]

An altogether different type of evidence for rapid change came from improved observations of Arctic and Antarctic regions. New views from satellites, plus vigorous programs of precise measurements from airplanes and on the ground, showed that enormous glaciers could quickly change their speed of travel, while entire ice sheets could break up within a matter of months. As one expert remarked, this "ran counter to much of the accepted wisdom regarding ice sheets." That accepted wisdom, he explained, "lacking modern observational capabilities, was largely based on 'steady-state' assumptions."[2] Now the plausible possibility that a swift alteration of land or sea ice could transform climate had to be added to all the other potential feedbacks from global warming. *For an extended discussion of possible ice collapse see the essay on "Ice Sheets, Rising Seas, Floods."*

The new view of climate was reinforced by one of the last great achievements of the Soviet Union, an ice core drilled with French collaboration at Vostok in Antarctica. By the end of the 1990s their record reached back through nearly four complete glacial-interglacial cycles—and drastic temperature changes peppered almost every stretch of data. This Antarctic record was too fuzzy to say whether any of these changes had come and gone on the decade-size timescale of the Younger Dryas. But warm interglacial periods had certainly been subject to many severe swings of temperature, each lasting for centuries. Especially striking to the researchers, by contrast, was our own era, the ten thousand years since the last glaciation. It was, "by far, the longest stable warm period recorded in Antarctica during the past 420 [thousand years]." When Bryson, Schneider, and others had warned that the century or so of stability in recent memory did not reflect "normal" long-term variations, they had touched on an instability grander than they guessed. The entire rise of human agriculture and civilization had taken place during a period of equable climate that was unique in the long record. The climate known to history appeared to be a lucky anomaly.

Paleoclimatologist William Ruddiman argued that the stability was not a coincidence. He amassed convincing evidence that the rise of agriculture, with its deforestation, livestock and rice paddies, had added a lot of methane and CO_2 to the atmosphere—indeed enough to hold back the gradual cooling that had come in every other ice-age cycle soon after the temperature peaked. The

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[1] Clathrate warming would take thousands of years: Archer and Buffet (2005). Oil spill (Deepwater Horizon): Kessler et al. (2011); see review, Ruppel and Kessler (2017). Craters: Andreassen et al. (2017); see Davies et al. (2024) for another speculative release mechanism. Younger Dryas: Nisbet (1990b); Nisbet (1992); far past (ending "snowball Earth" episodes): Kennedy et al. (2008). Young carbon: Petrenko et al. (2017).

[2] Rignot and Thomas (2002), p. 1505.

well-recorded history of the most recent century or so happened to show even more unusual stability, compared with what new evidence was revealing about variations in earlier millennia.[1]

A Paradigm Shift

The accumulation of evidence, reinforced by at least one reasonable explanation (the reorganization of ocean circulation) destroyed long-held assumptions. Most experts now accepted that abrupt climate change, huge change, global change, was possible at any time. A report written by a National Academy of Sciences committee in 2001 said that the recognition, during the 1990s, of the possibility of abrupt global climate change constituted a fundamental reorientation of thinking, a "paradigm shift for the research community."[2]

The first strong consensus statement had come in 1995 from the Intergovernmental Panel on Climate Change, representing the considered views of nearly all the world's climate scientists. The report included a notice that climate "surprises" were possible—"Future unexpected, large, and rapid climate system changes (as have occurred in the past)."[3] The report's authors did not emphasize the point, however, and the press seldom mentioned it.

Despite the profound implications of this new viewpoint, hardly anyone rose to dispute it. Not only for climate but for many other complex systems, scientists had come to accept that a small, even random, event could trigger sweeping changes. Yet while they did not deny the facts head-on, many denied them more subtly, by failing to revise their accustomed ways of thinking about climate. For example, few of the scientists studying pollen in bogs went back to their data and took on the difficult task of looking for catastrophically rapid shifts in the past. "Geoscientists are just beginning to accept and adapt to the new paradigm of highly variable climate systems," said the Academy committee in 2001. Beyond geoscientists, "this new paradigm has not yet penetrated the impacts community," that is, the economists and other specialists who tried to calculate the consequences of climate change.[4] Policy-makers and the public lagged even farther behind in grasping what the new scientific view could mean.

Within a few years that changed. Scientists' attention focused on Antarctic and Arctic ice changes. New evidence and theories suggested that the Greenland and West Antarctic ice sheets might melt much faster than had been suspected, bringing a serious sea-level rise within the next few centuries—or even sooner. "Every time we make a big discovery in Greenland," one NASA researcher lamented, "we find out that the probability of a really fast collapse of the Greenland ice

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[1] "Longest stable:" Petit et al. (1999), p. 434. On Ruddiman see footnote in the essay on "The Biosphere."

[2] National Academy of Sciences (2002), p. 16, see also pp. 1, 119, 121.

[3] IPCC (1996a), p. 7.

[4] National Academy of Sciences (2002), p. 121.

sheet is higher than we previously expected." West Antarctica was starting to look even more unstable.[1]

Still more alarming, to scientists and the public alike, were startling changes in"before and after" satellite pictures of sea ice in the Arctic. The ice pack was getting thinner and shrinking. "At the present rate," one group of scientists reported, "a summer ice-free Arctic Ocean within a century is a real possibility." That had last been seen millions of years ago, in an epoch with a sea level roughly 25 meters above the present. As the Arctic seas opened to the winds there would be profound effects on weather far to southward The feedback loop foreseen by Budyko a generation earlier was underway (see above). But the sea ice was seen to be dwindling faster than modern computer models predicted. Reviewing the familiar feedback where less ice and snow meant more sunlight absorbed, one group commented dryly that approaching some critical point "may produce unexpected system responses."[2]

Media ranging from science magazines to movies reflected the new science in their distorted mirrors, offering scenarios of a climate that could change within a few decades or even, according to Hollywood, a few weeks. Around 2005 the term "tipping point" appeared in stories on climate, an admission that change could be not only rapid but irreversible. Since a change might take centuries although it would be irreversible once begun, some preferred the term "critical threshold." Moreover, some mechanisms with thresholds might not end with an irreversible tipping over, but were feedbacks that amplified whatever warming was underway. If we could get the planet to a state where it was not absorbing more energy from the Sun than it was emitting, such feedbacks could reverse and accelerate cooling. An expanding number of groups set to work to pin down just what thresholds might exist, at what temperature they would be passed, and how the approach to a transition might be detected.[3]

Some of the most worrisome thresholds (sometimes mistaken for fatally irreversible tipping points) arose from biological and other feedbacks in the carbon cycle. Although data were spotty (mostly short-term studies of only a few of the countless living systems), results in the early 2000s were discouraging. More likely than not, as soils got warmer they were releasing additional CO_2, methane and other greenhouse gases. A rise in wildfires, accelerated by heat waves, emitted

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[1] Josh Willis quoted in Mike Damanskis, "NASA Is Flying Over Greenland to Predict the Future of Our Coastlines," Earther.com (Jan. 5, 2017) https://earther.com/nasa-is-flying-over-greenland-to-predict-the-future-of-1821811204

[2] Old data from submarines (some of it released on the initiative of Vice President Gore) revealed thinning of ice, Rothrock et al. (1999); for sea ice extent, Overpeck et al. (2005), Lindsay and Zhang (2005), Stroeve et al. (2005). Weather effects: Francis and Hunter (2006). Computer projection of an ice-free Arctic by Holland et al. (2006) were widely publicized. Ice more sensitive to warming than models predicted: Stroeve et al. (2007).

[3] The seminal paper was Lenton et al. (2008). On the phrase "tipping point" see note {n. 150}in the essay on the Public and Climate. "Critical threshold:" Kopp et al. (2016b); J. Hansen pointed out how the term "tipping point" is often misused.

further carbon. The system of carbon uptake and release by forests, in particular, was so poorly understood that scientists admitted there was a "potential for major abrupt change."[1]

Arguably the most dangerous carbon storage system was the vast Arctic tundra, where researchers from Canada to Siberia saw greenhouse gases bubbling out of melting soil before their eyes. Permafrost was thawing and emissions climbing much faster than anyone had predicted. A Russian researcher called it an "ecological landslide that is probably irreversible and is undoubtedly connected to climatic warming." In 2022 a group calculated that a tipping point for a collapse of boreal permafrost might possibly be passed at a global rise of 3° above the pre-industrial temperature and was likely to be passed around 4°; the process would probably take half a century or more but could conceivably be faster.[2]

The good news was, nobody had yet found a mechanism that, outside Ice Age conditions, could plausibly bring a tremendous global climate change faster than over several decades. For example, a thorough review of research reached the not entirely reassuring conclusion that "increased permafrost carbon emissions in a warming climate are more likely to be gradual and sustained rather than abrupt and massive."[3] Unless scientists had completely overlooked something essential (which was possible but unlikely), whatever changes happened would accumulate gradually. The bad news was that if "rapid" meant "within my lifetime," then rapid change was visibly underway.

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[1] For example, Best (2006) speculated that increased organic sediments sent down rivers due to deforestation, factory farming, etc., once buried in the seabed, will be converted to methane by bacteria, perhaps seriously adding to greenhouse gas emissions. Another potential threat was a dieback of the Amazon rainforest. It was the IPCC's conclusion that little is understood about the "potential for major abrupt change... in the uptake and storage of carbon by terrestrial systems," Randall et al. (2007), p. 642.

For an early general review of possible abrupt changes in the climate system see Alley et al. (2003). Carbon cycle: e.g., Bellamy et al. (2005), Heath et al. (2005), Govindasamy et al. (2005); ocean biological systems in general had instabilities, e.g., Hsieh et al. (2005).

[2] Tundra "tipping points" suggested, *i.a.,* by Foley (2005). Russian (Sergei Kirpotin) quoted by Pearce (2005a), along with a report that "the permafrost of western Siberia is turning into a mass of shallow lakes as the ground melts," lakes were expanding on the North Slope of Alaska, Walter et al. (2006) found methane hotspots in eastern Siberia where the bubbling gas kept the surface from freezing in winter, etc. See also Lawrence and Slater (2005). Also, melting of permafrost allowed dark shrubs to spread, which would increase local heating, Chapin et al. (2005). Also, more wildfires as the Arctic warmed could bring "exponentially increasing" carbon emissions from the fires themselves and from exposed permafrost, Descals et al. (2022). Permafrost "thawing much more quickly than models have predicted:" Turetsky et al. (2019). Evidence from the past suggested that a little warming could cause extensive melting of permafrost, Vaks et al. (2013), and indicated "a sensitive trigger for a threshold-like permafrost climate change feedback," Martens et al. (2020). Threshold alculation: Armstrong McKay et al. (2022).

[3] Schuur et al. (2015).

Each ten-year period since the 1970s had been noticeably warmer on average than the preceding ten years, a global change far swifter than anything recorded in human history. And the feedbacks long anticipated were kicking in. As the oceans warmed, sea water was measurably slower at taking up CO_2. Uptake by plants and soils was also lagging or even reversing into net emission (from tundra and wildfires), while humanity's production of greenhouse gases continued to climb.

In 2007 experts and the public were alarmed to see the summer Arctic ice pack shrink more swiftly than ever before. In the next few years it recovered slightly, but the long-term trend still suggested that much of the ice pack could give way to open ocean in late summer within just a few decades. In a 2013 study, a National Academy of Sciences panel called the dwindling of Arctic ice an already visible "abrupt" climate change, likely to deeply affect weather around the Northern Hemisphere. The panel also emphasized that a gradual temperature rise could have abrupt impacts as critical thresholds were crossed, for example in the extinction of species or in agriculture.[1]

Computer models were generally reassuring—but how reliable were they for such matters? The models were adjusted until they were reasonably stable, and were unable (as Broecker had remarked decades earlier) to reproduce the sudden shifts actually seen in Ice Age records. One sobering indication was a 2008 report on a new and superbly detailed Greenland ice core. The layers displayed radical changes in three years or less, the temperature stepping as much as 4°C in a single year. Had the entire atmospheric circulation gone through a massive reorganization from one year to the next? It matched what Broecker had hypothesized half a century earlier: the climate system lurching back and forth between two states, interglacial and glacial. "Neither the magnitude of such shifts nor their abruptness," the team warned, "is currently captured by state-of-the-art climate models." As an expert on past climates noted a few years later, even the best models were "largely untested against actual occurrences of abrupt change. It is a huge leap of faith to assume that simulations of the coming century with these models will provide reliable warning of sudden, catastrophic events."[2]

In its 2001 report the IPCC had briefly mentioned "large-scale discontinuities" in the climate system. They estimated a "moderate" risk that triggering something bad would begin if global warming reached 4° above the 19th-century level, and a "high" risk starting around 5–6°. Over the next decades scientific opinion shifted. For example, a widely cited 2008 study identified no less than six elements of the climate system that "could surprise us by exhibiting a nearby tipping point," and worried that "society may be lulled into a false sense of security by smooth projections of global change." In its 2015 report, the IPCC lowered the thresholds to 2° for moderate risk and 4° for high risk. Among other things, scientists now understood that it was not enough to calculate each type of change separately. One type of damage could interact with another type, multiplying the threat. Computer modelers confirmed that there were many routes to a tipping point. And

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[1] Latest data are available from the US National Snow and Ice Data Center, http://nsidc.org/arcticseaicenews/. National Research Council (2013).

[2] Steffensen et al. (2008). Valdes (2011), see commentary in *Nature* **486**: 183-84 (2012).

scientists kept turning up more possible mechanisms for feedbacks that could accelerate warming. Concern spread in the research community as evidence accumulated that there might remain unknown critical thresholds, and the known ones might be passed at lower temperatures than had been expected. In 2018 the IPCC issued a major interim report that saw a risk anywhere above 1.5°. That meant we could conceivably pass some fatal threshold by mid-century.[1]

In short, if humanity did not quickly rein in its emissions, we could suffer rapid, unpredictable, self-sustaining and irreversible changes in the entire climate system. Scientists planning the IPCC's 2021 report belatedly resolved to give much more attention than in past reports to abrupt climate change. The report mentioned several "tail" possibilities. For example, it recognized that an ice-sheet collapse might bring a 2-meter sea-level rise by 2100. For the first time the IPCC quietly admitted that beyond what it calculated to be likely, "abrupt responses and tipping points" bringing even worse disasters "cannot be ruled out."

Not all of these involved abrupt changes. There was an unquantifiable risk that warming would set in motion slow but irreversible feedbacks, processes that would inexorably work themselves out over centuries of changing ice sheets, forests, soils and so forth. In Earth's interconnected physical and biological systems, passing one type of threshold could push another system, perhaps on the other side of the globe, past its own tipping point in a domino-like cascade. The end could be a radically hotter planet, severely risking "health, economies, political stability... and ultimately, the habitability of the planet for humans." Dozens of the potential physical and biological feedback loops had not been fully incorporated into computer models of climate. As one of the leading IPCC authors explained, "We now consider these 'low probability, high impact' scenarios an increasingly critical part of our work."[2]

In 2022 a team published a synthesis of observations, model results, and expert opinion for many of the proposed "Climate Tipping Points." They concluded that somewhere between a warming of 1.5 and 2°C above pre-industrial, the world was likely to pass the thresholds for the collapse of the Greenland Ice Sheet, the collapse of the West Antarctic Ice Sheet, and an abrupt thaw of the boreal permafrost. Indeed we might have passed some of these thresholds already. Less likely but possible above 1.5° would be passing the tipping point for a collapse of the Atlantic Ocean circulation (AMOC) and of vulnerable East Antarctic glaciers. Additional thresholds would be

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[1] Note the "Burning embers" diagram in IPCC (2001b), p. 11; see Zommers et al. (2020). Modelers: Wunderling et al. (2021). "Lulled...could surprise:" Lenton et al. (2008), p. 1792, see Lenton et al. (2019). IPCC (2018a), chap. 3.

[2] IPCC (2021b), C.3.2 and Fig. SPM.8. "Domino-like cascade," "habitability:" Steffen et al. (2018); for an example of "teleconnection" (Amazon rainforest and ice sheets) see Liu et al. (2023). Dozens not incorporated: Ripple et al. (2023). "Critical part:" Joëlle Gergis, "We Are Seeing the Very Worst of Our Scientific Predictions Come to Pass in These Bushfires," *The Guardian*, Jan. 2, 2020, online at https://www.theguardian.com/commentisfree/2020/jan/03/we-are-seeing-the-very-worst-of-our-scientific-predictions-come-to-pass-in-these-bushfires.

passed with greater warming. As for rapidity, they figured the entire disintegration of any of the colossal ice masses would probably take several millennia, but at an uneven pace with sporadic abrupt rises in sea level. The timescale for Atlantic Ocean circulation or boreal permafrost collapse might be as little as a decade or two, although somewhere between half a century and a few centuries was more likely. These were only the most obvious of the potentially irreversible irreversible processes that might be triggered by the warming expected before the end of the century, unless nations made major policy changes.[1]

See the separate essay on Impacts of Global Warming.

A lesson about how science proceeds can be learned from this history. Asked about the discovery of abrupt climate change, many climate experts today would put their finger on one moment: the day they read the 1993 report of the analysis of Greenland ice cores. Before that, nobody confidently believed that the climate could change massively within a decade or two; after the report, 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 we have waited until we 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 so forth had held evidence of rapid climate shifts before their eyes. They easily dismissed it. There were plausible reasons to believe that global cataclysm was a fantasy of crackpots and Bible fundamentalists. Records of the past were mostly too fuzzy to show rapid changes, and where such a change did plainly appear, scientists readily attributed it (usually correctly) to something other than climate. Sometimes the scientists' assumptions were actually built into their procedures. When pollen specialists routinely analyzed their clay cores in 10-centimeter slices, they could not possibly see changes that took place within a centimeter's worth of layers.[2] If the conventional beliefs had been the same in 1993 as in 1953—that significant climate change always takes many thousands of years—scientists would have passed over the decade-scale fluctuations in ice cores as meaningless noise.

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[1] Armstrong McKay et al. (2022). Another major survey, describing 14 Earth System tipping points: Lenton et al. (2023).

[2] There is a famous comparable case in another field of science. In the 1930s, physicists used thin screens to block extraneous large particles from their instruments as they measured the tiny particles resulting from nuclear reactions. Since they never imagined that an atom could split into two large chunks, they automatically prevented themselves from discovering uranium fission. For discussion on the difficulties of detecting rapid change, I am grateful to Ken Brown, Daniel A. Livingstone and other respondents from the QUATERNARY and PALEOLIM listservs.

First scientists had to convince themselves, by shuttling back and forth between historical data and studies of possible mechanisms, that it made sense to propose shifts as “rapid” as a thousand years. Only then could they come around to seeing that shifts as “rapid” as a hundred years could be plausible. And only after that could they credit changes within a decade or so, and later still, possibly within a couple of years. Without this gradual shift of understanding, the Greenland cores would never have been drilled. The funds required for these heroic projects came to hand only after scientists reported that climate could change in damaging ways on a timescale meaningful to governments. In an area as difficult as climate science, where all is complex and befogged, it is hard to see what one is not prepared to look for.

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