How Ice Age Climate Got the Shakes

Records in Greenland ice, ocean mud, and ancient corals are revealing stunningly abrupt climate shifts during the last ice age–and hints of the ballet of ice sheets and ocean that caused them

Climate, like the weather, is always changing. A few hundred years ago Europe shivered through the Little Ice Age. A thousand years ago, during the Medieval Warm Period, the climate of Europe was as warm as it is today. Twenty thousand years ago Earth was still deep in the last ice age. And climate researchers are finding that in North America and Europe, at least, the grip of even this 100,000-year cold spell was not steady.

Every few thousand years, the climate system seems to have changed its mind about being in an ice age and jerked toward warmer times—over just a few years —only to head back into extreme cold again. Just what flipped the climate system back and forth between warm and cold is still a mystery. But the question has more than historical interest, given predictions of global warming. "Our human response to climate change is based on the assumption that climate is like a light with a dimmer switch," says Richard Alley of Pennsylvania State University, a leader in deciphering the climate records locked in the Greenland ice sheet. The record of the ice age around the Atlantic region, says Alley, makes climate there look more like an on-off switch. "Is there a switch out there that humans are going to throw? It's a realm that needs looking into."

The more climate researchers learn about the workings of climate in the last ice age, the less they think that the same switch is likely to flip in today's world. But the climate system's shudders during the last ice age may hold deeper lessons about the climatic future, says Gerard Bond of Columbia University's Lamont-Doherty Earth Observatory. "It's like just before plate tectonics [revolutionized geology]," says Bond, who has been analyzing marine data. "Everything then was in a state of confusion. A few key pieces of evidence came to light, and then it looked simple. There could be a new theory coming out of this for how the earth's climate system operates."

The pieces that are now coming together include more than climate shifts in the depths of the last ice age. The system's fickleness worsened about 13,000 years ago as the end of the ice age approached. The world had already started to warm toward today's interglacial climate, and then the North Atlantic region, at least, plunged back into the depths of the ice age for more than 1000 years before warming again. Through all of this the great ice sheets were suffering crises of their own: Every 10,000 years or so, at least one ice sheet partially collapsed, launching armadas of icebergs across the North Atlantic.

Until recently, scientists could only guess at the relations, if any, among these climatic fits and starts. But new, more detailed records, extracted from the Greenland ice sheet and from core samples of ocean sediments, are now suggesting that the climate shifts of the ice age, the final hesitation before it ended, and the iceberg surges could be different faces of the same phenomenon: a series of oscillations, hundreds to thousands of years long, that persisted right to the very end of the ice age.


RICHARD ALLEY/GISP

The rigors of Greenland. Drilling shallow supplementary holes at the GISP site, which has yielded records of an even colder time.

Evidence from ice

Much of the understanding of these oscillations comes from new and better records of climate found in the ice cores recently drilled out of the Greenland ice sheet. Earlier ice cores were extracted from the flanks of the ice, where summer melting and the flowing of the ice sheet over bedrock may have distorted the record. But both the U.S.-staffed Greenland Ice Sheet Project II (GISP2) and the Greenland Ice-Core Project (GRIP), conducted by European scientists, have taken their cores near its summit, where the layer of snow laid down each year rarely melts before being deeply buried and the 3-kilometer-thick ice sheet has flowed little. GISP2 workers have counted annual layers marked by summer dust and other markers as far back as 40,000 years ago, and they are still counting.

A dramatic example of the new, sharper resolution the ice cores are yielding comes at the close of the Younger Dryas, a 1300-year cold snap so named because it was marked in Europe by the resurgence of the polar wildflower *Dryas octopetala*. Falling between 12,900 and 11,600 years ago, it was the last swing back to glacial cold—a drop of 7°C in Greenland—after the climate had already started warming in a period called the Bølling-Allerød. At the end of the Younger Dryas, the climate jumped back toward the relative warmth of the past 10,000 years—and that last leap out of the ice age was a humdinger, according to the latest analyses of ice cores. Alley and 10 U.S. colleagues in GISP2 reported last month that at the end of the Younger Dryas, a warmer, wetter climate doubled the rate of snow accumulation in only 3 years. Most of the increase occurred in a single year.

The well-preserved ice records of GISP2 and GRIP are also making it clear that this abrupt shift from cold to warm was virtually a replay of something that had happened many times before, during the ice age itself. Studying the changing ratio of oxygen isotopes—thought to be an indication of temperature—in earlier ice cores, Willi Dansgaard of the University of Copenhagen and Hans Oeschger of the University of Bern had claimed to see a series of 500- to 2000-year swings from full glacial conditions to warmer times. But many researchers had doubted the reality of the climate swings because of the intermittent melting and layering distortions from nearby bedrock in those ice records.

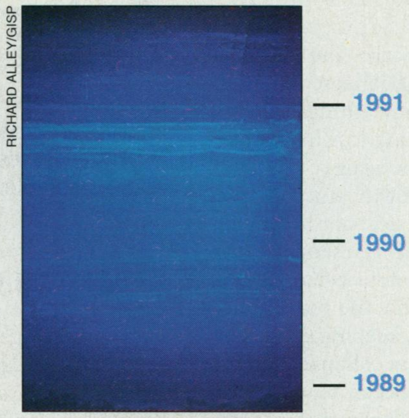
Now Sigfus Johnsen and H. B. Clausen of the University of Copenhagen, Dansgaard, and their GRIP colleagues have found all 10 previously identified Dansgaard-Oeschger events of 22,000 to 37,000 years ago in the new GRIP core. The improved record shows that like the Younger Dryas, the earlier cycles of the climate system last from centuries to a couple of millennia, jumping abruptly from cold to relatively warm phases before sliding gradually back into glacial cold.

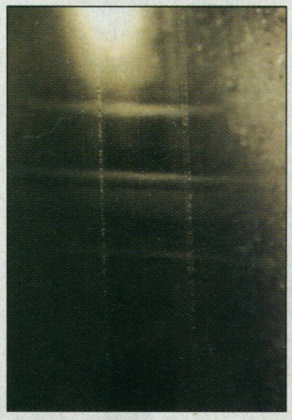
As unity emerges in the history of these climate swings, some researchers are searching for unity in their causes: a common mechanism. The favored hunting ground has been the circulation of the North Atlantic. In today's circulation, surface currents carry heat and salt into the far North Atlantic as part of a globe-girdling "conveyor belt" of currents. A key turning point in the conveyor is the sinking of the salty—hence dense—waters of the North Atlantic to form a cold, deep current that flows back to the south. Wallace Broecker of Lamont has proposed that changes in the saltiness of the North Atlantic, by turning the sinking on and off, could act as an ice-age climate switch with a built-in clock—just the thing to drive a long series of climate oscillations.

In the warm phase of each cycle, the conveyor belt's heat would begin to melt surrounding ice sheets. As the resulting fresh water streamed into the far North Atlantic, salinity would drop, lowering the density of surface waters until deep water formation stopped and the conveyor belt shut down. With the heat from the south now cut off, temperatures would fall, and ice melting would stop. To complete an oscillation, salinity would have to rise again, either by the accumulation of salt carried north by the remnant of the Gulf Stream or by the loss of fresh water from the Atlantic by evaporation. Then the conveyor would switch on again, causing an abrupt surge in warmth.

That elegant, simple picture of the ice age climatic switch, however, may not be enough to explain the stubbornly complex reality of climatic change, as new results from coral reefs are showing. The reefs grow to keep up with rising sea level and also store clues to ocean circulation in the composition of their carbon isotopes, which varies depending on how rapidly surface waters exchange with deep waters in the world's oceans. As a result, dated samples of old coral can provide clues to both the timing of meltwater pulses and changes in ocean circulation. On page 962 of this issue of *Science*, Lawrence Edwards of the University of Minnesota and his colleagues show that the sequence of events recorded by a coral reef in New Guinea during the Younger Dryas isn't what the ocean switch scenario predicts: A meltwater pulse does coincide with the beginning of the cold period, but the cold persists even when the conveyor belt seems to be on.

Similar evidence has come from other studies, and such findings lead many researchers to suspect that it may take only a partial shutdown of deep water formation in the North Atlantic, or a shift in its location, to transform North Atlantic climate. That would be one key complication to the simple conveyor belt model. Another, grander complication has been introduced into the picture in the form of evidence from the floor of the North Atlantic. This new evidence has some researchers wondering whether the ocean switch acts alone; the master climate switch, they say, might actually be in the ice rather than in the ocean.





High and low. Layers of summer hoarfrost mark recent snow *(top)*; deep in the core, dust delineates annual layers of snow squeezed to ice.

Iceberg armadas

The notion of an ice switch has its roots in a 1988 discovery by Hartmut Heinrich of Germany's Federal Office for Marine Navigation and Hydrography in Hamburg. By measuring the amount of rocky debris dropped from passing icebergs onto the sea floor, he found six intervals in glacial times, each lasting from 1000 to 2000 years, when huge numbers of icebergs must have suddenly begun sweeping across the Atlantic to Europe's doorstep.

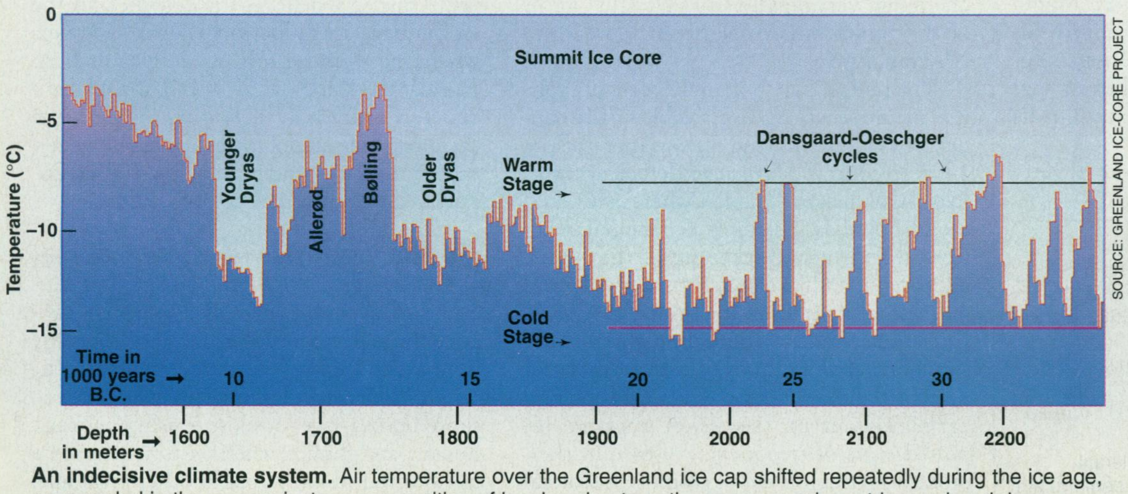
Now Bond, Broecker, Heinrich, and their colleagues have reanalyzed old sediment cores to get a clearer picture of the size and nature of these events, which took place at intervals of 10,000 years or so. Judging by the mineral composition of the ice-rafted debris, the icebergs came from the Laurentide ice sheet of eastern Canada. "The numbers of icebergs must have been immense," says Bond. "The Laurentide ice sheet was undergoing massive collapse."

These collapses, say Bond and his colleagues, are part of the emerging picture of ice-age climate oscillations. By determining the proportion of shells from cold-loving plankton in the sediment, the researchers found that each iceberg armada was preceded by a deepened chill across the Atlantic. And when the researchers compared the pattern of the ocean cold and iceberg surges with that of the Dansgaard-Oeschger oscillations, they found that the last four iceberg events coincided with cold phases of the climate swings over Greenland.

The iceberg releases don't recur with each climate swing; instead, as Bond reported at last December's meeting of the American Geophysical Union, the two kinds of events take place in counterpoint. Each ice sheet collapse marks the last of a series of increasingly colder swings of the climate system. After each collapse the climate system somehow resets itself; it makes an extreme swing to the warm side and begins a new sequence of oscillations.

How to explain this intricate dance of ice and climate is anybody's guess, says Bond. "We're learning so much, so fast, that any new model is liable to be quickly shown to be wrong." Still, the puzzle is so tempting that researchers are already venturing explanations.

At the annual meeting of the American Association for the Advancement of Science in February, for example, glaciologist Douglas MacAyeal of the University of Chicago offered an admittedly speculative two-stage scenario in which the ice sheet



An indecisive climate system. Air temperature over the Greenland ice cap shifted repeatedly during the ice age, as recorded in the oxygen isotope composition of ice. Ice sheets or the ocean may have triggered such jumps.

acts as master switch. MacAyeal notes that the Laurentide ice sheet served as a huge insulating blanket for the underlying bedrock, trapping the heat that flows up from Earth's interior. Eventually, the bottom layer of ice would have melted, he proposes. With the meltwater as a lubricant, the ice sheet would lose its footing and collapse to half its 2-kilometer height by unleashing icebergs. Then the ice sheet, having lost its pent-up heat, would begin to grow again.

That cycle of ice growth and collapse, MacAyeal thinks, might account for the repetitive temperature shifts seen in the Greenland ice record. Before collapse, cold winds would whip around the massive ice sheet in eastern Canada, keeping the region cold. But after the ice sheet collapsed and the cold winds abated, the ocean would warm gradually. The resulting evaporation, according to MacAyeal's scheme, would increase salinity and turn on deep-water formation and its attendant flow of heat from the south. Thus each ice sheet collapse would trip the ocean switch, unleashing a major pulse of warming. Between collapses, says MacAyeal, the ocean switch would make smaller oscillations of its own, driving the smaller intervening climate shifts.

If it takes ice sheets to flip the conveyor belt, that same climate switch should be pretty stable in today's post-ice-age world, say researchers. "My views have changed in the last year," says paleoceanographer Scott Lehman of the Woods Hole Oceanographic Institution. He had been quoted as saying that recent findings of abrupt climate change late in the ice age suggested that "the present climate is very delicately poised." Now Lehman says, "It seems that the conveyor may be a little more robust...than some scenarios had it."

But if the climate system has one switch, it may have others. Today's climate seems to have its own tremors, as researchers studying a link between changes in the Pacific and a decade of wild and woolly weather over North America have learned (*Science*, 20 March 1992, p. 1508). By studying the unruly climate of the last ice age, researchers are hoping they can find any other switches and put them out of bounds before humanity in its ignorance fiddles with them.

–Richard A. Kerr

Additional Reading

R. B. Alley *et al.*, "Abrupt Increase in Greenland Snow Accumulation at the End of the Younger Dryas Event," *Nature* **362**, 527 (1993).

G. Bond *et al.*, "Evidence for Massive Discharges of Icebergs Into the North Atlantic Ocean During the Last Glacial Period," *Nature* **360**, 245 (1992).

S. J. Johnsen *et al.*, "Irregular Glacial InterStadials Recorded in a New Greenland Ice Core," *Nature* **359**, 311 (1992).

MEETING BRIEFS

Old Feuds, New Finds Mark Anthropologists' Meeting

At the annual meeting of the American Association of Physical Anthropologists (AAPA), held in Toronto from 14 to 17 April, there were few dazzling fossils or fresh theories to steal the show. So researchers concentrated on the field's long-standing controversies. *Science* offers a sampler of some of the more spirited debates.

Seesawing on Syphilis

Ever since a syphilis-like disease ravaged Europe in the early 1500s, scientists and historians have been searching for the cause of the dreaded epidemics. One theory in particular has had a roller-coaster history, being favored in the early 1900s, rejected in the 1960s, and resurrected in the past few years. That's the idea that Columbus and his crew brought the scourge back from the New World. But new data presented at the Toronto meeting support the idea that the *Treponema* bacteria, which cause syphilis and related diseases, was present in the Old World long before Columbus set sail. The European picture is changing "very rapidly," says Donald Ortner of the Smithsonian's National Museum of Natural History.

D. J. ORTNER

Syphilitic sign. Crater-like scar suggests syphilis-causing bacteria were in Europe before 1492.

The notion that Columbus brought syphilis to Europe was made plausible by the paucity of evidence for the disease there before 1492. In contrast, *Treponema* left clear tracks in pre-Columbian America, where many skeletons show classic signs of treponemal infection: lesions and thickening of the bones, and, occasionally, a distinctive crater-like scar with radiating lines in the skull. At AAPA, three independent teams brought forward similar cases from Europe. Both Ortner and Ann Stirland, an independent anthropological consultant in Towcester, England, reported signs of treponemal disease in skeletons from English burial grounds; historical records suggest the bodies were buried before 1492. Stirland recovered three such skeletons from the church cemetery of St. Margaret In Combusto, in Norwich. Most convincingly, on the skull of one middle-aged male, she found the pattern of pits and star-shaped lines that is a definitive sign of treponemal infection. Ortner and his English colleagues reported on a young woman buried in Black Friar's Cemetery, Gloucester, whose skull also exhibits the stellate lesions, and whose limb bones have the characteristic scarring.

And *Treponema* may have plagued Europeans long before the Renaissance if Maciej Henneberg and his wife Renata Henneberg of the University of the Witwatersrand in Johannesburg, South Africa, are right. They found signs of treponemal disease, including thickened skulls and shin bones, in 47 of 272 skeletons found at Metaponto, a rural Greek colony in what is now southern Italy. Grave goods buried with the skeletons suggest dates of 600 B.C. to 250 B.C.

But these finds haven't convinced everyone. While the Metaponto skeletons are undeniably ancient, the bony pathologies they display could have been caused by other diseases, such as anemia, insists George Armelagos of Emory University in Atlanta. And the English skulls haven't been precisely dated yet. Armelagos believes the evidence for the Columbian introduction theory is "overwhelming —thousands of individuals from Florida to Ohio," while the European evidence is equivocal, relying on a handful of skeletons. He and Ortner agree, however, that more data—and better dates—from European graveyards may resolve the issue.

Gorilla Genetics

Some of the most interesting science happens through serendipity, and anthropology is no exception. For example, Maryellen Ruvolo of Harvard University was seeking to shore up her case for close kinship between humans and chimps, when she turned up some unexpected results about another great ape, the gorilla. Her new data, and unpublished